   

ReefBudget: Introduction and Underpinning Concepts

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1. Introduction and underpinning concepts

1.1 Coral reef carbonate production, cycling and carbonate budgets

A range of physical, chemical and biological processes are involved in the production, modification and breakdown of calcium carbonate within reef environments. These processes operate at the scale of the individual coral colony but aggregate to influence reef accretion over larger spatial units. Some processes are responsible for carbonate production, whilst others result in the breakdown of previously deposited skeletal carbonate and, in some cases, result in its conversion to sediment. Such detrital sediment can be either: incorporated within the reef framework; exported off-reef; or deposited within the broader reef geomorphic system to construct sedimentary landforms (e.g., beaches, sand aprons, reef islands). These carbonate 'cycling' processes may thus exert either a 'constructive' or 'destructive' (*sensu* Scoffin 1992) influence on reef-related carbonate accumulation (reviewed in Perry and Hepburn 2008) and interact to determine net $CaCO_3$ accumulation rates on a coral reef, the rates of which are both spatially and temporally variable within individual reef systems. Corals typically (but not always) represent the primary constructional components on many reefs and add significant amounts of carbonate per unit area of reef (see Vecsei 2004). However, other 'constructive' processes also add additional calcium carbonate to reef framework structures, the most important being by calcareous encrusters (especially crustose coralline algae), and the precipitation of syn- and early post-depositional cements (Perry and Hepburn 2008). Both sets of processes can contribute significant amounts of carbonate to the accumulating reef framework and both may actually dominate calcium carbonate accumulation in specific reef settings (Steneck and Adey 1976; Bosence 1984; Spratcha et al. 2001; Camoin et al. 2006; Cabioch et al. 2006).

A range of destructive physical and biological processes are also important in determining net $CaCO_3$ accumulation rates. Bioerosion is facilitated by a wide range of reef-associated faunas, including by specific fish and echinoid taxa, and endolithic forms of cyanobacteria, chlorophytes, fungi, sponges, bivalves and worms (Spencer 1992; Glynn 1997; Edinger et al. 2000; Perry and Hepburn 2008). These biological agents of destruction play two key roles in reefs: 1) they directly degrade the primary and secondary framework, increasing susceptibility to physical and chemical erosion and thus strongly influence carbonate budgets (Goreau and Hartman 1963; Frydl and Stearn 1978; Bak 1994), and 2) they may produce large amounts of sediment (Neumann 1966; Gygi 1975; Moore and Shedd 1977). Physical disturbance, associated with severe storms and cyclones, is an important episodic process that influences reef framework development, largely through the generation of coral rubble, the deposition of which is an important reef-building process it its own right (Hubbard 1997; Blanchon and Jones 1997; Rasser and Riegl 2002).

The relative role of these different processes is clearly crucial to reef-building potential, a concept that is defined by the carbonate budget approach to conceptualizing and quantifying reef geomorphic performance. A carbonate budget is the sum of gross carbonate production from corals and calcareous encrusters, as well as sediment produced within or imported into the reef, less that lost through biological or physical erosion, dissolution or sediment export (Chave et al. 1972). The balance represents the net accumulation rate of $CaCO_3$ and can be considered as a quantitative measure of the functional state of a reef. This approach allows understanding of the relative importance of different processes in different reef environments since the measures can be applied both at reef system and intra-reef (i.e. reef sub-environment - reef flat, reef slope etc.) scales. It is also highly likely that production rates both at the whole reef and the sub-environment scale will vary temporally, either as a reef reaches a more mature evolutionary state or as short-term ecological changes (i.e. ecological phase shifts) drive episodic fluctuations or more permanent transitions in the abundances of carbonate producers and destroyers. Such dynamics are fundamental for understanding reef geomorphology and for assessing phases of reef construction and coral reef framework erosion and degradation (see, for example, Eakin 2001). They are also highly relevant to understanding the development of reef-associated sedimentary landforms (beaches, reef islands) as phases of framework degradation may trigger the release of pulses of sediment, or modify sediment production rates.

1.2. The framework production status approach (Perry et al. 2008 *Coral Reefs*)

The balance between those processes that produce (deposit) calcium carbonate and those that remove it or convert it to sediment thus strongly influences net rates of reef carbonate production and accumulation at a range of scales in time and space. Modifications to the rates at which any of the individual, or combined, processes (either constructive or destructive) operate consequently have important implications for reef structures and reef-associated sedimentary landforms because they may shift the balance of the carbonate budget. The drivers of such change may be linked either to direct anthropogenic activities (see Done 1999; Hallock 2001), or to climate-change induced shifts in sea level, temperature and seawater chemistry. All these factors have the potential to modify the ecological functioning of reefs - changes that are consistent with the 'phase shift' concept (Done 1992) - and thus to alter the carbonate depositional system. As discussed by various authors, therefore, a logical aspect of reef 'health' assessments should be a consideration of a reef's carbonate budget state (e.g., Rose & Risk 1985; Edinger et al. 2000; Risk et al. 2001). In particular, consideration should be given to the relative contributions to carbonate accumulation made by both corals and calcareous encrusters, and to the key role played by framework bioeroders (a component group encompassing the bioeroding species of fish and echinoids, and the infaunal macro- and microboring taxa; see also Edinger et al. 2000). Perry et al. (2008) adopted the terminology of Scoffin (1981; 1992) to distinguish between 'primary' (coral) and 'secondary' (calcareous encruster) carbonate producers, and the destructive group of bioeroders. At the most fundamental level, it is these three key biogenic component groups that exert the most important influence on net rates of carbonate framework accumulation on a reef and which are most directly impacted by environmental and ecological changes.

The relative importance of these three key biogenic process groupings, primary production (coral), secondary production (calcareous encrusters) and bioerosion, and the resultant reef framework production states, have been depicted using a ternary approach (Perry et al. 2008) (Fig. 1). Here the key processes define the triangle apices and different budget states are represented by different areas within the ternary space. Within this space, it is possible to identify areas where reefs are in net accretionary, net erosional, or static budgetary states. This approach allows representation of variations in the relative importance of these different process groups, thus acknowledging that whilst corals often dominate carbonate production, in some reef settings it is the calcareous encrusters (especially the coralline algae) that make an equal or greater contribution to biogenic framework carbonate production. For example, coralline algae are often the most important carbonate producers and framework-builders in shallow, high-energy, reef crest settings (Steneck and Adey 1976; Bosence 1984). Similarly, this approach allows representation of the key role played by bioeroders in determining net rates of carbonate production.

In this context it is informative to consider the locations of different reefs and reef environments for which quantitative carbonate production and erosion data exists. Most reefs for which appropriate budgetary data is available plot within areas characterised by states of net accretion (Fig. 1). In most cases corals, with varying levels of contribution from calcareous encrusters, dominate carbonate production. However, the net production values for some reef sub-environments are so low that the environments/reefs can effectively be regarded as being in a state of stasis, whilst a few reefs (essentially those examined by Eakin in Panama (Eakin 1996) and some of those examined by Edinger et al. (2000) from Indonesia) have net erosional values (Fig.1). This conceptual approach thus provides a framework for quantifying the differences that exist in carbonate production states between reef environments and has the potential to recognise that the relative importance of carbonate producing and cycling processes are transitional over time and space within individual reef systems.

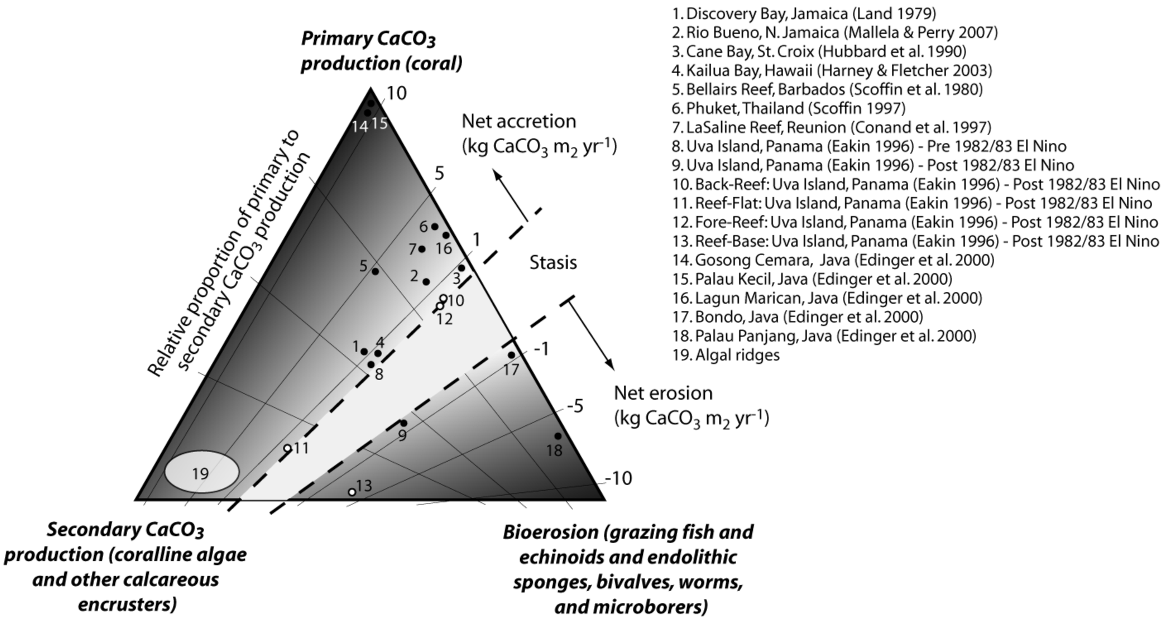

Fig. 1. *Ternary diagram showing different carbonate production states determined by variations in the relative importance of primary (coral) and secondary (calcareous encruster) carbonate production, and carbonate breakdown to sediment/dissolution by bioerosion. Also shown are the budget state points occupied by different reefs at the reef-wide scale (closed circles) and the reef sub-environment scale (open circles) from localities where appropriate carbonate budget data exists (from: Perry et al. 2008).*

1.3. Temporal transitions in carbonate production states

The ternary approach outlined in Fig. 1 also provides a mechanism by which temporal variations in the budgetary state of individual reefs might be tracked, especially where rapid ecological shifts (typically driven by extrinsic factors) may modify the relative production rates or the abundances of carbonate producers/eroders (see also Eakin 2001). Possible transition pathways are illustrated in Figure 2. This approach compliments the coral-macroalgal shifts identified in the ecological reef phase shift models by encompassing transitions in carbonate production states resulting from different community states and disturbance regimes. The production states shown as Points A and A^1 (Fig. 2) are essentially analogous to the 'production-dominated' reef states of Kleypas et al. (2001), where production is dominated by corals and calcareous encrusters respectively, whilst point C is analogous to the 'bioerosion-dominated' condition. Subtle transitions in production status (e.g., A-A^2 and vice versa) may occur due to intermittent disturbance events where the relative importance of carbonate producers and/or the ratio of production to bioerosion changes, but the system is still one of positive net production. These transitions can occur over a wide range of timescales (10^1 to 10^4 years), at shorter timescales linked to storms or cyclones, and at longer scales to relative sea-level fluctuations. It is also important to consider the point that these transitions may form part of natural temporal shifts in production mosaics (akin to the shifting steady-state mosaics of Done 1999) and not necessarily be linked to anthopogenically-driven ecological change. Residence time in different production states, and temporal dynamics of changes in specific states, are clearly critical to reef structure and to reef sedimentary landform development. However, the influence of such temporal behaviour in production states on geomorphic outcomes remains poorly resolved.

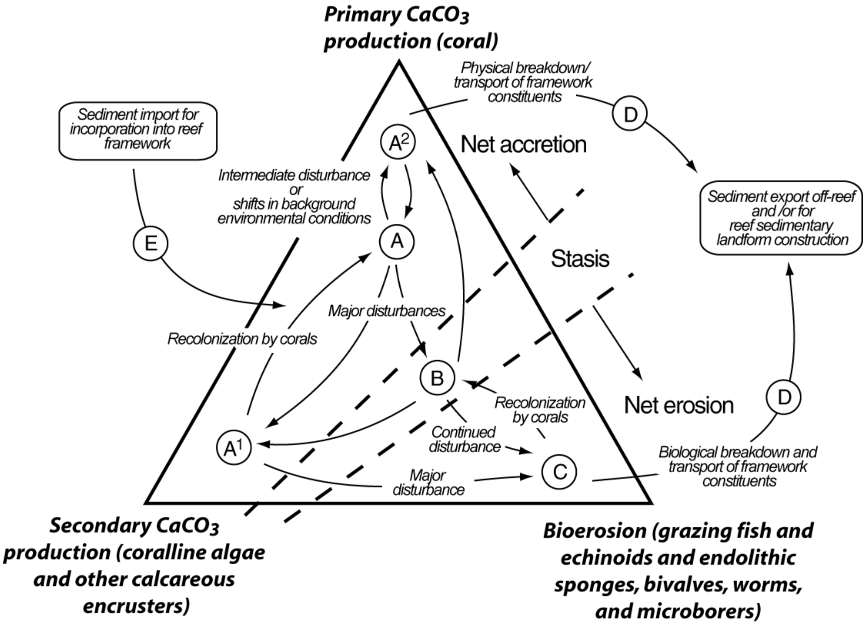

Fig. 2. *Conceptual model showing hypothetical transitions and potential pathways in reef carbonate production states driven by ecological or environmental change (from: Perry et al. 2008).*

Where major or prolonged disturbance occurs, more fundamental changes in reef production states can arise. In some cases this may result in a shift from a production-dominated to a bioerosion-dominated state. Here the pathway A-B-C is akin to the phase shift of Done (1992) but can be viewed in terms of carbonate cycling and the geomorphic performance of the reef. Under alternative scenarios, calcareous encrusters may become the dominant carbonate producers and, where bioerosion levels are low, the system may remain in a condition of positive net production (pathway A-A^1) (Fig. 2). Cessation of disturbance or an adaptation of the coral community (e.g., recruitment of, or replacement by, new, better adapted species) may allow transitions back to conditions of high carbonate production, with either similar (pathway C-B-A) or modified net production rates (C-B-A^2). Again, these transitions may occur over a wide range of timescales (10^1 to 10^4 years). Superimposed on these end members of production/degradation is the import and export of sediment. Under both positive and negative net production regimes sediment produced on reefs can be exported and made, in some cases, available for the construction of reef-associated sedimentary landforms e.g., beaches, islands (pathway D). Any such change in the relative rates of sediment generation may lag reef ecological states and may influence phases of beach or island development. In contrast, in some systems relatively low rates of primary and secondary carbonate production may be supplemented by the import of sediment (calcareous or terrigenous), that may contribute to the accumulating reef structure and help to maintain the system in a positive net accretionary state (pathway E in Fig. 2).

1.4 The *ReefBudget* approach:

The carbonate budget protocol recommended here (termed *ReefBudget*) aims to allow quantification of the carbonate budget status of different habitats or zones within individual coral reef systems. The focus, following the *framework production states* approach outlined above, is on quantifying net rates of reef framework production, encompassing estimates of carbonate production by corals and calcareous encrusters, and framework erosion by internal borers and substrate grazers. These can provide a measure of the functional performance of a reef in terms of the rates of primary framework production. Although clearly important in many systems and a volumetrically important aspect of the accumulating reef structure, sediment production *per se* is not quantified in this methodology. However, additional site specific observations on the abundance of detrital sediments in the areas under study, and on the composition of such sediments can be readily incorporated, providing important data on framework accretionary characteristics and carbonate sediment production regimes.

Key points regarding the methodology:

(1) The *ReefBudget* methodology as outlined has arisen from several field-based testing programmes undertaken at sites in The Bahamas and in Bonaire, with the individual process methodologies having been selected based on considerations of accuracy, ease and speed of use, and because of their non-reliance on expensive, high-tech equipment.

(2) At present the protocol (and supporting on-line database and data entry spreadsheets) has an entirely Caribbean focus, but the approaches recommended here have potential to be extrapolated to Indo-Pacific sites where suitable data exists.

(3) The methods can be applied to any reef site and depth zone, but considerations of regional variations in calcification rates etc, and of variations with depth need to be made as considered appropriate. Data should be collected along transects orientated parallel to the reef and along discrete depth contours within the reef zones that are of interest.

For detailed descriptions of the individual methodologies please refer to '*ReefBudget* Methodology' document on the website.