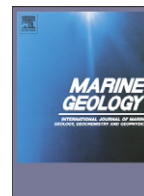




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Review article

Coral reefs and sea-level change

Colin D. Woodroffe ^{a,*}, Jody M. Webster ^b^a GeoQuest Research Centre, School of Earth and Environmental Sciences, University of Wollongong, NSW 2522, Australia^b Geocoastal Research Group, School of Geosciences, University of Sydney, NSW 2006, Australia

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ABSTRACT

Coral reefs provide significant evidence for former sea-level positions because of their geological preservation and suitability for dating. Interpretation of this evidence presumes an understanding of reef geomorphology, modern reef organism distributions, and environmental factors influencing them. Fossil reef terraces, formed during the last interglacial, marine oxygen isotope (MIS) substage 5e (~128–116 ka), are prevalent on many tropical shorelines and there has been ongoing debate as to the height reached by sea level during that highstand. Observations from numerous last interglacial sites suggest that sea level was at least 3 m above present sea level, implying less extensive icesheets than at present. An elevation of 6 m has commonly been adopted when correcting tectonically active sites for uplift. Recent compilations suggest elevations up to 8–9 m, but incorporate few observations from reefs where the last interglacial is found below sea level. Oscillation of sea level during MIS 5e has been interpreted from several sites, with recent studies inferring rapid rise of several metres at the end of the interglacial. These interpretations are at the limits to the precision with which corals can currently be dated and their palaeo-water depths inferred. It is not surprising that constraining last interglacial sea-level changes within uncertainties of less than 1–2 m remains controversial, considering sea-level variations recognised between reef sites in the Holocene, and observed geographical variation in isostatic or flexural adjustments. Fossil coral reefs on uplifting margins also provide clear evidence for MIS substages 5c and 5a, and those on Huon Peninsula indicate fluctuations related to Heinrich events (MIS 3). Interpretations show considerable variability between sites, with still greater uncertainties about sea-level timing and elevation during previous interglacials. Future study of extensive sequences of fossil reefs preserved on rapidly subsiding margins could address these uncertainties. Submerged reefs have already yielded important information about sea-level rise during the last deglaciation. Coring around Barbados and Tahiti, as well as on the Huon Peninsula, has produced a broadly consistent picture of ice melt, reflecting eustatic change since the last glacial maximum. These studies have shown the sensitivity of reefs to rapid sea-level rise associated with meltwater pulses, with some reefs drowning while others back-stepped. Integrated Ocean Drilling Program (IODP) expeditions to Tahiti, and recently the Great Barrier Reef, extended these records, but details of timing, nature and impact of deglacial meltwater pulses remain elusive. Studies of Holocene reefs have indicated different growth strategies; some kept up with sea level, while others caught up when sea level decelerated. Holocene sea level appears to have experienced a gradual rise up to present across the Caribbean, providing accommodation space for reefs to accrete vertically; whereas in the Indo-Pacific sea level has been near its present level since 7 ka, with many reef flats emergent following a slight fall of sea level caused by ocean siphoning. Microatolls on reef flats provide perhaps the clearest evidence of past sea-level position, but, in their absence, novel biological or other sea-level indicators are required to better constrain palaeo-water depths. There is an urgent need for further research from additional key reef locations, not only to decipher processes driving past sea-level change and its geographical variability, but also to better understand how coral reefs will respond in the context of future sea-level rise.

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1. Introduction

Coral reefs cover more than 250,000 km² of the ocean, with greatest diversity of species in the Indo-Pacific region and a second, less diverse, region centred on the western Atlantic. They extend from 33°N in Japan and 32°N at Bermuda to similar latitudes in the southern hemisphere at

Inhaca Island in southern Mozambique, Rottneest Island in Western Australia, and Lord Howe Island in the southern Pacific. Reefs require a suitable substrate on which to establish where sea-surface temperatures are favourable, primarily where they exceed 18 °C throughout the year (Veron, 1995). Reef-building corals maintain a symbiotic relationship with photosynthetic zooxanthellae, which limit them to the photic zone in which light is available for photosynthesis. They require relatively clear, warm waters with minimal suspended sediments, as well as a firm substrate on which to establish, although recently it has

* Corresponding author.

E-mail address: colin@uow.edu.au (C.D. Woodroffe).

been discovered that there are extensive mesophotic reefs developed in water depths of >40 m indicating that many corals can survive in a greater depth range than previously recognised (Abbey et al., 2011a; Bridge et al., 2011).

Coral reefs are commonly considered very effective indicators of sea level because reef-building (hermatypic) scleractinian corals occupy a narrow vertical depth range and have good geological preservation potential. Individual coral colonies can grow for decades, and in some circumstances centuries. After their death, corals are incorporated into the reef structure, which comprises coral framework together with other calcareous organisms such as foraminifera, molluscs and coralline algae. Fossil corals, composed of unaltered aragonite, can be dated by radiocarbon and uranium-series disequilibrium dating methods, as well as other dating methods (electron spin resonance). Ages are subject to uncertainties inherent in each dating technique, and to time-averaging effects through temporal mixing of different cohorts of fossil assemblages (Edinger et al., 2007); nevertheless, corals represent more reliable timekeepers than most other fossil organisms. They are often suitable for high-resolution geochemical studies of environmental conditions using stable isotope and trace element analyses. Assemblages of corals, or associated reef biota, may enable estimation of paleoenvironmental conditions, such as temperature, turbidity, paleo-water depth or exposure to wave energy.

Coral reefs have played a crucial role in providing evidence for the absolute position of past sea level and support for orbitally-driven glacial cycles, reflecting periodicities of 23 (precession), 41 (obliquity), and 100 (eccentricity) kyr, as proposed by Milankovitch. At the beginning of the 20th century, discrimination of successive glaciations in the Alps, particularly the work of Penck and Brückner (1909), indicated that there had been at least four glacial advances. It became apparent that these had been accompanied by a lowering of sea level as polar ice sheets expanded, and a subsequent transgression as they melted. Old shorelines were identified around the Mediterranean Sea, and initially these terraces, given the names Sicilian, Milazzian, Tyrrhenian, Monastirian and Nissian, were believed to record successively lower highstands from consecutive interglacials (Zeuner, 1945). In much the same way that the Mediterranean terraces had provided a discontinuous view of sea-level highstands, so too the early use of reefs enabled only glimpses of highstands during glacially-driven variations of sea level (Broecker et al., 1968; Chappell, 1974). It has since become apparent that reefs can be used in a broader range of sea-level studies, including the identification of interstadial and other shorter-term fluctuations of sea level, and the occurrence of abrupt sea-level rise associated with meltwater pulses. Nevertheless, the actual relationship between the structure and stratigraphy of a reef and the exact sea-level position at the time it formed is still poorly understood.

In this review we demonstrate how the study of reefs has progressed from an initial stage where near-horizontal terraces provided a constraint on the highest points that sea level reached. The facies architecture of modern reefs has been examined by shallow drilling which provided an insight into Holocene growth patterns (Davies and Montaggioni, 1985). From these studies a framework developed which enabled characterisation of reef accretion as keep-up, catch-up or give-up with respect to sea-level (Neumann and Macintyre, 1985).

Coral reefs continue to play an important role in the reconstruction of past sea levels, although a more complete record of climate-related fluctuations can now be derived from isotope and trace element analysis of deep-sea cores (Waelbroeck et al., 2002; Rohling et al., 2009), further substantiated by ice cores. Dating of corals usually offers more precise temporal resolution than achievable from deep-sea sediment reconstructions, but reefs may also provide more accurate constraints on the vertical position of past sea level (Chappell and Shackleton, 1986). Higher resolution dating of emergent reefs is providing greater insights into the last interglacial in particular, but also previous interglacials and other oscillations associated with shorter climate excursions, such as Heinrich events and meltwater pulses. More recently,

submerged reefs have started to reveal evidence of sea-level position over a greater part of glacial–interglacial cycles than previously accessible from emergent reef terraces, corroborating the longer-term oxygen isotope evidence, and in some cases providing evidence of shorter-term anomalies that cannot be detected from long-term but lower resolutions records. The sensitivity of corals to exposure by the lowest tides means that long-lived intertidal colonies, called microatolls, can contain a filtered record of low water levels, with the prospect of extrapolating this across recent centuries to millennia using preserved fossil colonies.

2. Reef composition, morphology and growth

Interpretation of fossil reefs depends on an understanding of the occurrence, ecology and zonation of modern reef organisms, and the presumption that similar factors controlled distributions of past life forms. The distribution of coral across an individual reef varies according to depth, and in response to several other environmental factors, such as stresses imposed by wave energy, light availability and sediment loading (Chappell, 1980). Different corals have different discrete tolerances; delicate corals, for example, are fractured if wave energy is high. Fig. 1 shows schematically the relative distribution of delicate branching forms, encrusting corals, and domal colonies of massive corals (Montaggioni, 2005). In the highest wave-energy settings encrusting coralline algae replace corals and the reef crest comprises an algal ridge (Montaggioni and Braithwaite, 2009). These other reef biota are also likely to preserve information on paleoenvironmental conditions, such as water depth, where clear differences in algae type and form, or other associated organisms, vary with light and depth.

Past relative changes in sea level have contributed to reef morphology. Exposure at low tide imposes a stress on many reef flats and sets an upper growth limit for corals at approximately Mean Low Water Springs (MLWS). In backreef environments or on shallow reef flats in the Indo-Pacific, several coral genera adopt a flat-topped microatoll growth morphology, described below, as a result of periodic subaerial exposure at low tide (Hopley et al., 2007). Although trends were suggested by Chappell (1980) in response to gradients in environmental factors, there is considerable diversity both in species occurrence and growth form on most forereefs.

In the Caribbean, the less diverse reefs commonly comprise broad zones linked to water depth and wave energy (Geister, 1977). The crest of the most exposed reefs is dominated by coralline algae or *Millepora*. The distinctive branching *Acropora palmata* forms monospecific thickets on many shallow windward reef fronts in water depths of up to 5 m. Although this coral can occur in deeper water, radiometric ages on *A. palmata* from reef facies in which it forms the framework have been used to indicate past sea level (Lighty et al., 1982). In more sheltered locations more delicately branching *Acropora cervicornis* or *Porites porites* occur on the reef crest.

In the more diverse reefs of the Indo-Pacific, it is more difficult to recognise depth-related zonation of corals, making them less suitable to indicate sea level. On the Huon Peninsula, *Acropora humilis* and *Isopora (Acropora) cuneata* are typical of reef crest facies (Chappell, 1980), found stratigraphically above *Isopora (Acropora) palifera*. However, the occurrence of coral species is not closely related to depth in either modern or fossil reefs on the Huon Peninsula, and crusts of coralline algae appear a more effective indicator of shallow water (Pandolfi, 1996). Montaggioni and Braithwaite (2009) provide a detailed summary of variation across the region and indicate recognition of six types of coral assemblages. A robust branching coral assemblage of wave-resistant growth forms of *Acropora* and *Pocillopora* is characteristic of many shallow windward reef fronts. For example, *Acropora robusta*, *A. digitifera* and *Pocillopora eydouxi* are found in shallow water in Luzon in the Philippines, and fossils of these have been used to reconstruct sea level (Shen et al., 2010). Sugihara et al. (2003) found that *Pocillopora verrucosa*, one of the most abundant coral species on the upper-reef slopes of fringing reefs in the Ryukyu Islands, has its

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