Skeletal mineralogy of coral recruits under high temperature and pCO_2

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Abstract

Aragonite, which is the polymorph of $CaCO_3$ precipitated by modern corals during skeletal formation, has a higher solubility than the more stable polymorph calcite. This higher solubility may leave animals that produce aragonitic skeletons more vulnerable to anthropogenic ocean acidification. It is therefore important to determine whether scleractinian corals have the plasticity to adapt and produce calcite in their skeletons in response to changing environmental conditions. Both high $p\mathrm{CO}_2$ and lower Mg/Ca ratios in seawater are thought to have driven changes in the skeletal mineralogy of major marine calcifiers in the past ~540 Ma. Experimentally reduced Mg/Ca ratios in ambient seawater have been shown to induce some calcite precipitation in both adult and newly settled modern corals; however, the impact of high $p\mathrm{CO}_2$ on the mineralogy of recruits is unknown. Here we determined the skeletal mineralogy of one-month old *Acropora spicifera* coral recruits grown under high temperature (+3°C) and $p\mathrm{CO}_2$ (~900 µatm) conditions, using X-ray diffraction and Raman spectroscopy. We found that newly settled coral recruits produced entirely aragonitic skeletons regardless of the treatment. Our results show that elevated $p\mathrm{CO}_2$ alone is unlikely to drive changes in the skeletal mineralogy of young corals. Not having an ability to switch from aragonite to calcite precipitation may leave corals and ultimately coral reef ecosystems more susceptible to predicted ocean acidification. An important area for prospective research would be to investigate the combined impact of high $p\mathrm{CO}_2$ and reduced Mg/Ca ratio on coral skeletal mineralogy.

1 Introduction

Scleractinian corals are the major reef builders, with their skeletons providing the structural basis for the habitats of many marine organisms. In modern adult corals, the skeletons are comprised of aragonite, a polymorph of calcium carbonate ($CaCO_3$) whose stability is highly sensitive to changes in ocean pCO_2 (Orr et al., 2005; Feely et al., 2009). However, examination of a 70 million year old scleractinian coral fossil showed that some ancient corals were able to produce skeletons entirely of calcite (Stolarski et al., 2007), the most stable and least soluble polymorph of $CaCO_3$ (de Leeuw et al., 1998; Boulos et al., 2014). Throughout the Phanerozoic (past 540 Ma), there have been oscillations between calcite and aragonite as the dominant polymorph precipitated by major reef building organisms. During this time period there have been three aragonite-facilitating periods or "aragonite seas" and two calcite-facilitating periods or "calcite seas". The cause of these transitions in mineralogy has been the topic of much debate over the past 30 years. One of the most important factors affecting skeletal mineralogy is the magnesium to calcium ratio (Mg/Ca) of seawater (Sandberg, 1983; Ries, 2010). If the Mg/Ca >2, then aragonite is predominantly precipitated and if the Mg/Ca <2, then calcite is predominantly precipitated. Currently conditions favour aragonite precipitation, with modern seawater having a Mg/Ca ratio of 5.2 (Lowenstein et al., 2001). A recent study found $CaCO_3$ polymorph precipitation to be a function of both Mg/Ca ratio and temperature, with aragonite precipitated at high temperature and Mg/Ca ratio and calcite precipitated at low temperature and Mg/Ca ratio (Balthasar and Cusack, 2015). Changes in atmospheric pCO_2 are also thought to contribute to changes in skeletal mineralogy (Sandberg, 1983; Zhuravlev and Wood, 2009; Lee and Morse, 2010), with rising pCO_2 and subsequent reductions in carbonate saturation state, potentially favouring the precipitation of minerals with higher stability and lower Mg content, such as calcite (Morse et al., 2006; Zhuravlev and Wood, 2009). The polymorphism of abiotically precipitated calcium carbonate varies with both temperature and pCO_2, but occurs only at low Mg/Ca ratios (Lee and Morse, 2010; Balthasar and Cusack, 2015). However less is known about the polymorphism of biologically precipitated $CaCO_3$. If ocean acidification favours the deposition of more stable carbonate minerals such as calcite (Mackenzie et al., 1983; Morse et al., 2006; Andersson et al., 2008), then organisms producing less stable aragonite skeletons will likely be more vulnerable to changes in ocean chemistry under high $p\mathrm{CO_2}$. Alternatively, organisms will be much less vulnerable if, under high $p\mathrm{CO_2}$ conditions, they have the ability to switch from predominantly aragonite to calcite precipitation, especially in their early developmental stages.

It is therefore important to determine whether modern aragonitic corals, like their ancestors, are able to produce calcite in response to changing seawater chemistry. Initial work on coral skeletal mineralogy reported the presence of calcite in modern corals (Houck et al., 1975; Constanz and Meike, 1990), however contamination by diagenetic recrystallization (Nothdurft and Webb, 2009) and deposits from microboring organisms (Nothdurft et al., 2007) and coralline algae (Goffredo et al., 2012) were later proposed to be the source of the calcite, rather than primary calcitic formation by the coral. Adult corals grown under low Mg/Ca ratios simulating “calcite seas”, have been shown to produce significant amounts of calcite (Reis et al., 2006), however again, some of this calcite production may be due to secondary infilling of pore spaces (Reis et al., 2006; Ries, 2010). Nevertheless it is accepted that modern adult corals grown under current ambient conditions have entirely aragonitic skeletons (Cuif et al., 1999).

Much less is known about the mineralogy of corals in the early post-recruitment phases. Early work on the mineralogy of new recruits reported the presence of calcite in only the very early post-settlement stages (Wainwright, 1963; Vandermeulen and Wantabe, 1973), leading to the assumption that unlike adults, newly settled recruits were able to precipitate both calcite and aragonite under ambient conditions (Goffredo et al., 2012). However, new recruits of *Acropora millepora* grown under carefully controlled ambient conditions did not show any evidence of calcite in their skeleton (Clode et al., 2011) with these authors concluding that initial reports of calcite in recruits was also likely to be artefactual. Similarly, an experiment growing new recruits under a range of seawater Mg/Ca ratios, reported that even under the lowest Mg/Ca ratio (0.5), the skeletal mineralogy was still dominated by aragonite and under current ambient conditions (Mg/Ca ratio = 5.3) skeletons were composed entirely of aragonite (Higuchi et al., 2014). Interestingly however, this study confirmed that coral recruits are capable of producing some primary calcite in their skeletons if the water chemistry is adjusted to "calcite sea" conditions (low Mg/Ca).

The impact of elevated pCO_2 on the skeletal mineralogy of new recruits is yet to be investigated. Here we tested whether the treatment conditions of high temperature, high pCO_2, or a combination of high temperature and high pCO_2, affected the skeletal mineralogy of newly settled corals. Specifically, we question whether high pCO_2 and reduced carbonate saturation facilitate the production of calcite within coral recruit skeletons.

2 Methods

2.1 Treatment conditions

A detailed description of the coral culturing methods and experimental set-up is given in Foster et al. (2015a). Briefly, adult *Acropora spicifera* colonies were collected from the Houtman Abrolhos Islands in Western Australia prior to spawning and maintained under ambient conditions (~24°C and pH 8.1). Larvae were similarly cultured and maintained under ambient conditions until they were motile, at which point they were transferred to treatment tanks. Treatment conditions were: ambient temperature and pCO_2 (Control: 24°C, ~250 µatm), high temperature and ambient pCO_2 (high temperature: 27°C, ~250 µatm), ambient temperature and high pCO_2 (high pCO_2: 24°C, ~900 µatm) and high temperature plus high pCO_2 (high temperature + pCO_2: 27°C, ~900 µatm). See Table 1 for more detail on the experimental conditions.

2.2 Processing of skeletons

Once the coral larvae had settled, the recruits were grown for 4 weeks under treatment conditions, before the experiment was concluded. To remove organic material, polyps were immersed in 3-7% sodium hypochlorite (NaOCl) and rinsed three times in deionized water. The skeletons were then stored in 100% ethanol until further examination and analysis were possible.

2.3 X-ray diffraction analysis

Bulk analysis of the skeletal mineralogy was conducted by obtaining X-ray diffraction (XRD) patterns of the skeletal material. Subsets of 5 juvenile skeletons were randomly selected from each treatment. Skeletons were removed from the ethanol and air dried, then detached from the transparency paper using a scalpel and gently crushed. The crushed skeletal material from each treatment was mounted on a low background holder (off angle piece of single crystal silicon) and attached to a reflection spinner stage. A PANalytical Empyrean X-ray diffractometer was used with CuK_{α} radiation to record the XRD patterns. The scanning rate was 250 seconds per step in 2 Theta ranging from 10° to 80°, with a step size of 0.006°. XRD patterns of skeletal material were compared to the XRD peaks for ICDS aragonite and calcite standards.

2.4 Raman spectroscopy

XRD provides an average analysis for the entire sample, however for calcium carbonate samples Raman spectroscopy has been shown to have lower detection limits and lower rates of error, though only the surfaces of selected fragments can be analysed at any one time (Kontoyannis and Vagenas, 2000). Therefore, complementary Raman spectroscopy was also used to check the skeletons for the presence of calcite within discreet skeletal fragments. A further 5 skeletons from each treatment were randomly selected and each skeleton was individually analysed. Raman spectra were collected from 10 random areas (~60 X 60 μm) in the crushed skeletal material of each sample, using a 633 nm red Helium neon laser. Spectra were measured every 1 μm along the gridded ~60 μm^2 area

(Figure 1) for each of the 10 areas per sample (~36,000 individual spectra were taken per sample). Spectra were similarly taken of both a polished calcite standard and a biogenic aragonite standard to use as references.

3 Results

Calcite was not detected in the XRD patterns of any of the skeletons, regardless of treatment. Prominent peaks were observed at 2 Theta ~ 26.2° and 27.2°, corresponding with the aragonite standard peaks, while no peaks were observed at 2 Theta ~ 29.4°, the location of the primary calcite peak (Figure 2). After analysing all of the skeletal material using XRD, the more sensitive Raman spectrometry was employed to collect spectra from random fragments of the skeleton. Similarly, no trace of calcite was detected in the spectra of any of the treatments. The calcite standard showed peaks at 154, 281, 713, and 1086 cm^{-1} and the biogenic aragonite standard showed peaks at 154, 205, 704, and 1086 cm^{-1}, which are typical of these polymorphs of $CaCO_3$ (Dandeu et al., 2006). Since both calcite and aragonite peak at ~154, ~710 and ~1086 cm^{-1}, the peaks of interest were the 281 cm^{-1} peak typical of calcite and the 205 cm^{-1} peak typical of aragonite (Dandeu et al., 2006). All spectra from all individuals, across all treatments, exhibited peaks typical of only aragonite mineralogy (Figure 3), with prominent peaks at ~207 cm^{-1} and no peaks at ~281 cm^{-1}. Both the XRD patterns and Raman spectra collected indicate that neither temperature nor pCO_2 had any effect on the skeletal mineralogy of 1-month old coral recruits, as all skeletons across treatments formed entirely aragonitic skeletons.

4 Discussion

Since aragonite is a more soluble polymorph of $CaCO_3$ than calcite, it would be advantageous for modern corals in a rapidly acidifying ocean to be able to produce calcite. Production of calcite has been shown to be a phenotypically plastic, with many marine calcifiers able to adjust both the proportion of calcite in their shell or skeleton as well as the Mg/Ca ratio (Ries, 2010; 2011). In this study both temperature and $p\mathrm{CO}_2$ were manipulated to assess their impact on skeletal mineralogy of newly settled coral recruits. Neither temperature nor $p\mathrm{CO}_2$ affected mineralogy, with all coral recruits analysed producing entirely aragonitic skeletons. Although temperature has been shown to significantly affect abiotic polymorph precipitation (as a function of Mg/Ca), calcite co-precipitation with aragonite is favoured at cooler temperatures and low Mg/Ca ratios (<20°C, Mg/Ca < 2, Balthasar and Cusack, 2015). As such, temperature treatments applied in this study (24 and 27°C), were within the range of temperatures favouring aragonite production. These temperatures were chosen because they are ecologically relevant to the sub-tropical corals used in this study, under both present ambient and future elevated temperature regimes.

Predicting the impact of high $p\mathrm{CO}_2$ on polymorph mineralogy is more complex. The extent to which oscillations between "calcite seas" and "aragonite seas" throughout the Phanerozoic were primarily driven by $p\mathrm{CO}_2$ or Mg/Ca ratios has received a lot of attention (see review by Ries, 2010). It is accepted that modern adult corals under current ambient conditions produce skeletons comprised entirely of aragonite (Cuif et al., 1999). Furthermore, despite initial work suggesting that new coral recruits were bimineralic (producing both calcite and aragonite), more recent studies have shown that under ambient conditions recruits produce purely aragonitic skeletons (Clode et al., 2011; Higuchi et al., 2014). However, under reduced Mg/Ca ratios, both adult and newly settled corals are able to produce some calcite (Ries et al., 2006; Higuchi et al., 2014). Despite this ability to switch to a bimineralic skeleton, corals still produce skeletons comprised mainly of aragonite, even under extremely reduced Mg/Ca ratios (Higuchi et al., 2014), suggesting that the ability of some corals in the fossil record to produce entirely calcitic skeletons (Stolarski et al., 2007), may not have been solely controlled by the Mg/Ca ratio of seawater. However it should also be noted that other coral lineages in the Cretaceous formed entirely aragonitic skeletons, even under highly reduced Mg/Ca ratios (Sorauf 1999). The impact of elevated pCO_2 on mineralogy has also been examined for a range of marine calcifiers (Ries, 2011). In bimineralic animals (*e.g.* whelks), the proportion of calcite in the skeleton increased with increasing pCO_2, however in monomineralic animals (entirely aragonitic skeletons), calcite was not incorporated into the skeleton as the pCO_2 increased. For the adult temperate coral *Oculina arbuscula*, a range of CO_2 treatments had no impact on skeletal mineralogy, with corals in all treatments producing aragonitic skeletons (Ries et al., 2010). Our study similarly observed no change in skeletal mineralogy under elevated pCO_2 for newly settled corals.

Both the elevated temperature and elevated pCO_2 conditions applied in this study were ecologically relevant values, chosen to correspond to future projections for atmospheric CO_2 by 2100, under a business-as-usual (RCP 8.5) emissions scenario (Meinshausen et al., 2011; IPCC, 2013). However, applying more extreme values for both temperature and pCO_2 could potentially identify changes in the mineralogy under extreme conditions. Nevertheless, this study is part of a growing body of evidence that indicates that corals do not produce calcite under current ambient or predicted near-future high pCO_2 scenarios, regardless of their life stage. It is likely that new coral recruits will continue to produce aragonitic skeletons under future emissions scenarios, however at reduced calcification rates (Cohen et al., 2009; Anlauf et al., 2011; Foster et al., 2015a) and forming skeletons that are smaller, malformed and show evidence of dissolution (Foster et al., 2015b). Recruits require high calcification rates and robust skeletons to both maintain their position on the substrate as they compete with other benthic organisms for space (Dunstan and Johnson 1998), and also to rapidly outgrow the high mortality rates of the smallest and most vulnerable size classes (Babcock 1991; Babcock and Mundy 1996; Doropoulos et al., 2012). Reduced calcification rates and more soluble aragonitic skeletons will have implications for the longer-term survival of young corals, as these factors will increase mortality rates in the early stages of growth and development thereby reducing the numbers of recruits that survive into adulthood.

While coral recruits exposed to extremely reduced Mg/Ca ratios still produced predominantly aragonitic skeletons (Higuchi et al., 2014), the combined impact of elevated $p\mathrm{CO}_2$ and reduced Mg/Ca ratio on the skeletal mineralogy of new recruits is yet to be tested. Since $p\mathrm{CO}_2$ and Mg/Ca ratio have varied approximately inversely proportionally to one another over geological time (Reis, 2010; 2011), this would be an interesting direction for future research. Certainly if elevated $p\mathrm{CO}_2$ and concomitant reductions in Mg/Ca ratio are driving the ocean towards “calcite sea” conditions (Andersson et al., 2008), then it will be important to examine the simultaneous impact of both acidified and low Mg/Ca ratio conditions on coral skeletal mineralogy.

Author contribution

T.F. and P.C. designed the experiment, T.F. conducted the experiment, T.F. and P.C. conducted laboratory work, T.F. wrote the manuscript and P.C. reviewed and commented on the manuscript.

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References

Andersson, A. J., Mackenzie, F. T. and Bates, N. R.: Life on the margin: implications of ocean acidification on Mg-calcite, high latitude and cold-water marine calcifiers, Mar Ecol Prog Ser, 373, 265–273, 2008.

Anlauf, H., D'croz, L., O'Dea, A.: A corrosive concoction: the combined effects of ocean warming and acidification on the early growth of a stony coral are multiplicative. J Exp Mar Bio Ecol, 397, 13–20, 2011.

Babcock, R., Mundy, C.: Coral recruitment: consequences of settlement choice for early growth and survivorship in two scleractinians. J Exp Mar Bio Ecol, 206, 179–201, 1996.

Babcock, R.C.; Comparative demography of three species of scleractinian corals using age-and size-dependent classifications. Ecol Monogr, 61, 225–244, 1991.

Balthasar, U. and Cusack, M.: Aragonite-calcite seas-Quantifying the gray area, Geology, 43, 99–102, 2015.

Boulos, R. A., Zhang, F., Tjandra, E. S., Martin, A. D., Spagnoli, D. and Raston, C. L.: Spinning up the polymorphs of calcium carbonate, Sci. Rep., 4, 1–6, 2014.

Clode, P. L., Lema, K., Saunders, M. and Weiner, S.: Skeletal mineralogy of newly settling *Acropora millepora* (Scleractinia) coral recruits, Coral Reefs, 30, 1–8, 2011.

Cohen, A.L., McCorkle, D.C., de Putron, S., Gaetani, G.A., Rose, K.A.: Morphological and compositional changes in the skeletons of new coral recruits reared in acidified seawater: Insights into the biomineralization response to ocean acidification. Geochem Geophys Geosys, 10, 1–12, 2009.

Constantz, B. and Meike, A.: Calcite centers of calcification in *Mussa angulosa* (Scleractinia). In: Origin, evolution and modern aspects of biomineralization in plants and animals, edited by R. E. Crick, Plenum Press, New York, 201–207, 1990.

Cuif, J.-P., Dauphin, Y. and Gautret, P.: Compositional diversity of soluble mineralizing matrices in some recent coral skeletons compared to fine-scale growth structures of fibres: discussion of consequences for biomineralization and diagenesis, Int J Earth Sci, 88, 582–592, 1999.

Dandeu, A., Humbert, B. and Carteret, C.: Raman Spectroscopy–A Powerful Tool for the Quantitative Determination of the Composition of Polymorph Mixtures: Application to CaCO3 Polymorph Mixtures, Chem Eng Technol, 29, 221–225, 2006.

de Leeuw, N. H. and Parker, S. C.: Surface structure and morphology of calcium carbonate polymorphs calcite, aragonite, and vaterite: an atomistic approach, J Phys Chem B, 102, 2914–2922, 1998.

Doropoulos, C., Ward, S., Marshell, A., Diaz-Pulido, G., Mumby, P.J.: Interactions among chronic and acute impacts on coral recruits: the importance of size-escape thresholds. Ecology 93, 2131–2138, 2012.

Dunstan, P.K., Johnson, C.R.: Spatio-temporal variation in coral recruitment at different scales on Heron Reef, southern Great Barrier Reef. Coral Reefs 17, 71–81, 1998.

Feely, R. A., Doney, S. C. and Cooley, S. R.: Ocean Acidification: present conditions and future changes in a high CO2 world, Oceanography, 22, 36–47, 2009.

Foster, T., Gilmour, J.P., Chua, C.M., Falter, J.L., McCulloch, M.T.: Effect of ocean warming and acidification on the early life stages of subtropical *Acropora spicifera*. Coral Reefs, 34, 1217-1226, 2015a.

Foster, T., Falter, J.L., McCulloch, M.T., Clode, P.L.: Ocean acidification causes structural deformities in juvenile coral skeletons. Science Advances, 2015b, accepted.

Goffredo, S., Caroselli, E., Mezzo, F., Laiolo, L., Vergni, P., Pasquini, L., Levy, O., Zaccanti, F., Tribollet, A., Dubinsky, Z. and Falini, G.: The puzzling presence of calcite in skeletons of modern solitary corals from the Mediterranean Sea, Geochim Cosmochim Ac, 85, 187–199, 2012.

Higuchi, T., Fujimura, H., Yuyama, I., Harii, S., Agostini, S. and Oomori, T.: Biotic Control of Skeletal Growth by Scleractinian Corals in Aragonite–Calcite Seas, PLoS One, 9, e91021, 2014.

Houck, J. E., Buddemeier, R. W. and Chave, K. E.: Skeletal low-magnesium calcite in living scleractinian corals, Science, 189, 997–999, 1975.

IPCC, Climate Change 2013: The Physical Science Basis. An overview of the Working Group 1 contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, 2013.

Kontoyannis, C. G. and Vagenas, N. V.: Calcium carbonate phase analysis using XRD and FT-Raman spectroscopy, Analyst, 125, 251–255, 2000.

Lee, J. and Morse, J. W.: Influences of alkalinity and pCO2 on CaCO3 nucleation from estimated Cretaceous composition seawater representative of "calcite seas," Geology, 38, 115–118, 2010.

Lowenstein, T. K., Timofeeff, M. N., Brennan, S. T., Hardie, L. A. and Demicco, R. V.: Oscillations in Phanerozoic seawater chemistry: evidence from fluid inclusions, Science, 294, 1086–1088, 2001.

Mackenzie, F. T., Bischoff, W. D. and Bishop, F. C.: Magnesian calcites; low-temperature occurrence, solubility and solid-solution behavior, in: Carbonates: Mineralogy and Chemistry, edited by R. J. Reeder, Mineralogical Society of America, 97–144, 1983.

Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J-F, Matsumoto, K., Montzka, S.A., Raper, S.C.B., Riahi, K., Thomson, A., Velders, G.J.M., van Vuuren, D.P.P.: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic change, 109, 213–241, 2011.

Morse, J. W., Andersson, A. J. and Mackenzie, F. T.: Initial responses of carbonate-rich shelf sediments to rising atmospheric pCO2 and "ocean acidification": Role of high Mg-calcites, Geochim Cosmochim Ac, 70, 5814–5830, 2006.

Nothdurft, L. and Webb, G.: Earliest diagenesis in scleractinian coral skeletons: implications for palaeoclimate-sensitive geochemical archives, Facies, 55, 161–201, 2009.

Nothdurft, L. D., Webb, G. E., Bostrom, T. and Rintoul, L.: Calcite-filled borings in the most recently deposited skeleton in live-collected *Porites* (Scleractinia): Implications for trace element archives, Geochim Cosmochim Ac, 71, 5423–5438, 2007.

Orr, J. C., Fabry, V. J., Aumont, O., Bopp, L., Doney, S. C., 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.

Ries, J. B.: Review: geological and experimental evidence for secular variation in seawater Mg/Ca (calcite-aragonite seas) and its effects on marine biological calcification, Biogeosciences, 7, 2795–2849, 2010.

Ries, J. B.: Skeletal mineralogy in a high-CO2 world, J Exp Mar Bio Ecol, 403, 54–64, 2011.

Ries, J. B., Cohen, A. L. and McCorkle, D. C.: A nonlinear calcification response to CO2-induced ocean acidification by the coral *Oculina arbuscula*, Coral Reefs, 29, 661–674, 2010.

Ries, J. B., Stanley, S. M. and Hardie, L. A.: Scleractinian corals produce calcite, and grow more slowly, in artificial Cretaceous seawater, Geology, 34, 525–528, 2006.

Sandberg, P. A.: An oscillating trend in Phanerozoic non-skeletal carbonate mineralogy, Nature, 305, 19–22, 1983.

Sorauf, J. E.: Skeletal microstructure, geochemistry, and organic remnants in Cretaceous scleractinian corals: Santonian Gosau Beds of Gosau, Austria, J Paleontol, 73, 1029–1041, 1999.

Stolarski, J., Meibom, A., Przenioslo, R. and Mazur, M.: A Cretaceous scleractinian coral with a calcitic skeleton, Science, 318, 92–94, 2007.

Vandermeulen, J. H. and Watabe, N.: Studies on reef corals. I. Skeleton formation by newly settled planula larva of *Pocillopora damicornis*, Mar Biol, 23, 47–57, 1973.

Wainwright, S. A.: Skeletal organization in the coral, *Pocillopora damicornis*, Quart J Microsc Sci, 104, 169–183, 1963.

Zhuravlev, A. Y. and Wood, R. A.: Controls on carbonate skeletal mineralogy: Global CO2 evolution and mass extinctions, Geology, 37, 1123–1126, 2009.

Tables

Table 1. Physical and chemical conditions maintained for the duration of the experiment (mean ± SD). Table from Foster et al., (2015a).

Treatment	Temperature (°C)	pH_T	TA (μmol kg^{-1})	pCO$_2$ (μatm)	Ω_{ar}
Control	24.4 ± 0.5	8.22 ± 0.05	2308 ± 40	242 ± 22	4.51 ± 0.14
High temperature	27.6 ± 0.8	8.18 ± 0.05	2312 ± 26	275 ± 24	4.68 ± 0.17
High pCO$_2$	24.1 ± 0.6	7.77 ± 0.06	2307 ± 30	872 ± 58	1.93 ± 0.08
High temperature + pCO$_2$	27.4 ± 0.9	7.75 ± 0.08	2309 ± 32	976 ± 103	2.03 ± 0.12

TA: total alkalinity; pCO$_2$: partial pressure of carbon dioxide; Ω_{ar}: aragonite saturation state.

Figures

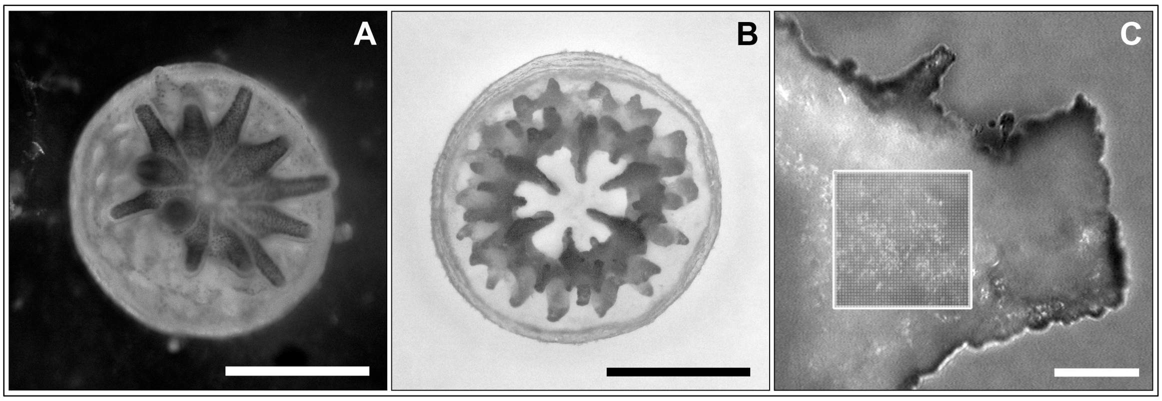

Figure 1: One month old living *Acropora spicifera* recruit (**A**), a typical *Acropora spicifera* recruit skeleton with organic material removed (**B**) and crushed skeletal material showing a typical ~60 μm^2 scan area grid analysed by Raman spectroscopy (**C**). Scale bars for A and B = 500 μm and scale bar for C = 40 μm.

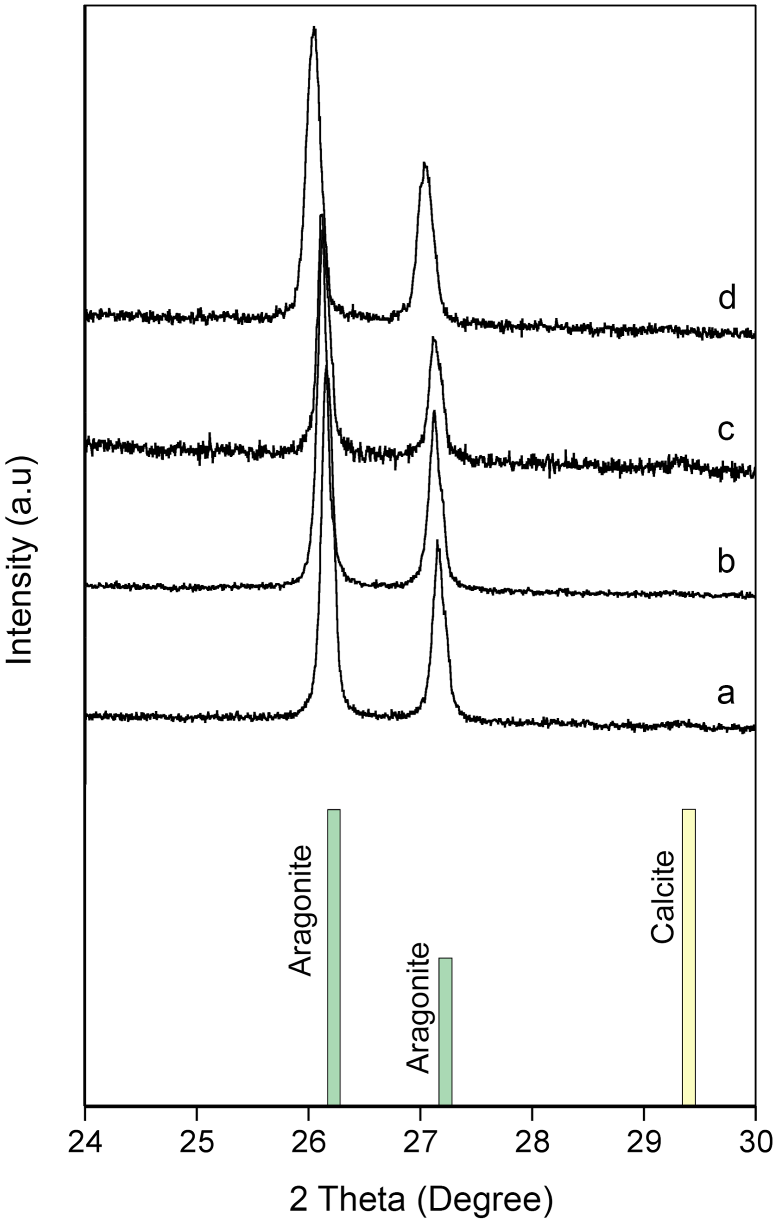

Figure 2. XRD patterns for *Acropora spicifera* coral recruit skeletons grown under control (**a**), high temperature (**b**), high $p\mathrm{CO_2}$ (**c**) and high temperature + $p\mathrm{CO_2}$ (**d**) conditions. Aragonite standard peaks occur at 26.2° and 27.2° (green bars), and the calcite standard peak occurs at 29.4° (yellow bar).

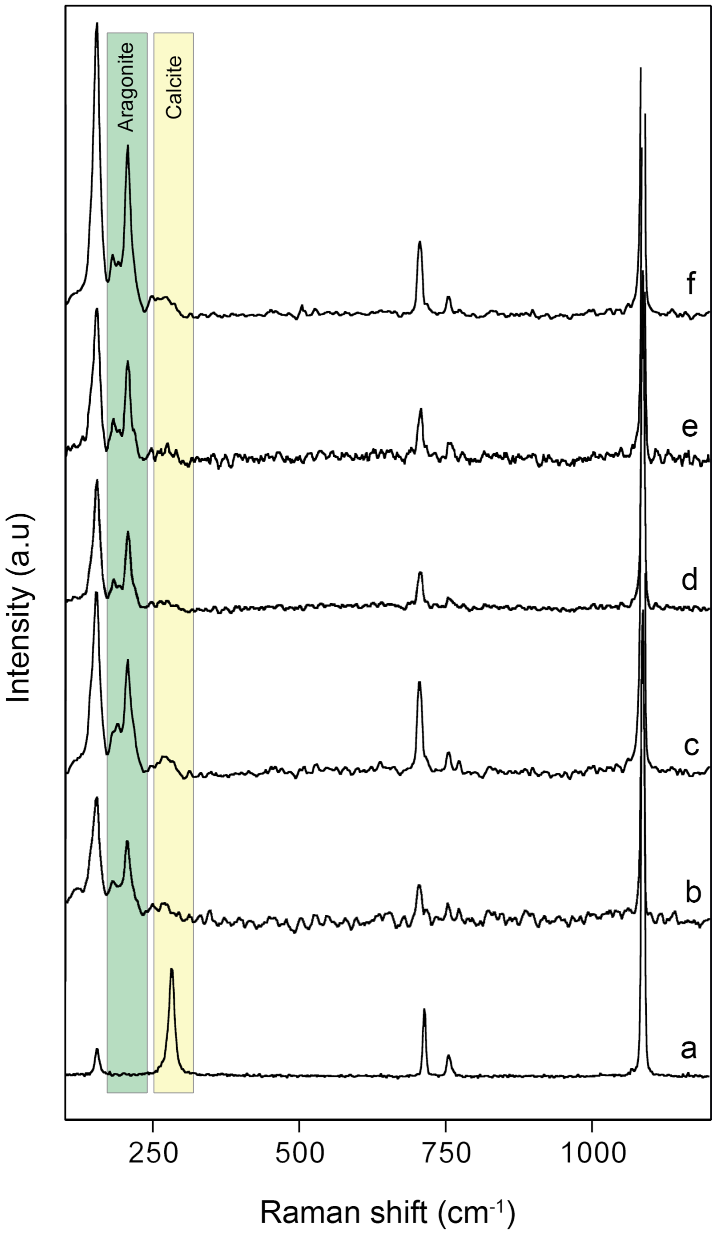

Figure 3: Specific Raman shift of a calcite standard (**a**) and a biogenic aragonite standard (**b**) and skeletal material from control (**c**), high temperature (**d**), high pCO_2 (**e**), and high temperature + pCO_2 (**f**) treated *Acropora spicifera* coral recruits. The ~205 peak specific to aragonite is highlighted in green and the ~281 peak specific to calcite is highlighted in yellow.