Chapter 7. Calcium Carbonate Production and Contribution to Coastal Sediments

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1. Calcium carbonate production in coastal environments

Biological production of calcium carbonate in the oceans is an important process. Although carbonate is produced in the open ocean (pelagic, see Chapter 5), this chapter concentrates on production in coastal waters (neritic) because this contributes sediment to the coast through skeletal breakdown producing sand and gravel deposits on beaches, across continental shelves, and within reefs. Marine organisms with hard body parts precipitate calcium carbonate as the minerals calcite or aragonite. Corals, molluscs, foraminifera, bryozoans, red algae (for example the algal rims that characterize reef crests on Indo-Pacific reefs) are particularly productive, as well as some species of green algae (especially *Halimeda*). Upon death, these calcareous organisms break down by physical, chemical, and biological erosion processes through a series of discrete sediment sizes (Perry et al., 2011). Neritic carbonate production has been estimated to be approximately 2.5 Gt year^{-1} (Milliman and Droxler, 1995; Heap et al., 2009). The greatest contributors are coral reefs that form complex structures covering a total area of more than 250,000 km^2 (Spalding and Grenfell, 1997; Vecsei, 2004), but other organisms, such as oysters, may also form smaller reef structures.

Global climate change will affect carbonate production and breakdown in the ocean, which will have implications for coastal sediment budgets. Rising sea level will displace many beaches landwards (Nicholls et al., 2007). Low-lying reef islands called sand cays, formed over the past few millennia on the rim of atolls, are particularly vulnerable, together with the communities that live on them. Rising sea level can also result in further reef growth and sediment production where there are healthy coral reefs (Buddemeier and Hopley, 1988). In areas where corals have already been killed or damaged by human activities, however, reefs may not be able to keep pace with the rising sea level in which case wave energy will be able to propagate more freely across the reef crest thereby exposing shorelines to higher levels of wave energy (Storlazzi et al., 2011; see also Chapter 43).

Reefs have experienced episodes of coral bleaching and mortality in recent years caused by unusually warm waters. Increased carbon dioxide concentrations are also causing ocean waters to become more acidic, which may affect the biological production and supply of carbonate sand. Bleaching and acidification can reduce coral growth and limit the ability of reef-building corals and other organisms to produce calcium carbonate (Kroeker et al., 2010). In some cases, ocean acidification may lead to a reduced supply of carbonate sand to beaches, increasing the potential for erosion (Hamylton, 2014).

1.1 Global distribution of carbonate beaches

Beaches are accumulations of sediment on the shoreline. Carbonate organisms, particularly shells that lived in the sand, together with dead shells reworked from shallow marine or adjacent rocky shores, can contribute to beach sediments. Dissolution and re-precipitation of carbonate can cement sediments forming beachrock, or shelly deposits called coquina. On many arid coasts and islands lacking river input of sediment to the coast, biological production of carbonate is the dominant source of sand and gravel. Over geological time (thousands of years) this biological source of carbonate sediment may have formed beaches that are composed entirely, or nearly entirely, of calcium carbonate. Where large rivers discharge sediment to the coast, or along coasts covered in deposits of glacial till deposited during the last ice age, beaches are dominated by sediment derived from terrigenous (derived from continental rocks) sources. Carbonate sediments comprise a smaller proportion of these beach sediments (Pilkey et al., 2011).

Sand blown inland from carbonate beaches forms dunes and these may be extensive and can become lithified into substantial deposits of carbonate eolianite (wind-blown) deposits. Significant deposits of eolianite are found in the Mediterranean, Africa, Australia, and some parts of the Caribbean (for example most of the islands of the Bahamas). The occurrence of carbonate eolianites is therefore a useful proxy for mapping the occurrence of carbonate beaches (Brooke, 2001).

Carbonate beaches may be composed of shells produced by tropical to sub-polar species, so their occurrence is not limited by latitude, although carbonate production on polar shelves has received little attention (Frank et al., 2014). For example, Ritchie and Mather (1984) reported that over 50 beaches in Scotland are composed almost entirely of shelly carbonate sand. There is an increase in carbonate content towards the south along the east coast of Florida (Houston and Dean, 2014). Carbonate beaches, comprising 60-80 per cent carbonate on average, extend for over 6000 km along the temperate southern coast of Australia, derived from organisms that lived in adjacent shallow-marine environments (James et al., 1999; Short, 2006). Calcareous biota have also contributed along much of the western coast of Australia; carbonate contents average 50-70 per cent, backed by substantial eolianite cliffs composed of similar sediments along this arid coast (Short, 2010). Similar non-tropical carbonate production occurs off the northern coast of New Zealand (Nelson, 1988) and eastern Brazil (Carannante et al., 1988), as well as around the Mediterranean Sea, Gulf of California, North-West Europe, Canada, Japan and around the northern South China Sea (James and Bone, 2011).

On large carbonate banks, biogenic carbonate is supplemented by precipitation of inorganic carbonate, including pellets and grapestone deposits (Scoffin, 1987). Ball (1967) identified marine sand belts, tidal bars, eolian ridges, and platform interior sand blankets comprising carbonate sand bodies present in Florida and the Bahamas. This is also one of the locations where ooids (oolites) form through the concentric precipitation of carbonate on spherical grains. Inorganic precipitation in the Persian Gulf, including the shallow waters of the Trucial Coast, reflects higher water temperature and salinity (Purser, 1973; Brewer and Dyrssen, 1985).

1.2 Global distribution of atolls

The most significant social and economic impact of a possible reduction in carbonate sand production is the potential decrease in supply of sand to currently inhabited, low-lying sand islands on remote reefs, particularly atolls. Atolls occur in the warm waters of the tropics and subtropics. These low-lying and vulnerable landforms owe their origin to reef-building corals (see Chapter 43 which discusses warm-water corals in contrast to cold-water corals dealt with in Chapter 42). The origin of atolls was explained by Charles Darwin as the result of subsidence (sinking) of a volcanic island. Following an initial eruptive phase, volcanic islands are eroded by waves and by slumping, and gradually subside, as the underlying lithosphere cools and contracts. In tropical waters, fringing coral reefs grow around the volcanic peak. As the volcano subsides the reef grows vertically upwards until eventually the summit of the volcano becomes submerged and only the ring of coral reef (i.e., an atoll) is left behind. The gradual subsidence can be understood in the context of plate tectonics and mantle "hot spots". Many oceanic volcanoes occur in linear chains (such as the Hawaiian Islands and Society Islands) with successive islands being older along the chain and moving into deeper water as the plate cools and contracts (Ramalho et al., 2013).

Most atolls are in the Pacific Ocean (in archipelagoes in the Tuamotu Islands, Caroline Islands, Marshall Islands, and the island groups of Kiribati, Tuvalu and Tokelau) and Indian Ocean (the Maldives, the Laccadive Islands, the Chagos Archipelago and the Outer Islands of the Seychelles). The Atlantic Ocean has fewer atolls than either the Pacific or Indian Oceans, with several in the Caribbean (Vecsei, 2003; 2004). The northernmost atoll in the world is Kure Atoll at 28°24' N, along with other atolls of the northwestern Hawaiian Islands in the North Pacific Ocean. The southernmost are the atoll-like Elizabeth (29°58' S) and Middleton (29°29' S) Reefs in the Tasman Sea, South Pacific Ocean (Woodroffe et al., 2004). The occurrence of seamounts (submarine volcanoes) is two times higher in the Pacific than in the Atlantic or Indian Oceans, explaining the greater frequency of atolls.

Corals, which produce aragonite, are the principal reef-builders that shape and vertically raise the reef deposit, and there are secondary contributions from other aragonitic organisms, particularly molluscs, as well as coralline algae, bryozoans and foraminifera which are predominantly made of calcite. Carbonate sand and gravel is derived from the breakdown of the reef. Bioerosion is an important process in reefs, with bioeroders, such as algae, sponges, polychaete worms, crustaceans, sea urchins, and boring molluscs (e.g., *Lithophaga*) reducing the strength of the framework and producing sediment that infiltrates and accumulates in the porous reef limestone (Perry et al., 2012). Erosion rates by sea urchins have been reported to exceed 20 kg $CaCO_3$ m^{-2} $year^{-1}$ in some reefs, and parrotfish may produce 9 kg $CaCO_3$ m^{-2} $year^{-1}$ (Glynn, 1996). Over time, cementation lithifies the reef. Whereas the reef itself is the main feature produced by these calcifying reef organisms, loose carbonate sediment is also transported from its site of production. Transported sediment can be deposited, building sand cays. Broken coral or larger boulders eroded from the reef by storms form coarser islands (termed *motu* in the Pacific). Sand and gravel can be carried across the reef and deposited together with finer mud filling in the lagoon (Purdy and Gischler, 2005).

Carbonate production on reefs has been measured by at least three different approaches; hydrochemical analysis of changes in alkalinity of water moving across a section of reef, radiometric dating of accretion rates in reef cores, and census-based approaches that quantify relative contributions made by different biota (including destruction by bioeroders). These approaches indicate relatively consistent rates of ~10 kg $CaCO_3$ m^{-2} $year^{-1}$ on flourishing reef fronts, ~4 kg $CaCO_3$ m^{-2} $year^{-1}$ on reef crests, and <1 kg $CaCO_3$ m^{-2} $year^{-1}$ in lagoonal areas (Hopley et al., 2007; Montaggioni and Braithwaite, 2009; Perry et al., 2012; Leon and Woodroffe, 2013). These rates have been described in greater detail in specific studies (Harney and Fletcher, 2003; Hart and Kench, 2007), and have been used to produce regional extrapolations of net production (Vecsei, 2001, 2004).

2. Changes known and foreseen –sea-level rise and ocean acidification.

Several climate change and oceanographic drivers threaten the integrity of fragile carbonate coastal ecosystems. Anticipated sea-level rise will have an impact on the majority of coasts around the world. In addition, carbonate production is likely to be affected by changes in other climate drivers, including warming and acidification. Tropical and subtropical reefs would appear to be some of the worst affected systems. However, it is also apparent that already many degraded systems can be attributed to impacts from social and economic drivers of change; pollution, overfishing and coastal development have deteriorated reef systems and many severely eroded beaches can be attributed to poor coastal management practices.

2.1 Potential impacts of sea-level rise on beaches

Sea-level rise poses threats to many coasts. Between 1950 and 2010, global sea level has risen at an average rate of 1.8 ± 0.3 mm $year^{-1}$; approximately 10 cm of anthropogenic global sea-level rise is therefore inferred since 1950. Over the next century, the mean projected sea-level rise for 2081-2100 is in the range 0.26-0.54 m relative to 1986-2005, for the low-emission scenario (RCP 2.6). The rate of rise is anticipated to increase from ~3.1 mm $year^{-1}$ indicated by satellite altimetry to 7-15 mm $year^{-1}$ by the end of the century (Church et al., 2013). The rate experienced on any particular coast is likely to differ from the global mean trend as a result of local and regional factors, such as rates of vertical land movement or subsidence. Beach systems can be expected to respond to this gradual change in sea level, and the low-lying reef islands on atolls appear to be some of the most vulnerable coastal systems (Nicholls et al., 2007).

Based on predictions from the Bruun Rule, a simple heuristic that uses slope of the foreshore and conservation of mass, sea-level rise will cause erosion and net recession landwards for many beaches (Bruun, 1962). Although this approach has been widely applied, it has been criticized as unrealistic for many reasons, including that it does not adequately incorporate consideration of site-specific sediment budgets (Cooper and Pilkey, 2004). Few analyses consider the contribution of biogenic carbonate and none foreshadow the consequences of any reduction in supply of carbonate sand. This is partly because of time lags between production of carbonate and its incorporation into beach deposits, which is poorly constrained in process studies and which is subject to great variability between different coastal settings, ranging from years to centuries (Anderson et al., 2015). In view of uncertainties in rates of sediment supply and transport, probabilistic modeling of shoreline behavior may be a more effective way of simulating possible responses, including potential accretion where sediment supply is sufficient (Cowell et al., 2006).

2.2 Potential impacts of sea-level rise on reef islands

Small reef islands on the rim of atolls appear to be some of the most vulnerable of coastal environments; they are threatened by exacerbated coastal erosion, inundation of low-lying island interiors, and saline intrusion into freshwater lenses upon which production of crops, such as taro, depends (Mimura, 1999). Sand cays, on atolls as well as on other reefs, have accumulated incrementally over recent millennia because reefs attenuate wave energy sufficiently to create physically favourable conditions for deposition of sand islands (Woodroffe et al., 2007), as well as enabling growth of sediment-stabilizing seagrasses and mangrove ecosystems (Birkeland, 1996). Sand cays are particularly low-lying, rarely rising more than a few metres above sea level; for example, <8 per cent of the land area of Tuvalu and Kiribati is above 3 m above mean sea level, and in the Maldives only around 1 per cent, reaches this elevation (Woodroffe, 2008). This has led to dramatic warnings in popular media and inferences in the scientific literature that anthropogenic climate change may lead to reef islands on atolls submerging beneath the rising ocean, with catastrophic social and economic implications for populations of these atoll nations (Barnett and Adger, 2003; Farbotko and Lazrus, 2012).

However, reef islands may be more resilient than implied in these dire warnings (Webb and Kench, 2010). Unlike the majority of temperate beaches that have a finite volume of sediment available, biogenic production of carbonate sediments means that there may be an ongoing supply of sediment to these islands. Although coral is a major contributor, it is not necessarily the principal constituent of beaches; large benthic foraminifera (particularly *Calcarina, Amphistegina* and *Baculogypsina*) contribute more than 50 per cent of sediment volume on many islands on Pacific atolls (Woodroffe and Morrison, 2001; Fujita et al., 2009). One survey of Pacific coral islands (Webb and Kench, 2010) reported that 86 per cent of islands had remained stable or increased in area over recent decades, and only 14 per cent of islands exhibited a net reduction in area; however, the greatest increases in area resulted from artificial reclamation (Biribo and Woodroffe, 2013). Further studies of shoreline changes on atoll reef islands using multi-temporal aerial photography and satellite imagery indicate accretion on some shorelines and erosion on others, but with the most pronounced changes associated with human occupation and impacts (Rankey, 2011; Ford, 2012; Ford 2013; Hamylton and East, 2012; Yates et al., 2013).

The impacts of future sea-level rise on individual atolls remain unclear (Donner, 2012). Healthy reef systems may be capable of keeping pace with rates of sea-level rise. There is evidence that reefs have coped with much more rapid rates of rise during postglacial melt of major ice sheets than are occurring now or anticipated in this century. Reefs have responded by keeping up, catching up, or in cases of very rapid rise giving up, often to backstep and occupy more landward locations (Neumann and Macintyre, 1985; Woodroffe and Webster, 2014). Geological evidence suggests that healthy coral reefs have exhibited accretion rates in the Holocene of 3 to 9 mm year^{-1} (e.g., Perry and Smithers, 2011), comparable to projected rates of sea-level rise for the 21st century. However, reef growth is likely to lag behind sea-level rise in many cases resulting in larger waves occurring over the reef flat and affecting the shoreline (Storlazzi et al., 2011; Grady et al., 2013). It is unclear whether these larger waves, and the increased wave run-up that is likely, will erode reef-island beaches, overtopping some and inundating island interiors, or whether they will more effectively move sediments shoreward and build ridge crests higher (Gourlay and Hacker, 1991; Smithers et al., 2007). Dickinson (2009) inferred that reef islands on atolls will ultimately be unable to survive because once sea level rises above their solid reef-limestone foundations, which formed during the mid-Holocene sea-level highstand 4,000 to 2,000 years ago, formerly stable reef islands will be subject to erosion by waves.

2.3 Impact of climate change and ocean acidification on production

The impact of climate change on the rate of biogenic production of carbonate sediment is also little understood, but it seems likely to have negative consequences. Although increased temperatures may lead to greater productivity in some cases, for example by extending the latitudinal limit to coral-reef formation, ocean warming has already been recognised to have caused widespread bleaching and death of corals (Hoegh-Guldberg, 1999; Hoegh-Guldberg, 2004; Hoegh-Guldberg et al., 2007). Ocean acidification will have further impacts, and may inhibit some organisms from secreting carbonate shells; for example reduction in production of the Pacific oyster has been linked to acidification (Barton et al., 2012). Decreased seawater pH increases the sensitivity of reef calcifiers to thermal stress and bleaching (Anthony et al., 2008). Based on the density of coral skeleton in >300 long-lived *Porites* corals from across the Great Barrier Reef, De'ath et al. (2009) inferred that a decline in calcification of ~14 per cent had occurred since 1990 manifested as a reduction in the extension rate at which coral grows, which they attributed to temperature stress and declining saturation state of seawater aragonite (which is related to a decrease in pH). However, this extent of the apparent decline has been questioned because of inclusion of many young corals (Ridd et al., 2013); it is not observed in corals collected more recently from inshore (D'Olivo et al., 2013).

There has been some debate about the role of carbonate sediments acting as a chemical buffer against ocean acidification; in this scenario, dissolution of metastable carbonate mineral phases produces sufficient alkalinity to buffer pH and carbonate saturation state of shallow-water environments. However, it is apparent that dissolution rates are slow compared with shelf water-mass mixing processes, such that carbonate dissolution has no discernable impact on pH in shallow waters that are connected to deep-water, oceanic environments (Andersson and Mckenzie, 2012). The seawater chemistry within a reef system can be significantly different from that in the open ocean, perhaps partially offsetting the more extreme effects (Andersson et al., 2013; Andersson and Gledhill, 2013). Corals have the ability to modulate pH at the site of calcification (Trotter et al. 2011; Venn et al. 2011; Falter et al., 2013). Internal pH in both tropical and temperate coral is generally 0.4 to 1.0 units higher than in the ambient seawater, whereas foraminifera exhibit no elevation in internal pH (McCulloch et al., 2012).

Changes in the severity of storms will affect coral reefs; storms erode some island shorelines, but also provide inputs of broken coral to extend other islands (Maragos et al., 1973; Woodroffe, 2008). Alterations in ultra-violet radiation may also have an impact, as UV has been linked to coral bleaching. Furthermore, if reefs are not in a healthy condition due to thermal stress (bleaching) coupled with acidification and other anthropogenic stresses (pollution, overfishing, etc.), then reef growth and carbonate production may not keep pace with sea-level rise. This could, in the long-term, reduce carbonate sand supply to reef islands causing further erosion, although ongoing erosion of cemented reef substrate is also a source of sediment on reefs, indicating that supply of carbonate sand to beaches is dependent upon several interrelated environmental processes. Disruption of any one (or combination) of the controlling processes (carbonate production, reef growth, biological stabilization, bioerosion, physical erosion and transport) may result in reduction of carbonate sand supply to beaches.

3. Economic and social implications of carbonate sand production.

More than 90 per cent of the population of atolls in the Maldives, Marshall Islands, and Tuvalu, as well many in the Cayman Islands and Turks and Caicos (which all have populations of less than 100,000), live at an elevation <10 m above sea level and appear vulnerable to rising sea level, coastal erosion and inundation (McGranahan et al., 2007). The social disruption caused by relocating displaced people to different islands or even to other countries is a problem of major concern to many countries (Farbotko and Lazrus, 2012, see also Chapter 26). Beach aggregate mining is a small-scale industry on many Pacific and Caribbean islands employing local peoples (McKenzie et al., 2006), but mining causes environmental damage when practised on an industrial scale (Charlier, 2002; Pilkey et al., 2011, see also Chapter 23). In the Caribbean, illegal beach mining is widespread but there is little information on what proportion is carbonate (Cambers, 2009). Beach erosion reduces the potential opportunities associated with tourism (see Chapter 27), and decreases habitat for shorebirds and turtles (Fish et al., 2005; Mazaris et al., 2009).

Without coral reefs producing sand and gravel for beach nourishment and protecting the shoreline from currents, waves, and storms, erosion and loss of land are more likely (see also Chapter 39). In Indonesia, Cesar (1996) estimated that the loss due to decreased coastal protection was between 820 United States dollars (for remote areas) and 1,000,000 dollars per kilometre of coastline (in areas of major tourist infrastructure) as a consequence of coral destruction (based on lateral erosion rates of 0.2 m $year^{-1}$, and a 10 per cent discount rate [similar to an interest rate] over a 25-year period). In the Maldives, mining of coral for construction has had severe impacts (Brown and Dunne, 1988), resulting in the need for an artificial substitute breakwater around Malé at a construction cost of around 12,000,000 dollars (Moberg and Folke, 1999).

4. Conclusions, Synthesis and Knowledge Gaps

There has been relatively little study of rates of carbonate production, and further research is needed on the supply of biogenic sand and gravel to coastal ecosystems. Most beaches have some calcareous biogenic material within them; carbonate is an important component of the shoreline behind coral-reef systems, with reef islands on atolls entirely composed of skeletal carbonate.

The sediment budgets of these systems need to be better understood; direct observations and monitoring of key variables, such as rates of calcification, would be very useful. Not only is little known about the variability in carbonate production in shallow-marine systems, but their response to changing climate and oceanographic drivers is also poorly understood. In the case of reef systems, bleaching as a result of elevated sea temperatures and reduced calcification as a consequence of ocean acidification seem likely to reduce coral cover and production of skeletal material. Longer-term implications for the sustainability of reefs and supply of sediment to reef islands would appear to decrease resilience of these shorelines, although alternative interpretations suggest an increased supply of sediment, either because reef flats that are currently exposed at low tide and therefore devoid of coral, may be re-colonized by coral under higher sea level, or because the disintegration of dead stands of coral may augment the supply of sediment.

Determining the trend in shoreline change, on beaches in temperate settings and on reef islands on atolls or other reef systems, requires monitoring of beach volumes at representative sites. This has rarely been undertaken over long enough time periods, or with sufficient attention to other relevant environmental factors, to discern a pattern or assign causes to inferred trends. Although climate and oceanographic drivers threaten such systems, the most drastic erosion appears to be the result of more direct anthropogenic stressors, such as beach mining, or the construction of infrastructure or coastal protection works that interrupt sediment pathways and disrupt natural patterns of erosion and deposition.

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