Author Response to Reviewers

***Note:** All changes to the text are highlighted in blue.

Reviewer #1

Comment: However, the paper lacks general flow, appearing poorly written in some sections (e.g. the introduction is redundant).

Answer: We have re-worded several sections in the introduction for easier reading.

Comment: Because of the simplicity of the analyses, it would be interesting the addition of other treatments and not only of the range ecologically relevant used. Extreme values of temperature and pCO2 could consolidate the conclusions that neither temperature nor pCO2 affected mineralogy on coral recruits.

Answer: This experiment was designed as part of a larger study looking at the impacts of ecologically relevant temperature and pCO2 treatments on larval and juvenile coral physiology. We chose to use values that are relevant to what corals will be subjected to in the near future in order to provide practical insights into their ability to adapt and survive. Although we chose to use only ecologically relevant values for this study, Reviewer #1 is correct in suggesting that effects of temperature and pCO2 on mineralogy under extreme conditions could be investigated and perhaps a change in mineralogy would be observed. We have added the following section to the Discussion to acknowledge this: “Both the elevated temperature and elevated $p\mathrm{CO}_2$ 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 $p\mathrm{CO}_2$ could potentially identify changes in the mineralogy under extreme conditions.”

Comment: In the discussion not much debate is posed about ecologically implication for coral recruits survival: how these organisms without the production of calcitic skeletons can face out to future scenarios of “calcite sea” conditions?

Answer: We have added the following to the Discussion: “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.”

Reviewer #2

The paper by Foster & Clode focuses on skeletal mineralogy of juvenile skeletons of scleractinian corals (Acropora spicifera) grown under high temperature (elevated by +3◦C) and high pCO2 levels (~900 μatm). The main rationale for using this experimental setting was to check if "modern aragonitic corals, like their ancestors, are able to produce calcite in response to changing seawater chemistry". Aragonite has higher solubility than calcite hence if corals would have plasticity to adapt and produce calcite skeleton under high pCO2 they would be less vulnerable to anthropogenic ocean acidification. There are two aspects that should be better commented in the paper:

Comment 1

It is not clearly explained what are the values of pCO2 and the temperature that could - theoretically - induce inorganic calcite precipitation at modern 5.1 mol/mol Mg/Ca seawater ratio. Noteworthy, the experiments with inorganic calcium carbonate precipitation (with noticable effects on CaCO3 polymorphism) were performed by Lee & Morse (2010: Geology 38:115-118) at different pCO2 levels but at really low Mg/Ca values (1.2 mol/mol and 1.7 mol/mol). Also Balthasar and Cusack (2015: Geology 43:99–102) showed that none of the carbonic acid parameters had a noticeable systematic influence on CaCO3 polymorph proportions, thus suggesting that these influences were overprinted by Mg/Ca and temperature. In turn, Fine & Tchernov (2007: Science 315:1811) showed that in highly acidic waters (pH values of 7.3 to 7.6 for 12 months) skeleton of Oculina patagonica was completely dissolved but polyps maintained basic life functions as skeleton-less ecophenotypes. This experiment points to a lack of strong functional significance of the skeleton for the animal in experimental, aquarium conditions (opposite to real reef environment) and suggests that corals in highly acidic waters will rather lose the skeleton (skeleton will be dissolved) than they will keep it inducing it's mineralogical change. The experiment would be perhaps more interesting if the authors would test Mg/Ca and pCO2 values as in Lee & Morse (2010) experiments that in "inorganic world" promote calcite over aragonite precipitation.

Answer 1:

We agree with Reviewer #2 that we need to further discuss the role of Mg/Ca ratio and how our high or modern Mg/Ca ratios would likely influence mineralogy. This experiment was part of a larger experiment investigating the impacts of acidification and temperature on juvenile calcification. In the other assays (Foster et al 2015a and 2015b) we saw a strong negative impact of high $p\mathrm{CO}_2$ on juvenile calcification. This is discussed further in the response to Comment 2.

As Reviewer #2 suggests, studies investigating inorganic CaCO3 precipitation have found that calcite is only produced at low seawater Mg/Ca ratios (Lee and Morse 2010, Balthasar and Cusack 2015), thus in the context of inorganic precipitation it was unlikely that our newly settled coral recruits would produce calcite at modern Mg/Ca ratios, even under high $p\mathrm{CO}_2$ conditions. However, constraints on inorganic precipitation are only applicable to living organisms up to a point, as animals such as corals (adults) are able to adjust their internal chemistry. Also, given the lack of studies on the mineralogy of newly recruited corals, the confusion surrounding their mineralogy in early works (Wainwright, 1963; Vandermeulen and Wantabe, 1973) and the body of recent studies that have shown that corals (and other invertebrates) appear to have more plasticity in the early life stages and thus a higher potential for coping with change (Byrne and Przeslawski 2013; Moya et al 2015; Foster et al 2015a), we thought it worthwhile to re-visit juvenile mineralogy and check if calcite formation was possible under high $p\mathrm{CO}_2$ alone *i.e* with unaltered Mg/Ca ratios. We have added the following to consider inorganic calcite precipitation:

"The polymorphism of abiotically precipitated calcium carbonate varies with both temperature and $p\mathrm{CO}_2$, 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."

We have confirmed that high $p\mathrm{CO}_2$ alone does not appear to impact juvenile skeletal mineralogy. As Reviewer #2 suggests, it would be interesting to now test the impacts of both high $p\mathrm{CO}_2$ and low Mg/Ca ratio. We have made this suggestion in both our Abstract and Discussion sections:

Abstract:

"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."

Discussion:

"While coral recruits exposed to extremely reduced Mg/Ca ratios still produced predominantly aragonite 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 pCO$_2$ and concomitant reductions in Mg/Ca ratio are driving the ocean towards "calcite sea" conditions (Andersson et al., 2008), then studying the impact of both acidified and low Mg/Ca ratio conditions on skeletal mineralogy is necessary."

Comment 2

Even if skeletal mineralogy of solitary Cretaceous coral Coelosmilia described by Stolarski et al. (2007: Science 318: 92-94) was originally calcitic, there is no reason to believe that all corals share "ancient ability (...) to produce entirely calcitic skeleton". Especially Acropora which is phylogenetically very distant from Cretaceous solitary "caryophyliid" Coelosmilia. There are many coral lineages that in the Cretaceous formed aragonitic skeletons under highly reduced Mg/Ca ratio conditions (e.g., Sorauf 1999: J Paleontol 73:1029–1041); it is therefore more likely that coral response to environmental change is taxon-specific. Such taxon-specific response to ocean acidification (skeleton dissolution not mineralogical change) was actually showed by Rodolfo-Metalpa et al. (2011: Nature Climate Change 1:308–312): Cladocora caespitosa (large parts of the skeleton exposed) showed clear marks of dissolution, whereas Balanophyllia europaea (skeleton completely covered in tissue) was unaffected.

Answer 2:

We have revised the wording "ancient ability" in the Discussion. It now reads:
"…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."

We agree that the differences between taxa need to be considered and have added the following sentence to the Discussion:
"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)."

We also agree with Reviewer #2 that dissolution and reduced skeletal deposition are more likely outcomes than a change in mineralogy under elevated pCO$_2$. Indeed we have shown in other work (Foster et al 2015b) that elevations in pCO$_2$ to 900 uatm can have severe impacts on calcification and that skeletal surfaces show evidence of dissolution in newly settled coral recruits even when a layer of tissue is present (as opposed to the adult corals in Rodolfo-Metalpa et al 2011, which only showed signs of dissolution in species with sections of the skeleton exposed). Therefore we have added the following section to the Discussion to highlight the likely reduction in skeletal deposition under future pCO$_2$ scenarios:
"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."

Skeletal mineralogy of coral recruits under high temperature and $p\mathrm{CO}_2$

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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 $p\text{CO}_2$. Alternatively, organisms will be much less vulnerable if, under high $p\text{CO}_2$ 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 errors, 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 $p\mathrm{CO}_2$ 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.

Acknowledgements

This work was funded by the ARC Centre of Excellence for Coral Reef Studies (CE0561435). We thank the Batavia Coast Maritime Institute and the Centre for Microscopy, Characterisation and Analysis (UWA) for access to facilities, T. Becker and A. Dodd for technical assistance with the Raman spectroscopy and X-ray diffraction work respectively and M. McCulloch for project funding support and helpful comments on the manuscript. We would also like to thank those who volunteered their time during the experimental phase of this work, particularly; A. Basile, T. Basile, T. Foster, L. Foster, J. Melvin, C. Chua, C. Wood, Z. Snedden and K. Antipas.

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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

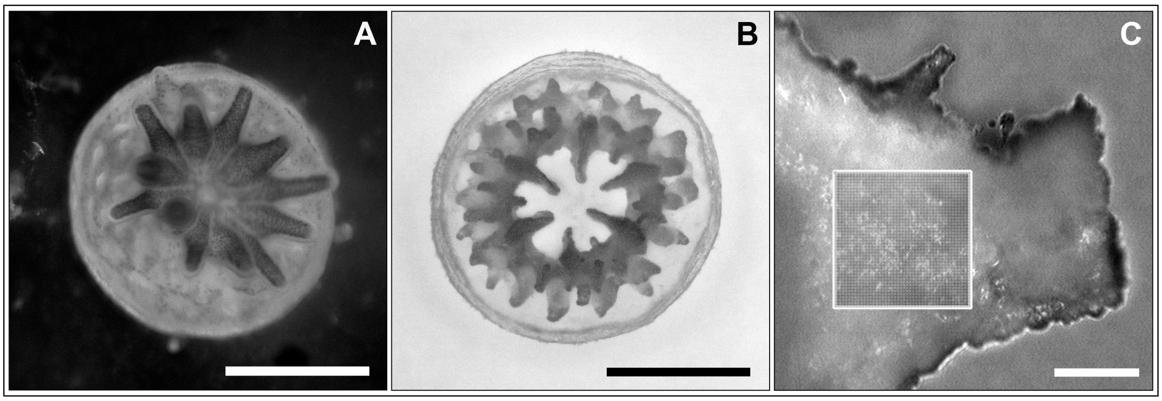

Figure 1: One month old living *Acropora spicifera* recruit (**A**), a typical *Acropora spicifera* recruit skeleton with organic material removed (**B**) and crushed skeletal material showing a typical ~60 μm^2 scan area grid analysed by Raman spectroscopy (**C**). Scale bars for A and B = 500 μm and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

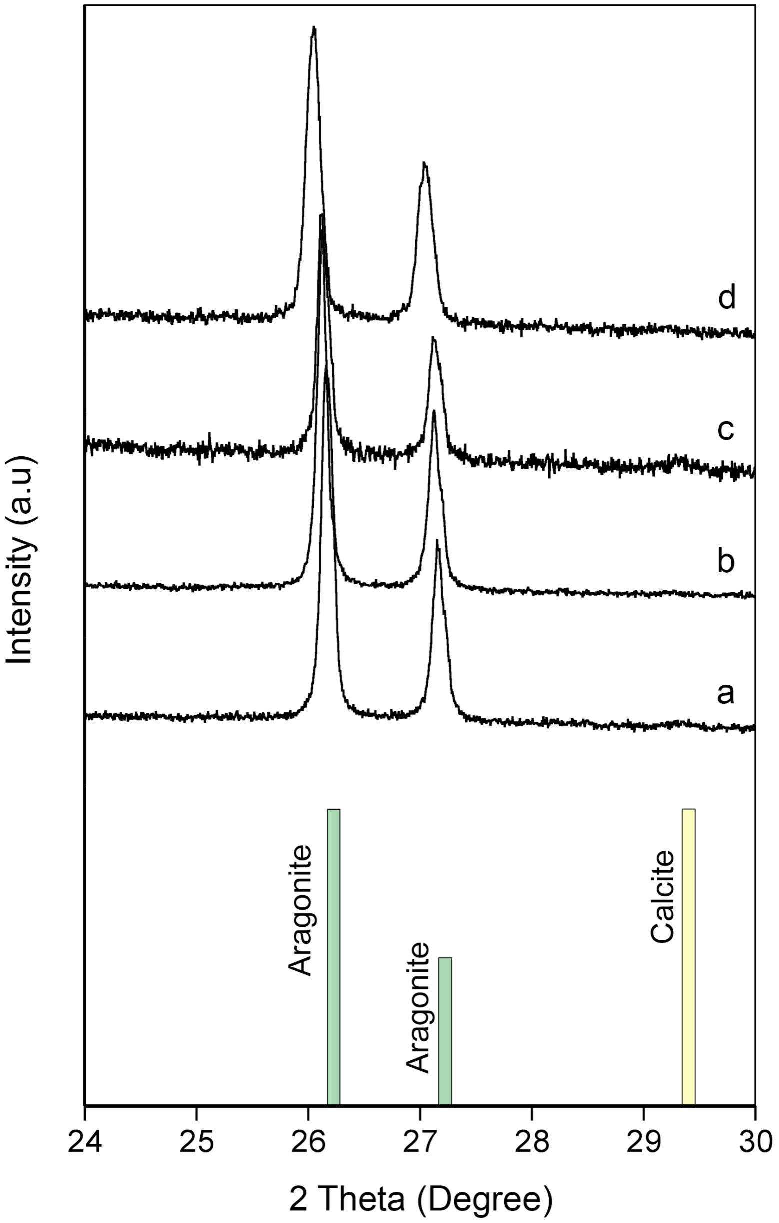

Figure 2. XRD patterns for *Acropora spicifera* coral recruit skeletons grown under control (**a**), high temperature (**b**), high *p*CO_2 (**c**) and high temperature + *p*CO_2 (**d**) conditions. Aragonite standard peaks occur at 26.2° and 27.2° (green bars), and the calcite standard peak occurs at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

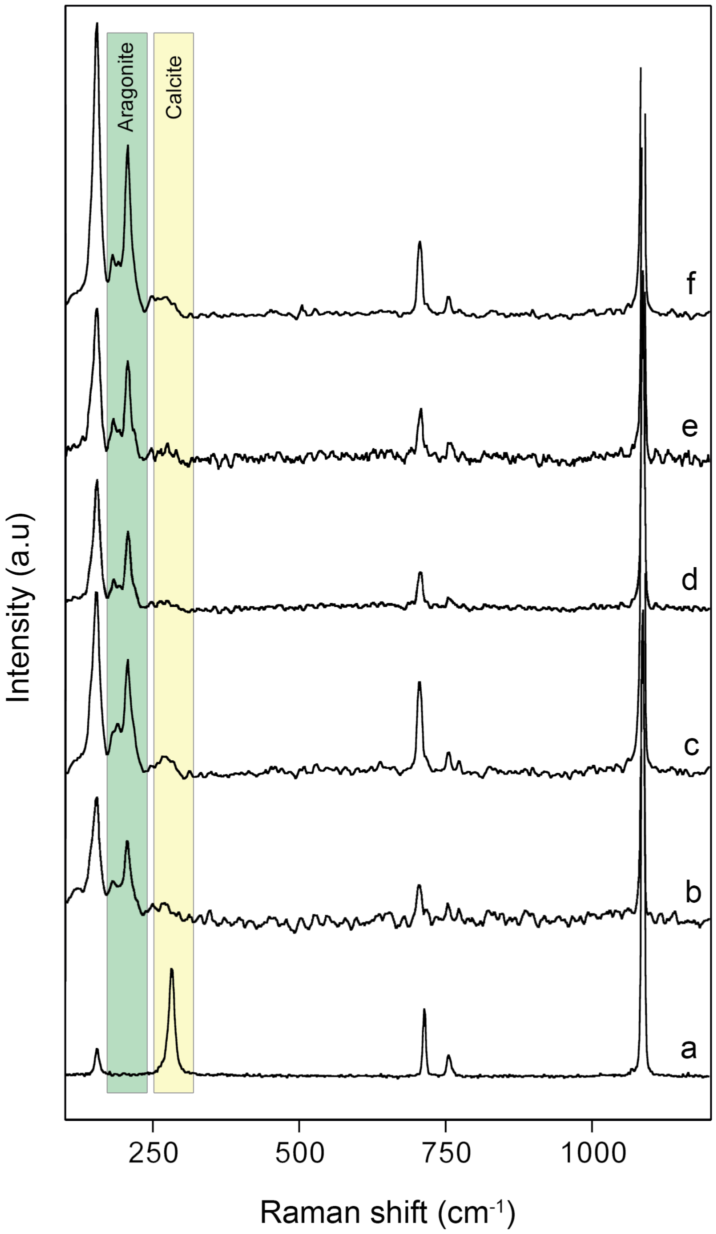

Figure 3: Specific Raman shift of a calcite standard (**a**) and a biogenic aragonite standard (**b**) and skeletal material from control (**c**), high temperature (**d**), high $p\mathrm{CO}_2$ (**e**), and high temperature + $p\mathrm{CO}_2$ (**f**) treated *Acropora spicifera* coral recruits. The ~205 peak specific to aragonite is highlighted in green and the ~281 peak specific to calcite is highlighted in yellow.