Reef growth and limestone erosion

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With the discovery of glaciation and glacio-eustatic sea level change in the late 19th century, researchers recognised that the foundations of modern coral reefs had been alternately exposed and submerged as the polar ice caps waxed and waned (Daly 1910, 1915; Davis 1915). This recognition prompted an ongoing debate concerning the extent to which modern reef morphology is a product of construction during interglacial periods versus erosion during glacial periods. Contemporary viewpoints in the debate see Holocene reef morphology as either primarily constructional, reflecting an interplay between reef-building organisms and their environment (Bloom 1974; Halley et al. 1977; Sammarco, Andrews & Risk 1991; Walbran 1994; Kennedy & Woodroffe 2002; Blanchon 2011; Schlager & Purkis 2015; Salas-Saavedra et al 2017), or primarily erosional, perpetuating the topography of karst erosion forms in underlying limestone (Purdy 1974; Steers & Stoddart 1977; Purdy & Bertram 1993; Purdy & Winterer 2001; Purdy, Gischler & Lomando 2003; Davies 2011; Gischler, Storz & Schmitt 2013).

The karst hypothesis is based on compelling but circumstantial evidence, primarily the remarkable morphological similarities between coral reefs and karst limestones. Yet, as coring and seismic research over the last few decades has begun to reveal the internal structure of reefs, evidence for karst control has been equivocal and often contradictory, with several karst-like reef features shown to be entirely constructional. Cellular reefs (terminology after Hoskin 1963) are perhaps the best example, because although they appear virtually identical to, and remain widely interpreted as, karst doline terrains (fields of subcircular erosion depressions), coring and seismic work undertaken 20 to 30 years ago in the cellular reefs of Mataiva Atoll in the Tuamotu Archipelago (GIE Raro Moana 1985; Rossfelder 1990) and the Houtman Abrolhos Islands in Western Australia (Collins et al. 1993; Collins, Zhu & Wyrwoll 1996; 1998) unambiguously demonstrated their constructional origin. Thus, the current status of the karst hypothesis is paradoxical, because it remains widely accepted despite crucial elements in the karst argument having been falsified long ago.

Here I use cellular automata simulations to investigate the basic premise of the karst hypothesis: that coral reefs resemble karst limestones too closely for coincidence. I show that the resemblance is not coincidental, but arises because reef growth and limestone erosion are fundamentally the same process, running in opposite directions. Coral reef landscapes resemble karst because they are in fact *inverse* karst—the basic spectrum of reef growth forms mirrors the basic spectrum of limestone erosion forms (Fig. 1). In both growth and erosion, the development

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of form is a self-organized process emerging from local-scale interactions. The essential morphological control in both cases is slope stability, which depends on the composition of each system: coral type in reefs and lithology (rock type) in limestones. Solid, well-cemented reefs and limestones, which can maintain steep slopes without collapsing, produce nodular reefs and tower karst respectively, whereas unconsolidated, friable reefs and limestones, which frequently collapse, produce cellular reefs and cone karst (Video S1 and S2).

Visual interpretation of both morphological spectra becomes more ambiguous as slope stability is reduced and the proportion of collapse increases. The forms generated by pure growth (Fig. 1A) and dissolution (Fig. 1B) appear straightforward and intuitively correct, whereas collapse-controlled forms are difficult to visually parse within their respective growth and erosion contexts. This difficulty arises because collapse itself contains elements of both erosion and growth (deposition). Collapse-controlled landforms therefore present visually dissonant images; cellular reefs being growth forms with an element of erosion and cone karsts being erosion forms with an element of growth. The enigmatic appearance of cellular reefs and cone karst has probably been a significant factor impeding the conceptual understanding of their development.

The growth forms produced in the model should theoretically apply to all modular skeleton-building organisms growing in a fluid medium, and may therefore provide useful templates in the search for extraterrestrial life. The erosion forms are less direct indicators of life but, on earth at least, are best developed in biogenic rocks. This relationship may apply universally because organisms that build skeletons by precipitating compounds from solution will tend to converge on compounds that are close to their saturation state and require relatively little transition energy, and such compounds will be liable to dissolution as external conditions change. None of the forms produced in the model can be considered unequivocally diagnostic of life, because all could conceivably arise through inanimate crystallisation and dissolution. However, the model's seemingly accurate rendition of biogenic carbonate morphology on earth suggests that it may provide a useful foundation for evaluating and exploring the range of macroscale self-organized biogenic structures that could arise on other planets.

The model, and some testable predictions arising from it, are described in Blakeway & Hamblin (2015). That article presents the growth situation only, however the erosion situation is a direct inversion, with no other alterations.

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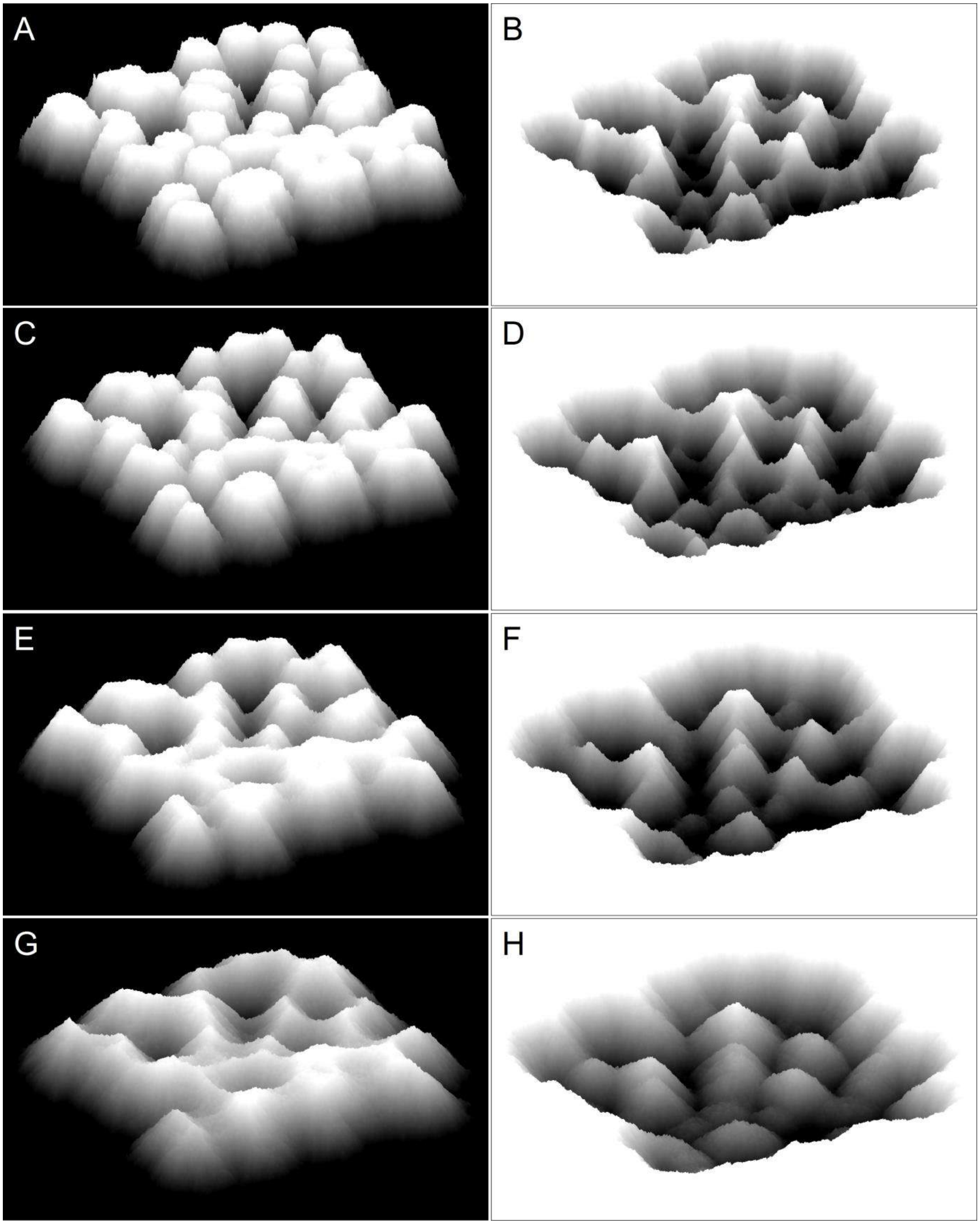

Figure 1. Basic reef growth and limestone erosion forms produced by incrementally reducing slope stability in the model. The left column shows the range of patch reef growth forms, from steep-sided nodular reefs (A) to gently-sloping cellular reefs (G) and the right column shows the range of limestone erosion forms, from steep-sided tower karst (B) to gently-sloping cone karst (H). The limestone erosion forms are direct inversions of their growth counterparts.

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Additional author comment

This preprint is a summary of an article I intend to develop and submit to PeerJ. While I'm reasonably confident in the growth aspect of the model, through the work described in Blakeway & Hamblin (2015), the erosion aspect is speculative, particularly the conclusion that cone karst is a collapse-controlled landform. However, multiple lines of evidence appear to support this conclusion, including apparently consistent correlations between karst morphology and limestone lithology (cone karst occurring in weakly consolidated, friable limestones), the very consistent slope gradients recorded in cone karst terrains (I interpret these as angle of repose slopes), and the close resemblance between cone karst and known collapse-controlled constructional landforms such as mullock heaps and cinder cones:
http://www.australiantraveller.com/coober-pedy/038-noodle-for-opals-at-coober-pedy/
http://marsmobile.jpl.nasa.gov/images/20070403_DianaBlaney4_070301105112-br2.jpg

Additional direct evidence is provided by striking images of earthquake-induced slope failure in the cone karst of the Chocolate Hills, Bohol, Philippines (Fig. 2). These events occurred during the Bohol earthquake of October 15th, 2013. The resulting scars are clearly visible on Google Earth satellite imagery. Although cloud cover obscures most of the area at the time of the earthquake, before-and-after images of many scars are evident (see for example 9.8331°N, 124.1365°E). A significant aspect of these images is how rapidly the scars are overgrown by vegetation. If, instead of occurring simultaneously, the landslides had occurred intermittently over centuries, each would be rapidly overgrown, and their cumulative significance would not be immediately apparent. Seemingly equivalent scars are present in cone karsts elsewhere, for example Guizhou, China at 26.7638°N, 104.5451°E, Saint Ann, Jamaica at 18.2053°N, 77.1866°W, and Gunung Sewu, Indonesia at 8.1222°S, 110.5396°E.

Further supporting evidence comes from a comprehensive study of symmetrical cone-shaped limestone hills on Abaco Island in the Bahamas by Walker et al. (2009). Walker et al. use field observations and measurements to demonstrate that slope failure has been instrumental in the morphological development of the Abaco cones. Walker et al. ultimately classify the Abaco cones as pseudokarst, not cone karst. With the backing of the model I feel on firmer ground (☺) in claiming that the Abaco cones *are* cone karst, and that Walker et al. have hit upon the mechanism—slope failure—by which all cone karsts develop.

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Figure 2. Earthquake-induced landslides in the Chocolate Hills cone karst, Bohol Province, Philippines. Photos by Mack Milay.

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