

This discussion paper is/has been under review for the journal Biogeosciences (BG).  
Please refer to the corresponding final paper in BG if available.

# Pteropods from the Caribbean Sea: dissolution as an indicator of past ocean acidification

**D. Wall-Palmer<sup>1</sup>, M. B. Hart<sup>1</sup>, C. W. Smart<sup>1</sup>, R. S. J. Sparks<sup>2</sup>, A. Le Friant<sup>3</sup>,  
G. Boudon<sup>3</sup>, C. Deplus<sup>3</sup>, and J. C. Komorowski<sup>3</sup>**

<sup>1</sup>School of Geography, Earth & Environmental Sciences, University of Plymouth, Drake Circus,  
Plymouth PL4 8AA, UK

<sup>2</sup>Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road,  
Bristol BS8 1RJ, UK

<sup>3</sup>Institute du Physique du Globe de Paris, Case 89, 1 rue Jussieu, 75238 Paris cedex 05,  
France

Received: 24 June 2011 – Accepted: 6 July 2011 – Published: 13 July 2011

Correspondence to: D. Wall-Palmer (deborah.wall-palmer@plymouth.ac.uk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

**BGD**

8, 6901–6917, 2011

## Pteropods from the Caribbean Sea

D. Wall-Palmer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

The aragonite shell-bearing thecosome pteropods are an important component of the oceanic plankton. However, with increasing  $p\text{CO}_2$  and the associated reduction in oceanic pH (ocean acidification), thecosome pteropods are thought to be particularly vulnerable to shell dissolution. The distribution and preservation of pteropods over the last 250,000 years have been investigated in marine sediment cores from the Caribbean Sea close to the island of Montserrat. Using the *Limacina* Dissolution Index (LDX), fluctuations in pteropod dissolution through the most recent glacial/interglacial cycles is documented. By comparison to the oxygen isotope record (global sea ice volume), we show that pteropod dissolution is closely linked to global changes in  $p\text{CO}_2$  and pH and is, therefore, a global signal. These data are in agreement with the findings of experiments upon living pteropods, which show that variations in pH can greatly affect aragonitic shells. The results of this study provide information which may be useful in the prediction of future changes to the pteropod assemblage caused by ocean acidification.

## 1 Introduction

The faunal responses to ocean acidification are still largely unknown, although experimental evidence reveals that a reduction in pH typically leads to a decrease in calcification rates of a number of, but not all organisms (Feely et al., 2004; Orr et al., 2005; Guinotte and Fabry, 2008; Turley et al., 2010). To date, little information is available about important planktic producers of calcium carbonate. Several studies have investigated coccolithophore and planktic foraminiferal responses, but only three species of the aragonite-producing thecosome pteropods have been considered (Fabry et al., 2008; Comeau et al., 2009, 2010a, b). Here we demonstrate a relationship between the dissolution of pteropod shells and the oxygen isotope record through the last 250 000 yr. A diverse and abundant assemblage of pteropods and heteropods is

**BGD**

8, 6901–6917, 2011

## Pteropods from the Caribbean Sea

D. Wall-Palmer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



recorded from marine cores collected from the Caribbean Sea offshore Montserrat. A number of these cores contain intervals of well-preserved pteropods which are associated with the glacial periods of the Late Pleistocene (Messenger et al., 2010). These well-preserved levels appear to be of widespread significance and a response to global climate change.

The group of holoplanktic molluscs known as the Pteropoda consists of two orders; the shell-less gymnosomes and the shell-bearing thecosomes (Fig. 1). These two orders are now considered to be less closely related than originally thought, but the term “pteropod” is still widely used (van der Spoel, 1976; Bé and Gilmer, 1977; Lalli and Gilmer, 1989). Thecosome pteropods are a common component of the water column throughout the world’s oceans and can reach densities of up to 10 000 individuals per cubic metre (The Royal Society, 2005; Fabry et al., 2008). They are consequently important prey to a number of large cetaceans and commercial fish (The Royal Society, 2005). This study focuses on the species *Limacina inflata*, a common euthecosome (suborder of thecosomata) pteropod.

All euthecosome pteropods produce calcareous shells from aragonite, a polymorph of calcium carbonate, which is particularly susceptible to dissolution (50 % more susceptible than calcite): see Mucci (1983), Millero (1996), Morse and Arvidson (2002) and Klöcker et al. (2006). This makes their shells extremely vulnerable to dissolution due to ocean acidification and also means that, upon death, their shells frequently dissolve as they settle through the water column to the sea floor. This limits their occurrence in sediments to water depths of less than 3000 m and also restricts their presence in the geological record (Curry, 1971; Herman, 1971; Berner, 1977). The distribution of the modern fauna is well known (Bé and Gilmer, 1977) and “pteropod oozes” have been recognised for over one hundred years (Murray and Renard, 1891). With current increasing levels of atmospheric CO<sub>2</sub> and the resulting ocean acidification (Orr et al., 2005; The Royal Society, 2005), pteropods with their aragonitic shells are the subject of renewed interest, since they are likely to be the most vulnerable of the major planktic producers of CaCO<sub>3</sub>. They are also likely to be the first planktic fauna

**Pteropods from the Caribbean Sea**

D. Wall-Palmer et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

to experience persistent decreased  $\text{CaCO}_3$  saturation states. As an important part of the food web, especially in the Arctic and Southern Oceans, their potential demise is of great significance.

## 2 Marine sediment cores from Montserrat

5 In March 2002, as part of a multi-disciplinary project on the volcanic activity on the island of Montserrat, the RV *L'Atalante* recovered a series of piston-cores from the ocean floor surrounding the island (Fig. 2). Of the 12 cores collected on the “Caraval Cruise”, CAR-MON 2 provides the longest time record (Le Friant et al., 2008). The site of CAR-MON 2, in 1102 m of water, is located at  $16^\circ 27.699' \text{ N}$ ,  $62^\circ 38.077' \text{ W}$ . The other  
10 sediment cores used in this research (CAR-MON 1, 3 and 4) are of much shorter length but provide comparable records. The oxygen isotope ( $\delta^{18}\text{O}$ ) profile of CAR-MON 2 (Fig. 3) gives an accurate record of the Marine Isotope Stages (MIS) back  $\sim 250\,000$  yr BP and the record compares well with other studies (Imbrie et al., 1984; Prell et al., 1986). This  $\delta^{18}\text{O}$  profile has been verified using a limited number of AMS radiocarbon  
15 dates and  $^{39}\text{Ar}/^{40}\text{Ar}$  radiometric dates (Le Friant et al., 2008). Using the  $>150\ \mu\text{m}$  size fraction, counts of the planktic foraminifera have allowed the determination of the *Globorotalia menardii* zonation (Ericson and Wollin, 1956; Reid et al., 1996; Le Friant et al., 2008).

Dissolution of *Limacina inflata* shells has been quantified throughout CAR-MON 2  
20 using the scale published by Gerhardt and Henrich (2001). As the *Limacina* Dissolution Index (LDX) has only been used by a limited number of workers (e.g. Klöcker et al., 2006) on “fossil” material, its calculation is now described.

Pre-processed and dried sediment (Le Friant et al., 2008) was used to collect just  
25 over 300 (or as many as were present) pteropod specimens from two size fractions ( $>500\ \mu\text{m}$  and  $150\text{--}500\ \mu\text{m}$ ) at varying intervals. Only whole specimens that retained their protoconch and protoconch fragments were counted. Determination of the dissolution of the pteropod shells was made using the *Limacina* Dissolution Index (LDX)

**BGD**

8, 6901–6917, 2011

## Pteropods from the Caribbean Sea

D. Wall-Palmer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



which was devised by Gerhardt et al. (2000) and published as a scale by Gerhardt and Henrich (2001). This method involves the qualitative analysis of the surface of the pteropod shell on a scale of 0 to 5; 0 being a pristine, transparent, lustrous shell with a smooth surface and 5 being an opaque, white and completely lustreless shell with additional damage. At least 10 shells (max 30 shells) of adult *Limacina inflata* of a size of 300 µm or larger were allocated a value from this scale by the use of light microscopy for each sample. The average for each sample was then calculated to provide the LDX value.

### 3 Correlation of pteropod dissolution record

CAR-MON 2 records two levels of particularly well preserved, abundant and diverse pteropods (Fig. 3), which have been documented previously (Le Friant et al., 2008; Messenger et al., 2010) but not studied in detail. The upper concentration of pteropods is found in MIS 2 and has been dated at around 25 000 yr BP (55–80 cm), with a peak in pteropod preservation at MIS 2.2 (~20 000 yr BP). The lower concentration of pteropods is within MIS 6 (295–425 cm) with a peak in preservation at MIS 6.4, dated at about 150 000 yr BP. The upper concentration of pteropods corresponds almost exactly with the “pteropod sands” reported by Chen (1968) from the Gulf of Mexico, Venezuela Basin and other occurrences in the Caribbean Sea, Mediterranean Sea and Red Sea. Chen (1968) suggests that their widespread occurrence was controlled by Late Pleistocene climate changes, although this work is often overlooked in the modern literature.

This latest Pleistocene occurrence of abundant pteropods has also been recorded in the Andaman Sea (Sijinkumar et al., 2010), in the Red Sea (Almogi-Labin et al., 1991), off-shore Florida (Gardulski et al., 1990), on the western flank of the Great Bahama Bank (Eberli et al., 1997; Messenger et al., 2010), on the Brazilian Slope (Gerhardt et al., 2000), in the Caribbean Sea (Haddad and Droxler, 1996), off-shore Somalia (Klöcker and Henrich, 2006; Klöcker et al., 2006) and in the South China Sea (Wang et al., 1997). In the cores from the South China Sea and the Caribbean Sea, the concentrations at ~20 000 yr BP and 150 000 yr BP are both recorded, clearly

## Pteropods from the Caribbean Sea

D. Wall-Palmer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



demonstrating that this enhanced preservation of aragonitic fossils is of global significance and not the result of local variations in water chemistry (Peterson and Cofer-Shabica, 1987; Peterson, 1990, Broecker and Clark, 2002; Sepulcre et al., 2009). Elsewhere in the CAR-MON 2 core, increased shell dissolution occurs during interglacial periods and is particularly poor during extreme stages, such as at MIS 5.5. In the Gulf of Aden (Core KL15), Almogi-Labin et al. (2000) record the near absence of pteropods during interglacials (MIS 13, 11, 9, 7, 5 and 1). The record from this core shows that pteropod maxima appear to be at the glacial/interglacial transitions (especially the MIS 6 to MIS 5 transition). Such deglaciation “spikes” have also been noted by Frenzel (1975) and Berger (1977, 1990). Berger (1977) describes this world-wide phenomenon as a pteropod-rich layer present at the end of the last glacial, although, the exact timing and cause of this event are in some dispute. Serre-Bachet and Guiot (1987) also linked pteropod preservation to colder periods. This link is particularly striking in the post-MIS 2 records in the N.E. Atlantic Ocean (Ganssen and Lutze, 1982; Ganssen et al., 1991), Equatorial Atlantic Ocean (Kassens and Sarntheim, 1989) and the N. W. Indian Ocean (Klöcker et al., 2006). This preservation relationship to colder periods is, almost certainly, due to fluctuations in  $p\text{CO}_2$  causing higher pH during glaciations (Sanyal et al., 1995; Ruddiman, 2001; Hönisch and Hemming, 2005; Yu et al., 2007) and lower pH during interglacials. In the CAR-MON 2 data there are some unexpected excursions from the general trend, which show that variations in dissolution are not directly proportional to the  $\delta^{18}\text{O}$  signal. This can be seen particularly between MIS 5.1 and 5.5, where changes in dissolution appear to be accentuated.

Several factors during the sedimentation process, which are summarised in Fig. 4, may have influenced the LDX dissolution profile. The pattern produced by the LDX profile could not, however, be an artefact of sea floor dissolution and diagenesis. If pteropods within CAR-MON 2 showed a general trend from LDX 0–2 in the near-surface sediments to LDX 4–5 at depth, this would clearly be a diagenetic signal, however, this is not the case. Klöcker et al. (2006) have also noted that, in their core 905 from the N.W. Indian Ocean, diagenesis has had minimal effect on the LDX record.

**BGD**

8, 6901–6917, 2011

## Pteropods from the Caribbean Sea

D. Wall-Palmer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The correlation of pteropod abundances in MIS 2 and MIS 6 across a range of oceans and environments also implies that the LDX profile is caused by a global climate signal and not merely by variations in local water chemistry.

Water chemistry around the Lesser Antilles island arc is however, complicated by influences of several water masses flowing between the islands and through a number of deeper passages into the Caribbean Sea (Peterson and Cofer-Shabica, 1987; Peterson, 1990, Broecker and Clark, 2002; Sepulcre et al., 2009). Gerhardt and Henrich (2001) found that the influence of Antarctic Intermediate Water (AAIW), towards the south of the island arc, caused moderate to very poor preservation of *Limacina inflata*. However, towards the north of the island arc, the influence of AAIW is minor due to a large volume of Upper North Atlantic Deep Water (UNADW), which flows through the nearby Anegada Passage. This area consequently shows very good preservation of *Limacina inflata*. Gerhardt and Henrich (2001) place the aragonite saturation depth at 2000 m and the Aragonite Compensation Depth (ACD) at 3800 m water depth in this area. CAR–MON 2 was collected in 1102 m water depth, which is above the aragonite lysocline and ACD, thus discounting any effects that this may cause. A possible interference in the dissolution profile may be caused by inputs of volcanic ash, which can change the oceanic pH in the local area dramatically during and just after an eruption. A recent study has shown that, under laboratory conditions, volcanic materials entering sea water produce a significant change in pH (Jones and Gislason, 2008). This local impact on the pteropod fauna has been investigated and described elsewhere (Jones et al., 2009; Wall-Palmer et al., 2011). However, our observations suggest that, in this case, the ash from the South Soufrière Hills volcano has had little or no effect upon the overall LDX profile. This is because the ash found within CAR-MON 2 is the result of several relatively short-lived events rather than one large, long-lasting event. Ash from these individual eruptions would have been so greatly diluted upon entering the ocean, that the acidic impact upon surface water fauna would have been insignificant. The assumption that the LDX profile is the result of changing oceanic pH is in agreement with recent laboratory work on living pteropods (Fabry et al., 2008; Comeau et al.,

**BGD**

8, 6901–6917, 2011

## Pteropods from the Caribbean Sea

D. Wall-Palmer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2009, 2010a, b) and pteropods from sediment traps in the Southern Ocean (Roberts et al., 2008). It also compares favourably with shell-weight data of *Globigerina bulloides* provided by recent work in the Southern Ocean (Barker and Elderfield, 2002; Moy et al., 2009).

5 Our results suggest that the distribution and abundance of shelled pteropod and heteropod fauna, and the quality of their preservation through the last 250 000 yr, provides a model for changes caused by climate variations. This signal appears to be worldwide and may help to predict future changes in the aragonitic holoplanktic fauna caused by increases in  $p\text{CO}_2$  and the resulting changes in oceanic pH. However, since the level  
10 of anthropogenic  $\text{CO}_2$  entering the oceans is now increasing at a rate 100 times faster than any changes seen in the past 650 000 yr (Fabry et al., 2008), it might be inappropriate to apply such a model to the modern oceans. The fate of the modern-day aragonitic holoplankton is uncertain, however, this study shows that, at oceanic pH levels relatively higher than those predicted for the 21st Century, euthecosome pteropods  
15 have been noticeably affected.

*Acknowledgements.* The authors acknowledge receipt of a Research Grant from The Leverhulme Trust (F/00 568/P to Hart, Smart and Sparks), funding from NERC (NER/A/S2002/00963 to Sparks and Talling) for JR123 cruise to Montserrat in 2005 and funding from NERC to cover stable isotope analysis at the National Isotope Geoscience Laboratory (Keyworth). Some data  
20 presented here are part of a PhD (Wall-Palmer) funded by the University of Plymouth. The authors wish to thank G. M. Ganssen (The Netherlands) and A. Almogi-Labin (Israel) for their advice on the distribution of pteropods in the Late Pleistocene IGP contribution number 3198.

## References

- 25 Almogi-Labin, A., Hemleben, C., Meischner, D., and Erlenkeuser, H.: Paleoenvironmental events during the last 13,000 years in the Central Red Sea as recorded by Pteropoda, *Paleoceanography*, 6, 83–98, 1991.
- Almogi-Labin, A. Schmiedel, G., Hemleben, C., Siman-Tov, R., Segl, M., and Meischner, D.: The influence of the NE winter monsoon on productivity changes in the Gulf of Aden, NW

## Pteropods from the Caribbean Sea

D. Wall-Palmer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Pteropods from the Caribbean Sea

D. Wall-Palmer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Arabian Sea, during the last 530 kyr as recorded by foraminifera, *Mar. Micropaleontol.*, 40, 295–319, 2000.
- Barker, S. and Elderfield, H.: Foraminiferal calcification response to glacial-interglacial changes in atmospheric CO<sub>2</sub>, *Science*, 297, 833–836, 2002.
- 5 Bé, A. W. H. and Gilmer, R. W.: A zoogeographic and taxonomic review of *Euthecosomatous Pteropoda*, in: *Oceanic Micropaleontology*, edited by: Ramsay, A. T. S., Vol. 1, Academic Press, New York, 733–808, 1977.
- Berger, W. H.: Deep-sea carbonate and the deglaciation preservation spike in pteropods and foraminifera, *Nature*, 269, 301–303, 1977.
- 10 Berger, W. H.: The Younger Dryas cold spell – a search for causes, *Global and Planetary Change*, 89(3), 219–237, 1990.
- Berner, R. A.: Sedimentation and dissolution of pteropods in the ocean, in: *The fate of fossil fuel CO<sub>2</sub> in the oceans*, edited by: Anderson, N.R. and Malahoff, A., Plenus Press, New York, 243–260, 1977.
- 15 Broecker, W. S. and Clark, E.: Carbonate ion concentration in glacial-age deep waters of the Caribbean Sea, *Geochem. Geophys. Geosy.*, 3(3), 1–14, doi:10.1029/2001GC00023, 2002.
- Byrne, R. H., Acker, J. G., Betzer, P. R., Feely, R. A., and Gates, M. H.: Water column dissolution of aragonite in the Pacific Ocean, *Nature*, 312, 321–326, 1984.
- Chen, C.: Pleistocene pteropods in pelagic sediments, *Nature*, 219, 1145–1149, 1968.
- 20 Comeau, S., Gorsky, G., Jeffree, R., Teyssié, J.-L., and Gattuso, J.-P.: Impact of ocean acidification on a key Arctic pelagic mollusc (*Limacina helicina*), *Biogeosciences*, 6, 1877–1882, doi:10.5194/bg-6-1877-2009, 2009.
- Comeau, S., Jeffree, R., Teyssié, J.-L., and Gattuso, J.-P.: Response of the Arctic Pteropod *Limacina helicina* to projected future environmental conditions, *PLoS ONE*, 5(6), e11362, 1–7, 2010a.
- 25 Comeau, S., Gorsky, G., Alliouane, S., and Gattuso, J.-P.: Larvae of the pteropod *Cavolinia inflexa* exposed to aragonite undersaturation are viable but shell-less, *Marine Biology*, 157(10), 2341–2345, 2010b.
- Curry, D.: The occurrence of pre-Quaternary pteropods, in: *The Micropalaeontology of Oceans*, edited by: Funnell, B. M. and Reidel, W. R., Cambridge University Press, Cambridge, 595, 1971.
- 30 Eberli, G. P., Swart, P. K., Malone, M. J., Anselmetti, F. S., Arai, K., Berner, K. H., Betzler, C., Christensen, B. A., De Carlo, E. H., Déjardin, P. M., Emmanuel, L., Frank, T. D., Haddad,

## Pteropods from the Caribbean Sea

D. Wall-Palmer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- G. A., Isern, A. R., Katz, M. E., Kenter, J. A. M., Kramer, P. A., Kroon, D., McKenzie, J. A., McNeill, D. F., Montgomery, P., Nagihara, S., Pirmez, C., Reijmer, J. J. G., Sato, T., Schovsbo, N. H., Williams, T., and Wright, J. D.: Site 1003, Proceedings of the Ocean Drilling Program, Initial Reports, College Station, Texas (Ocean Drilling Program), 166, 71–116, 1997.
- 5 Ericson, D. B. and Wollin, G.: Micropaleontological and isotopic determination of Pleistocene climates, *Micropaleontology*, 2, 257–270, 1956.
- Fabry, V. J., Seibel, B. A., Feely, R. A., and Orr, J. C.: Impacts of ocean acidification on fauna and ecosystem processes, *ICES J. Mar. Sci.*, 65, 414–432, 2008.
- 10 Feely, R. A., Sabine, C. L., Lee, K., Berelson, W., Kleyvas, J., Fabry, V. J., and Millero, F. J.: Impact of anthropogenic CO<sub>2</sub> on the CaCO<sub>3</sub> system in the oceans, *Science*, 305, 362–366, doi:10.1126/science.1097329, 2004.
- Frenzel, B.: The distribution pattern of Holocene climatic change in the Northern Hemisphere, in: Proceedings of the WMO/IAMAP Symposium on Long-Term Climatic Fluctuations, Geneva, convenor: Lamb, H., World Meteorological Organization, 105–118, 1975.
- 15 Ganssen, G. M. and Lutze, G. F.: The aragonite compensation depth at the northeastern Atlantic continental margin, “Meteor” *Forsch.-Ergebnisse, C*, No. 36, 57–59, 1982.
- Ganssen, G. M., Troelstra, S. R., Van Der Borg, K., and De Jong, A. M. F.: Late Quaternary pteropod preservation in Eastern North Atlantic sediments in relation to climate change, *Radiocarbon*, 33(3), 277–282, 1991.
- 20 Gardulski, A. F., Mullins, H. T., and Weiterman, S.: Carbonate mineral cycles generated by foraminiferal and pteropods response to Pleistocene climate: west Florida ramp slope, *Sedimentology*, 37, 727–743, 1990.
- Gerhardt, S. and Henrich, R.: Shell preservation of *Limacina inflata* (Pteropoda) in surface sediments from the Central and South Atlantic Ocean: a new proxy to determine the aragonite saturation state of water masses, *Deep-Sea Res. Pt. I*, 48, 2051–2071, 2001.
- 25 Gerhardt, S., Groth, H., Rühlemann, C., and Henrich, R.: Aragonite preservation in late Quaternary sediment cores on the Brazilian Continental Slope: implications for intermediate water circulation, *Int. J. Earth Sci.*, 88, 607–618, 2000.
- Guinotte, J. M. and Fabry, V. J.: Ocean acidification and its potential effects on marine ecosystems, *New York Academy of Sciences*, 1134, 320–342, 2008.
- 30 Haddad, G. A. and Droxler, A. W.: Metastable CaCO<sub>3</sub> dissolution at intermediate water depths of the Caribbean and western North Atlantic: implications for intermediate water circulation during the past 200,000 years, *Paleoceanography*, 11, 701–716, 1996.

- Herman, Y.: 1971 Vertical and horizontal distribution of pteropods in Quaternary sequences, in: The Micropalaeontology of Oceans, edited by: Funnell, B. M. and Reidel, W. R., Cambridge University Press, Cambridge, 463–486, 1971.
- Hönish, B. and Hemming, N.G.: Surface ocean pH response to variation in  $p\text{CO}_2$  through two full glacial cycles, *Earth Planet. Sci. Lett.*, 239, 305–314, doi:10.1016/j.epsl.2005.04.027, 2005.
- Imbrie, J., Hays, J. D., Martinson, D. G., McIntyre, A. and Mix, A. C.: The orbital theory of Pleistocene climate: support from a revised chronology of the marine  $\delta^{18}\text{O}$  record, in: Milankovitch and Climate, edited by: Berger, A. L., Imbrie, J., Hays, J. D., Kukla, G., and Saltzman, B. Part 1, Reidel, Hingham, MA, 269–305, 1984.
- Jones, M. T. and Gislason, S. R.: Rapid releases of metal salts and nutrients following the deposition of volcanic ash into aqueous environments, *Geochim. Cosmochim. Ac.*, 72, 3661–3680, 2008.
- Jones, M. T., Fisher, J. K., and Palmer, M. R.: Ocean acidification from explosive volcanism as a cause of mass mortality of pteropods, *Geochim. Cosmochim. Ac.*, 73(13), Supplement 1, A604, 2009.
- Kassens, H. and Sarnthein, M.: A link between paleoceanography, early diagenetic cementation and shear strength maxima in Late Quaternary sediments, *Paleoceanography*, 4(3), 253–269, 1989.
- Klöcker, R. and Henrich, R.: Recent and Late Quaternary pteropod preservation on the Pakistan shelf and continental slope, *Mar. Geol.*, 231, 103–111, 2006.
- Klöcker, R., Ganssen, G., Jung, S. J. A., Kroon, D., and Henrich, R.: Late Quaternary millennial-scale variability in pelagic aragonite preservation off Somalia, *Mar. Micropaleontol.*, 59, 171–183, 2006.
- Lalli, C. M. and Gilmer, R. W.: *Pelagic Snails: The biology of holoplanktonic gastropod molluscs*, Stanford University Press, California, 1989.
- Le Friant, A., Harford, C. L., Deplus, C., Boudon, G., Sparks, R. S. J., Herd, R. A., and Komorowski, J. C.: Geomorphological evolution of Montserrat (West Indies): Importance of flank collapse and erosional processes, *J. Geol. Soc. London*, 161(1), 147–160, 2004.
- Le Friant, A., Lock, E. J., Hart, M. B., Boudon, G., Sparks, R. S. J., Leng, M. J., Smart, C. W., Komorowski, J. C., Deplus, C., and Fisher, J. K.: Late Pleistocene tephrochronology of marine sediments adjacent to Montserrat, Lesser Antilles volcanic arc, *J. Geol. Soc. London*, 165, 279–289, 2008.

## Pteropods from the Caribbean Sea

D. Wall-Palmer et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## Pteropods from the Caribbean Sea

D. Wall-Palmer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Messenger, R. W., Hart, M. B., Smart, C. W., Leng, M. J., Lock, E. J., and Howard, A. K.: Pteropod faunas as indicators of Late Pleistocene climate change in the Caribbean Sea, in: *Micropalaeontology, Sedimentary Environments and Stratigraphy: A tribute to Dennis Curry (1912–2001)*, edited by: Whittaker, J. E., and Hart, M. B., The Micropalaeontological Society Special Publications, 17–28, 2010.

Millero, F. J.: *Chemical Oceanography*, CRC Press, Boca Raton, Florida, USA, 1996.

Morse, J. W. and Arvidson, R. S.: The dissolution kinetics of major sedimentary carbonate minerals, *Earth-Sci. Rev.*, 58, 51–84, 2002.

Moy, A. D., Howard, W. R., Bray, S. G., and Trull, T. W.: Reduced calcification in modern Southern Ocean planktonic foraminifera, *Nature Geoscience*, doi:10.1038/NGEO460, 2009.

Mucci, A.: The solubility of calcite and aragonite in sea water at various salinities, temperatures and one atmosphere total pressure, *Am. J. Sci.*, 283, 780–799, 1983.

Murray, J. and Renard, A. F.: Deep-sea deposits, Scientific Report of the Challenger Expedition, 1873–1876, 1891.

Orr, J. C., Fabry, V. J., Aumont, O., Bopp, L., Feely, R. A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R. M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R. G., Plattner, G.-K., Rodgers, K. B., Sabine C. L., Sarmiento, J. L., Schlitzer, R., Slater, R. D., Totterdell, I. J., Weirig, M.-F., Yamanaka, Y., and Yool, A.: Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms, *Nature*, 437, 681–686, 2005.

Peterson, L. C.: Late Quaternary paleoceanography of the mid-depth Atlantic: Proxy records from the deep Caribbean Sea, *Eos Trans. AGU*, 43(71), 1382, 1990.

Peterson, L. C. and Cofer-Shabica, N. B.: Bruhes Cron records of sedimentation and abyssal paleocirculation in the Venezuela Basin, eastern Caribbean sea, *GSA, Abstracts with Programs*, 19, 804, 1987.

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., Benders, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E., and Stievenard, M.: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature*, 399, 429–436, 1999.

Prell, W. L., Imbrie, J., Martinson, D. G., Morley, J. J., Pisias, N. G., Shackleton, N. J. and Streeter, H. F.: Graphic correlation of oxygen isotope stratigraphy application to the Late Quaternary, *Paleoceanography*, 1, 137–162, 1986.

## Pteropods from the Caribbean Sea

D. Wall-Palmer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Reid, R. P., Carey, S. N., and Ross, D. R.: Late Quaternary sedimentation in the Lesser Antilles island arc, *Geol. Soc. Am. Bull.*, 108, 78–100, 1996.
- Ruddiman, W. F.: *Earth's climate past and future*, W. H. Freeman & Company, New York, p. 465, 2001.
- 5 Roberts, D., Howard, W. R., Moy, A. D., Roberts, J. L., Trull, T. W., Bray, S. G., and Hopcroft, R. R.: Interannual variability of pteropod shell weights in the high-CO<sub>2</sub> Southern Ocean, *Biogeosciences Discuss.*, 5, 4453–4480, doi:10.5194/bgd-5-4453-2008, 2008.
- Sanyal, A., Hemming, N. G., Hanson, G. N., and Broecker, W. S.: Evidence for a higher pH in the glacial ocean from boron isotopes in foraminifera, *Nature*, 373, 234–236, 1995.
- 10 Sepulcre, S., Tachikawa, K., Vidal, L., Thouveny, N., and Bard, E.: Preservation state of metastable magnesian calcite in periplatform sediments from the Caribbean Sea over the last million years, *Geochem. Geophys. Geosy.*, 10, Q11013, doi:10.1029/2009gc002779, 2009.
- Serre-Bachet, F. and Guiot, J.: Summer temperature changes from tree-rings in the Mediterranean area during the last 800 years, in: *Abrupt Climate Change*, edited by: Berger, W. H., and Labeyrie, L. D., D. Reidel, Dordrecht, Netherlands, 89–97, 1987.
- 15 Sijinkumar, A. V., Nagender Nath, B., and Guptha, M. V. S.: Late Quaternary record of pteropod preservation from the Andaman Sea, *Mar. Geol.*, 275, 221–229, 2010.
- Spoel, S. van der: *Pseudothecosomata, Gymnosomata and Heteropoda*, Bohn, Scheltema & Holkema, Utrecht, 1976.
- 20 The Royal Society: *Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide. Policy Document 12/05*. The Royal Society, London, UK, 2005.
- Turley, C., Eby, M., Ridgwell, A. J., Schmidt, D. N., Brownlee, C., Findlay, H. S., Fabry, V. J., Feely, R. A., Riebesell, U., and Gattuso, J.-P.: The societal challenge of ocean acidification, *Mar. Pollut. Bull.*, 60, 787–792, 2010.
- 25 Wall-Palmer, D., Jones, M. T., Hart, M. B., Fisher, J. K., Smart, C. W., Hembury, D. J., Palmer, M. R., and Fones, G. R.: Explosive volcanism as a cause for mass mortality of pteropods, *Mar. Geol.*, 282, 231–239, 2011.
- Wang, L. Jian, Z., and Chen, J.: Late Quaternary pteropods in the South China Sea: carbonate preservation and palaeoenvironmental variation, *Mar. Micropaleontol.*, 32, 115–126, 1997.
- 30 Yu, J., Elderfield, H., and Hönish, B.: B/Ca in planktonic foraminifera as a proxy for surface water pH, *Paleoceanography*, 22, PA2202, doi:10.1029/2006PA001347, 2007.

Pteropods from the  
Caribbean Sea

D. Wall-Palmer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

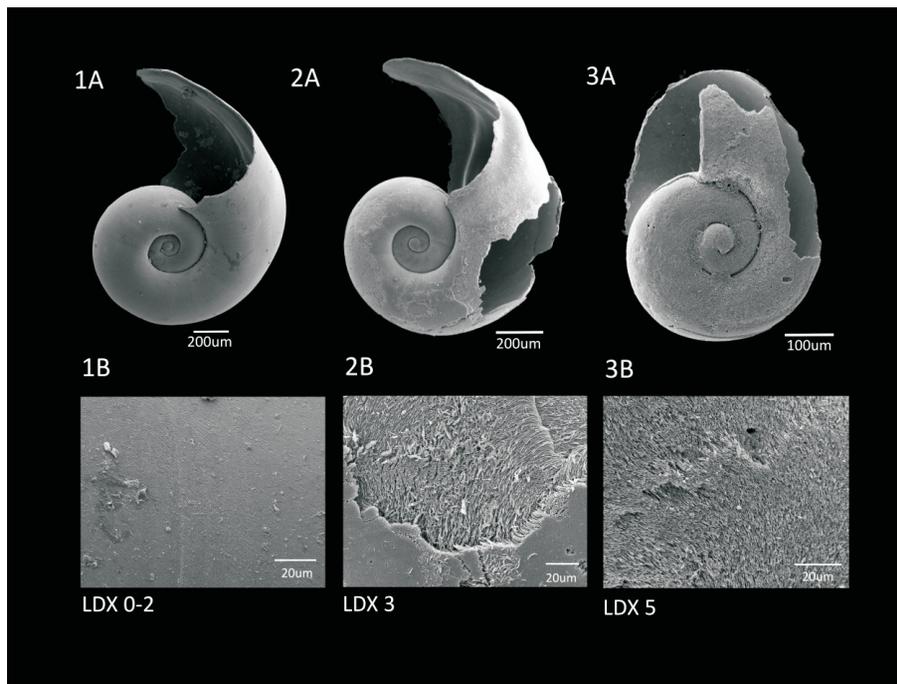
Back

Close

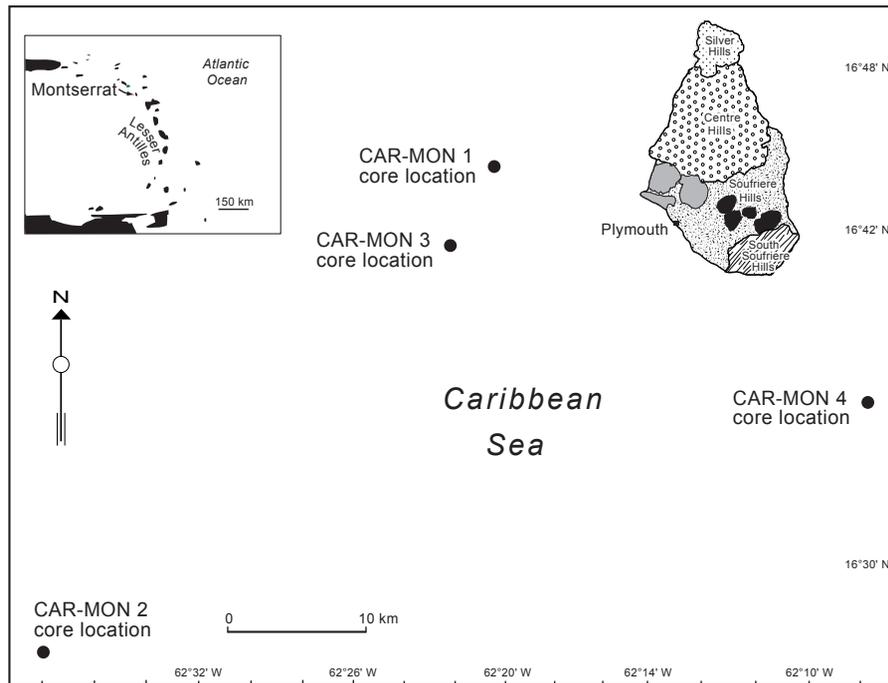
Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Fig. 1.** Thecosome pteropod *Limacina inflata* from the Caribbean Sea near Montserrat at different stages of shell dissolution.



**Fig. 2.** Map of the Lesser Antilles showing the island of Montserrat and the location of the cores CAR-MON 1, 2, 3 and 4. A full bathymetric map of the area is available in Le Friant et al. (2004).

**BGD**

8, 6901–6917, 2011

## Pteropods from the Caribbean Sea

D. Wall-Palmer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

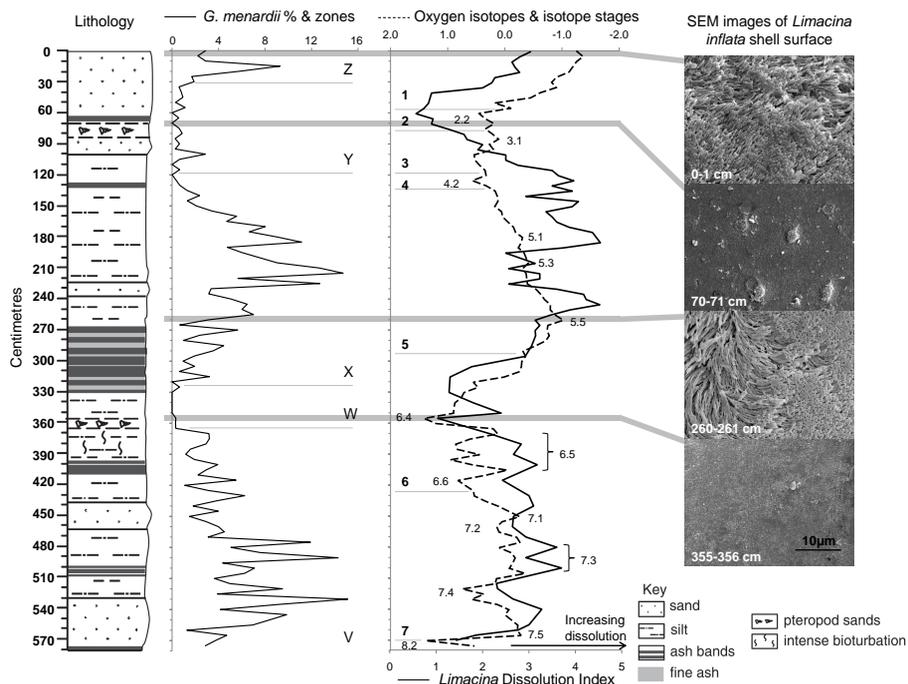
Printer-friendly Version

Interactive Discussion



Pteropods from the Caribbean Sea

D. Wall-Palmer et al.



**Fig. 3.** Sedimentary log for core CAR-MON 2, *Globorotalia menardii* stratigraphy, stable isotope stratigraphy (Marine Isotope Stages) and pteropod dissolution (LDX): partly modified after Le Friant et al. (2008).

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

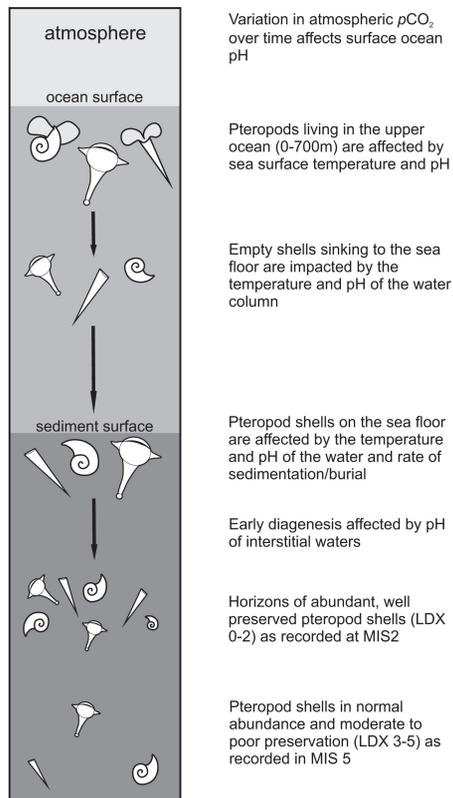
Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Fig. 4.** Hypothetical model of pteropod sedimentation, taphonomy and preservation for areas of the sea floor above the aragonite lysocline and aragonite compensation depth. Preservation of pteropod shells is, potentially, impacted by water chemistry during life, passage through the water column (probably minimal as they have quite high settling rates of  $1\text{--}2.5\text{ cm s}^{-1}$ ; see Byrne et al., 1984), on the water/sediment surface and during burial.

**Pteropods from the Caribbean Sea**

D. Wall-Palmer et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

