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Invited review

Coral indicators of past sea-level change: A global repository of U-series dated benchmarks

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ABSTRACT

Fossil corals provide valuable data for reconstructing past sea levels, as they are often well preserved in the fossil record and can be dated with U-series methods. Here we present a global and internally consistent database of U–Th dated fossil coral sea-level indicators, including full consideration of all (known) associated uncertainties (both vertical and chronological). We include carefully determined taxon-specific depth distributions, rather than blanket depth uncertainty terms as used in most previous work. This is based on a synthesis of extensive modern ecological information on depth ranges. These ranges are found to be spatially variable (between ocean basins, between regions, and on sub-regional scales) because depth itself is not limiting – instead, depth distributions arise from complex physical, chemical, and biological interactions with coral-reef growth, distribution, and composition. One of the main causes for recognition of the greater depth-variability of coral taxa has been the routine inclusion of deep-diving and ROV surveys in coral ecological studies over the past few decades, which has broken through the "shallow-water" bias of early surveys by adding frequent observations on deeper occurrences (although more are needed). It is also clear from our assessment that coral habitat-depth distributions must be determined on the species level to reduce uncertainties in reconstructions of past sea levels, and that application to sea-level studies then requires these studies also to identify fossil corals to the species level. Samples identified only to the genus level give rise to wide uncertainties in habitat depth and, hence, sea level. Our database contains extensive metadata to assist evaluations of dating quality, as well as geomorphic and stratigraphic metadata. We demonstrate with examples how such metadata can help to evaluate sea-level reconstructions, for example by identifying outlier points. One example discusses the Last Interglacial (LIG), where we use the available data with their uncertainties to assess probabilistically the time at which local sea levels exceed that of the present, which yields a mean age of 124.6 ka with 95% probability bounds at 118.5 and 129.5 ka. We conclude with identification of key outstanding issues relating to: (i) current incomplete understanding of tectonic setting (including the current lack of independent verification of uplift/subsidence rates and reliance of somewhat unsatisfactory, and circular, use of the elevation of Last Interglacial deposits); (ii) the depth-distributions of coral taxa and; (iii) the complete documentation of stratigraphic, geomorphological and other contextual information, with suggestions for strategies to address these issues.

1. Introduction

Fossil corals have provided valuable insights into past changes in sea level, from the early studies that tested Milankovitch pacing of glacial-interglacial cycles (e.g., Broecker et al., 1968; Mesolella et al., 1969), to more recent work on detailed, high-resolution reconstructions of past sea levels (e.g. Deschamps et al., 2012) that

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provide constraints for investigations of past ice-sheet dynamics (e.g. Clark et al., 2002; Stanford et al., 2011; Lambeck et al., 2014).

Fossil corals offer distinct advantages for reconstructing past sea levels, principally their good preservation potential, and the potential for obtaining precise, numerical ages using U-series dating. They also have a wide distribution in the topical/subtropical regions and many of these sites are far-field (i.e. far away from the centres of the former ice sheets), where glacio-isostatic adjustment (GIA) influences are minimised (e.g. Clark et al., 2002; Bassett et al., 2005). However, the coral data distribution is heterogeneous in space and time; i.e., they are limited to tropical/subtropical regions, represent periods of reef construction, and provide discrete data points rather than continuous sea-level records. In addition, taphonomic and diagenetic factors influence coral preservation, and the relationship between the present elevation of the fossil coral and former sea levels often remains insufficiently constrained. In this paper, we first review modern ecological studies of the main controls on coral growth, and formulate from this a comprehensive assessment of depth-distributions. Thereafter, we present and discuss a new compilation of U-series dated fossil coral data, which is quality-checked and internally consistent, includes relevant contextual metadata, and gives full consideration of uncertainties.

2. Principal controls on reef development and distribution

Sceleractinian ('hard') corals are composed of polyps that secrete an aragonitic skeleton using calcium and carbonate ions precipitated from seawater. Zooxanthellate sceleractinian corals have endosymbiotic photosynthetic algae. Scleractinian corals may take various growth forms (branching, massive, encrusting, solitary, free-living i.e. not attached to the substrate etc.) and in this review we concentrate on the reef-forming (hermatypic) corals.

Coral reefs are complex structures that consist of both primary (skeletogenesis) and secondary (e.g., marine (re)cementation) structures with a potential for significant biomineralisation (e.g., Barnes and Devereux, 1984). The exact mechanisms of calcification and the role of symbionts remain debated, and – despite considerable progress in recent decades (e.g., Cohen and McConnaughey, 2003) – understanding of how major and trace elements are incorporated into the coralline aragonite remains incomplete (Allemand et al., 2004, 2011). The principal components required for coral growth are: light, carbon dioxide and inorganic nutrients for photosynthesis; organic food for organic tissue and organic matrix synthesis; and calcium and carbonate ions for skeleton formation.

Coral reefs can be separated into three main geomorphological zones: (i) the back-reef and reef flat zone; (ii) the reef crest, and (iii) the fore-reef (which includes the reef slope), within which different benthic assemblages make statistically distinct contributions to reef framework construction (e.g., Hopley et al., 2007; Woodroffe and Webster, 2014). The back-reef zone is a low-energy zone with lagoons featuring sea-grass beds, patch reefs and sand plains. The reef flat and reef crest (or algal ridge where encrusting coralline algae replace corals in the highest wave-energy settings) is formed from consolidated calcareous material, corals, and coralline algae. This is a high-energy zone with potential for breakage, desiccation through exposure at low tide, and ultra violet (UV) light stress. The fore-reef continues seaward of the reef crest to depth. This lower-energy zone has steep gradients in light and temperature, with the greatest coral diversity typically at intermediate depths of 15–30 m (e.g., Burns, 1985; Huston, 1985; Cornell and Karlson, 2000) and decreasing with increasing depth. We refer the reader to Woodroffe and Webster (2014), Kennedy and Woodroffe (2002) and Montaggioni and Braithwaite (2009) for detailed considerations of reef morphology.

The interplay of physical, biological and chemical factors (e.g., substrate, incidence of severe storms, predation, disease, etc.) determines the structure and composition of coral reefs, including their growth form, taxonomic composition, distribution, and their preservation potential within the fossil record. These factors operate on a variety of geographic scales: some affect the global distribution of reefs; others control the dimensions and geometry of individual reefs; yet other factors influence – at the ecosystem level – the community composition, zonation, and habitat availability (including the distribution and abundance of populations/taxa); and, finally, several factors combine to affect corals at the individual level, through recruitment, growth rates, size, form, reproduction, and mortality.

In this section we review the main influences on coral growth (Fig. 1), with a focus on the ecological and hydrological factors.

2.1. Temperature

Sea surface temperature is a major determinant in the growth and distribution of modern coral reefs (Macintyre and Pilkey, 1969; Andrews and Gentien, 1982; Johannes et al., 1983; Veron and Minchin, 1992), influencing the composition and structure of reef communities, and regulating the aragonite saturation state of the surface waters (growth is optimal in warm waters that are supersaturated with respect to aragonite; Kleypas, 1997; Kleypas et al., 1999). Temperature also exerts a control on the latitudinal extent (geographical range) of species, and comparison between fossil and modern coral ranges suggests a substantial poleward expansion of the range of many coral taxa during the Last Interglacial (LIG) relative to the present as a result of increased temperatures, although equatorial diversity was reduced (Kiessling et al., 2012). Most modern coral reef growth is limited to waters with temperatures between ~18 and 31 °C for most of the year (Hubbard, 1997; Kleypas et al., 2008), but some reef corals are able to tolerate temperatures as low as 11° C (Veron, 2000). Prolonged exposure to temperatures outside this range may lead to reduced photosynthesis, coral bleaching, and mortality.

Coral reef growth is generally confined to tropical latitudes, although warm surface currents can enable growth outside the tropical latitudes (e.g., Kuroshio, Leeuwin, and Agulhas Currents). In addition, thermal gradients within basins, such as the Red Sea, may determine local/regional coral reef distribution and diversity (e.g., Veron, 1995, 2000). Changes in these local or regional conditions or currents and their associated temperature regimes can influence coral distributions resulting in the expansion or contraction of the latitudinal range of coral species (e.g., Roberts et al., 1982; Veron, 1992; Abram et al., 2001). For example, Greenstein and Pandolfi (2008) demonstrate a contraction in geographic range and a change in assemblage composition within modern reefs compared to fossil Last Interglacial reefs of Western Australia, in response to decreased temperatures from a weakened Leeuwin Current, given that this current brings warm equatorial waters to higher southern latitudes. Similarly, Muhs et al. (2002a, b, 2006) use molluscs and corals as part of the wider reef assemblage, to infer changing thermal conditions and ocean currents (for California, Hawaii and Bermuda).

2.2. Salinity

Corals are generally thought to be tolerant of salinity variations, generally growing within a range of 30–38 psμ with some species tolerating salinities of ~40 psμ. Extended exposure to low-salinity waters may reduce growth rates, reproductive success, photosynthesis, and respiration (Coles and Jokiel, 1992; Muthiga and Szmant, 1987; Richmond, 1993; Moberg et al., 1997; Porter et al., 1999;