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Morphological characterisation of reef types in Torres Strait and an assessment of their carbonate production

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ABSTRACT

Coral reefs represent major accumulations of calcium carbonate ($CaCO_3$). The particularly labyrinthine network of reefs in Torres Strait, north of the Great Barrier Reef (GBR), has been examined in order to estimate their gross $CaCO_3$ productivity. The approach involved a two-step procedure, first characterising and classifying the morphology of reefs based on a classification scheme widely employed on the GBR and then estimating gross $CaCO_3$ productivity rates across the region using a regional census-based approach. This was undertaken by independently verifying published rates of coral reef community gross production for use in Torres Strait, based on site-specific ecological and morphological data. A total of 606 reef platforms were mapped and classified using classification trees. Despite the complexity of the maze of reefs in Torres Strait, there are broad morphological similarities with reefs in the GBR. The spatial distribution and dimensions of reef types across both regions are underpinned by similar geological processes, sea-level history in the Holocene and exposure to the same wind/wave energetic regime, resulting in comparable geomorphic zonation. However, the presence of strong tidal currents flowing through Torres Strait and the relatively shallow and narrow dimensions of the shelf exert a control on local morphology and spatial distribution of the reef platforms. A total amount of 8.7 million tonnes of $CaCO_3$ per year, at an average rate of 3.7 kg $CaCO_3\,m^{-2}\,yr^{-1}$ (G), were estimated for the studied area. Extrapolated production rates based on detailed and regional census-based approaches for geomorphic zones across Torres Strait were comparable to those reported elsewhere, particularly values for the GBR based on alkalinity-reduction methods. However, differences in mapping methodologies and the impact of reduced calcification due to global trends in coral reef ecological decline and changing oceanic physical conditions warrant further research. The novel method proposed in this study to characterise the geomorphology of reef types based on classification trees provides an objective and repeatable data-driven approach that combined with regional census-based approaches has the potential to be adapted and transferred to different coral reef regions, depicting a more accurate picture of interactions between reef ecology and geomorphology.

1. Introduction

It is important to understand the interactions between atmospheric CO_2 and the carbonate budget of reefs (Berger, 1982), particularly in the context of the accelerated increase of CO_2 concentrations due to human-induced emissions and its implications in relation to the future of reef systems (Veron et al., 2009). Coral reefs sequester carbon in the form of calcium carbonate ($CaCO_3$) over geological time scales. The capacity of corals to deposit $CaCO_3$ is controlled by the saturation state of $CaCO_3$ in seawater (Ω). As concentrations of atmospheric CO_2 increase, Ω decreases and so does coral calcification (Kleypas et al., 1999). Over shorter historical time scales (10–100s of years), as the surface water geochemistry is modified, coral reef systems can release CO_2 and act as net contributors of CO_2 to the atmosphere (Ware et al., 1991).

A coral reef can be considered as a “carbonate factory” involving processes of $CaCO_3$ production and loss (Pomar and Hallock, 2008). From a geomorphic perspective, the balance represents net $CaCO_3$ accumulation, with a positive budget implying reef accretion, whilst processes such as physical abrasion, bioerosion and dissolution represent negative contributions to the budget. The carbonate budget approach is an appropriate framework that allows analysis of the various components of reef function and structure at appropriate spatial scales (e.g. within a whole-reef or between reefs) over time, effectively linking ecological and morphological changes (Buddemeier and Smith, 1988; Perry et al., 2008). However, current understanding of ecomorphodynamic interactions remain poorly resolved, with anticipated shifts in ecological processes due to climate change, adjustments in sediment production and transport that will affect associated landforms such as reef

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islands, and further implications for reef morphology (Perry et al., 2011).

Direct estimates of reef metabolism have shown that the intricate cycling and dynamics of $CaCO_3$ can result in intra-reef zones acting simultaneously as carbonate sources and sinks within coral reef systems (Kinsey and Davies, 1979; Gattuso et al., 1999; Yates and Halley, 2003). Such measurements, however, are complicated and prohibitively costly across large reef systems (Zhang et al., 2012). Maps of the geomorphic zones which characterise coral reefs can also be used to provide an indication of the distribution, patterns and extent of different coral reef biological communities and to estimate reef growth, productivity or coral health across regions (Andréfouët et al., 2006; Hamylton et al., 2012). Scaling-up coral reef gross production and calcification rates has been undertaken at different spatial scales and levels of generalization by linearly extrapolating metabolism rates based on the areal extent of geomorphic and benthic community zones, from individual reef platforms (Ahmad and Neil, 1994; Ryan et al., 2001), to synoptic coral reef regions (Kinsey and Hopley, 1991; Andréfouët and Payri, 2000; Brock et al., 2006; Moses et al., 2009), to global estimates (Vecsei, 2004).

The reefs of Torres Strait, between Cape York Peninsula and Papua New Guinea, comprise a particularly complex maze, termed the "labyrinth" by Captain James Cook, which extends across the continental shelf beyond the northern end of the Great Barrier Reef (GBR) (Fig. 1). They have continued to pose an obstacle to mariners since the skilled Galician navigator, Luis Vaz de Torres (after whom the strait is named), commanded the first known voyage through the passage in 1606, taking two months to battle the strong winds and tidal currents. As Hopley et al. (2007) noted, the reefs in Torres Strait still remain inadequately studied and mostly uncharted at a detailed level, away from major shipping routes, despite being adjacent to the well-studied GBR. This represents a gap in understanding regional spatial patterns of coral reef geomorphology and evolution, which are important for the long-term management of these ecosystems.

In this paper we describe the morphology of reefs in Torres Strait and estimate their gross $CaCO_3$ productivity based on detailed intra-reef geomorphological mapping in conjunction with comprehensive information about links between geomorphology and biological communities, and published metabolic rates. Estimates of the carbonate budget for an emergent reef in Torres Strait are described, extending the earlier studies of that reef (Hart and Kench, 2007). $CaCO_3$ productivity is extrapolated across the entire region adopting a regional census based approach (Vecsei, 2001, 2004) and building on methods to scale up the gross $CaCO_3$ production for the complete GBR reef system (Kinsey and Hopley, 1991) based on the geomorphic characteristics of these reef types (Hopley, 1982; Hopley et al., 2007).

2. Regional setting

Torres Strait lies between Cape York Peninsula, the northernmost point of mainland Australia, and the south coast of Papua New Guinea. It formed a land bridge between these two landmasses during the Late Pleistocene, but became submerged as sea level rose and flooded the underlying Oriomo Ridge. The Strait contains a discontinuous chain of granitic islands to the west (e.g. Thursday Island) and younger volcanic islands fringed by coral reefs to the east (e.g. Murray Island) (Fig. 1).

The central section comprises a maze of scattered coral reef platforms and submerged *Halimeda* banks (Heap and Sbaffi, 2008). Considerable reef growth was initiated over the mostly shallow shelf (15–30 m) as it was flooded by the sea. It is generally considered that the land bridge was severed when the sea rose beyond 12 m below present sea level. Platform reefs are common in the central Torres Strait region, rising abruptly from shallow depths. They are Holocene in age and appear to be founded on the remnants of earlier Pleistocene reefs and other non-reefal topographic remnants as shallow as 6 m below sea level (Woodroffe et al., 2000).

There are geomorphological similarities between coral reefs in Torres Strait and those on the GBR as both reef tracts have experienced a similar sea-level history during the Holocene. Hopley (1982) proposed a classification of coral reef types for the GBR based on interpretation of intra-reef geomorphic zones from large-scale aerial photography. It was complemented by a thorough analysis of surface and subsurface sediments, stratigraphy and radiocarbon dating and it remains central to description of GBR reefs, 25 years later (Hopley et al., 2007). The different reef types were interpreted to represent progressive evolutionary stages in platform development, from juvenile reefs (submerged and patches), through mature (crescentic and lagoonal), to senile reefs (planar). Additionally, ribbon and fringing reef types are also recognized (Fig. 5.6 and Table 5.3 in Hopley et al., 2007).

Preliminary geomorphological and geochronological studies indicate that several Torres Strait reefs have grown up to, and their upward growth was constrained by, a sea level slightly above present around 5000 years ago. Coring on Warraber (Sue) reef (Fig. 1) showed that the reef platform has built laterally since that time with much of the former reef top now emergent as a largely barren sandy reef flat exposed at low tide (Woodroffe et al., 2000). This reef platform is similar to planar reefs in the GBR in regards to the proportion of intra-reef geomorphic zones, although it has evidently not evolved through the infill of a lagoonal reef as implied in Hopley's model.

Additionally, reef platforms such as the extensive Warrior reefs (Fig. 1) are characterised by an incomplete reef rim best developed on the eastern windward margin and with sheltered backreef environments that remain beneath water at all stages of the tide. These are comparable to crescentic reef types. Moreover, numerous shelf-edge and dissected reefs occurring on the eastern edge of Torres Strait are comparable to the outer ribbon reefs of the northern GBR (Veron, 1978).

Conversely, there are several distinctive reef platforms in Torres Strait. For example, the Cumberland reef complex (Fig. 1) is a network of relatively large reefs (~50 km^2) with a pattern that resembles the smaller deltaic reefs in the GBR. Evidence suggests that such reef platforms have grown from deep shelf valley systems incised by strong tidal currents (Harris et al., 2005). The strong tidal currents funnelling from the Coral Sea into the Gulf of Carpentaria (Saint-Cast, 2008) have also been attributed to the distinctive east–west orientation of many reef platforms in Torres Strait (Brander et al., 2004).

Jones (1995) related the elongated morphology of Torres Reefs (several distinct linear west–east reefs just north of Hammond Island, Fig. 1) to the progressive lateral colonisation of reef patches over sediment transported and accumulated by strong tidal currents of up to 2 m s^{-1}. Analysis of seismic profiles showed that the intertidal reef "tail-end" was composed of reef patches infilled with unconsolidated sediment, which was explained as a consequence of the stepwise growth of the platform margin. Woodroffe et al. (2000) came to similar conclusions based on coring and dating of the linear coral-covered features parallel to the modern reef crest, considered former reef crests, on the elongated Warraber reef platform.

3. Methods

Our study involved two steps. The first step classified reef platform types in Torres Strait based on Hopley's classification scheme. The second step consisted of scaling-up gross $CaCO_3$ production from individual reef types to a regional scale across Torres Strait. This was undertaken by adapting published rates of coral reef community gross production for use in Torres Strait, based on site-specific ecological and morphological data. Gross production rates adapted to Torres