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Geochemistry-based coral palaeoclimate studies and the potential of 'non-traditional' (non-massive *Porites*) corals: Recent developments and future progression

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A B S T R A C T

Understanding the natural variability of the Earth's climate system and accurately identifying potential anthropogenic influences requires long term, geographically distributed records of key climate indicators, such as temperature and precipitation that extend prior to the last 400 years of the Holocene. Reef corals provide an excellent source of high resolution climate records, and importantly represent the tropical marine environment where palaeoclimate data are urgently required. Recent decades have seen significant improvement in our understanding of coral biomineralisation, the associated uptake of geochemical proxies and methods of identifying and understanding the effects of both early and late, post depositional diagenetic alteration. These processes all have significant implications for interpreting geochemical proxies relevant to palaeoclimatic reconstructions. This paper reviews the current 'state of the art' in terms of coral based palaeoclimate reconstructions and highlights a key remaining problem. The majority of coral based palaeoclimate research has been derived from massive colonies of *Porites*. However, massive *Porites* are not globally abundant and may not provide material of a particular age of interest in those regions where they are present. Therefore, there is great potential for alternate coral genera to act as complimentary climate archives. While it remains critical to consider five key factors – vital effects, differential growth morphologies, geochemical heterogeneity in the skeletal ultrastructure, transfer equation selection and diagenetic screening of skeletal material – in order to allow the highest level of accuracy in coral palaeoclimate reconstructions, it is also important to develop alternate taxa for palaeoclimate studies in regions where *Porites* colonies are absent or rare. Currently as many as nine genera other than *Porites* have proven at least limited utility in palaeothermometry, most of which are found in the Atlantic/Caribbean region where massive *Porites* do not exist. Even branching taxa such as *Acropora* have significant potential to preserve environmental archives. Increasing this capability will greatly expand the number of potential geochemical archives available for longer term temporal records of palaeoclimate.

Contents

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1. Introduction

Quantification of the natural variability of the Earth's climate system with identification and isolation of potential anthropogenic influences requires long term, geographically distributed records of key climate indicators including temperature and precipitation (Guilderson and Schrag, 1999). Unfortunately instrumental records of environmental variables are typically restricted to the latter one-half of the 20th century (Guilderson and Schrag, 1999; Kuhnert et al., 1999; Kilbourne et al., 2004) and even fewer oceanic measurements exist (Draschba et al., 2000; Jansen et al., 2007). High resolution, multi-century marine proxy-based climate records are required urgently (Gagan et al., 1994; Shen et al., 1996; Guilderson and Schrag, 1999; Quinn and Sampson, 2002; Kilbourne et al., 2004). Tropical reef building corals in particular may provide the most critical proxy archives as they address two significant needs: 1) recent, pre-industrial archives (i.e., the Holocene epoch), and 2) archives that capture climate drivers in the tropical oceans.

With the modern rise in global mean temperature (Trenberth et al., 2007), palaeoclimate research is becoming increasingly focused on periods in Earth's recent history when climate was warmer than today (Broecker, 2001; Mann et al., 2009; Ljungqvist, 2011; Diaz, 2012). While these periods do not invariably represent a high atmospheric CO_2 world analogous to the predicted system, they can be useful for identifying driving forces of climate (Gagan et al., 2000) and the effects of such intervals on biological communities. Proxy data from the Holocene epoch is of particular importance as it allows analysis of changes in the background climate system, including temperature and orbital forcing, without the added complication of major variability in sea level or continental ice cover (Markgraf and Diaz, 2000). In particular, the Intergovernmental Panel on Climate Change (IPCC) identified a limit to our understanding of climate variability prior to the latest several hundred years, especially in the southern hemisphere and tropics (IPCC, 2007; Masson-Delmotte et al., 2013).

Despite the critical role of the tropical ocean–atmosphere system in global climate dynamics (Allison et al., 2005), phenomena such as El Niño Southern Oscillation (ENSO) and the equatorial monsoon remain notoriously difficult to model (Dunbar et al., 1994; Gagan et al., 1994; Draschba et al., 2000; Quinn and Sampson, 2002). Numerical simulations therefore require further empirical climate data from the tropics with at least monthly resolution (Gagan et al., 1994). Of the available marine records, deep sea sediment cores have been effectively used for palaeoclimate analysis, but low accumulation rates and bioturbation are commonly detrimental to the high resolution records required by climate modellers (Shen et al., 1992). Reef-building corals, on the other hand, are naturally abundant and an excellent source of high resolution, temporally constrained data for the tropical ocean (Shen et al., 1992; Gagan et al., 1994; Mitsuguchi et al., 1996; Gagan et al., 2000; Cohen and McConnaughey, 2003; Kuhnert et al., 2005; Grottoli and Eakin, 2007; Montaggioni and Braithwaite, 2009; Lough, 2010; Lough and Cooper, 2011; Neukom and Gergis, 2012). Limited studies also have been conducted on temperate reef-building corals, such as *Cladocora* (e.g., Montagna et al., 2007), however, this paper will focus on tropical reef-building Scleractinia.

The vast majority of palaeoclimate reconstructions based on reef building corals, particularly those in the Pacific and Indian oceans, have targeted massive *Porites* colonies, which form large coralla on the reef front and microatolls on reef flats (Gagan et al., 1994; Charles et al., 1997; Guilderson and Schrag, 1999; Kuhnert et al., 1999; Kilbourne et al., 2004; Gallup et al., 2006; Cahyarini et al., 2008). Although cores from these corals can provide multi-decadal to multi-century records, palaeoclimate reconstructions tend to be restricted to the last several hundreds of years (Grottoli and Eakin, 2007; Lough, 2010; Neukom and Gergis, 2012) with access to older corals more limited owing to a general lack of exposure (i.e., coverage by younger living corals) and the deleterious influence of diagenetic alteration. Microatolls that are thousands of years old may be preserved on reef flats (Yu and Zhao, 2010; McGregor et al., 2011b; Woodroffe et al., 2012), but even live collected reef flat coral samples may be severely affected by early marine diagenesis (Enmar et al., 2000; Hendy et al., 2007; McGregor and Abram, 2008; Nothdurft and Webb, 2009; Sayani et al., 2011) owing to the high levels of physical-chemical and biological activity in the intertidal and very shallow water zones (Nothdurft and Webb, 2009). Therefore, ancient corals stranded on the reef flat over thousands of years may have been subjected to significant marine diagenesis even in the absence of major meteoric diagenesis, thus altering the original geochemical signatures of the skeleton (Enmar et al., 2000; McGregor and Gagan, 2003; Lazar et al., 2004; Allison et al., 2005; Sayani et al., 2011).

An alternate means of obtaining coral palaeoclimate archives from throughout the Holocene is through shallow reef coring (e.g., Perry et al., 2008). Reef core collection techniques allow coral-based reconstructions to sample deeper into Earth's history; a requirement recently highlighted by the IPCC (IPCC, 2007; Masson-Delmotte et al., 2013). However, the disadvantage of this strategy is that specific coral species,