

FRACTALS IN THE FOSSIL RECORD: SELF-ORGANIZATION OF CARBONATES

Sam J. Purkis and Flora Beleznav

KEY FINDINGS

- Spatial self-organization, the process where coherent spatial patterns emerge through internal interactions, is widely observed in modern natural systems.
- However, the concept of self-organization and its potential effects on geological patterns is not yet widely discussed by the geological community, especially in carbonate depositional systems.
- Considerable work remains to understand process and products of spatial self-organization in the rock record.

SIGNIFICANCE

Earth surface systems often show patterning, though causes are not always obvious. Traditionally, many patterns—such as cyclical limestone strata—were attributed to external drivers like Milankovitch orbital cycles (e.g., Goldammer, 1987). More recent work recognizes diverse mechanisms, including autogenic processes that can create both ordered and irregular geomorphic and stratal products (Drummond and Wilkinson, 1993; Werner, 1999; Burgess, 2006).

A key subset of these are spatial self-organization processes, where interactions among organisms, or between organisms and their environment, produce regular patterns in depositional settings (Klausmeier, 1999; Rietkerk et al., 2004; van de Koppel et al., 2005). Abiotic examples also exist, such as geochemical self-patterning in rocks (Merino et al., 1983; Budd et al., 2006). Given their occurrence in modern systems, such structures likely characterized ancient environments and are preserved in the rock record.

Spatial self-organization is relevant to stratigraphic interpretation in three ways. First, it can generate recognizable patterns across scales, from stromatolites to patch reefs (Dill et al., 1986). Second, because controls are distributed, the resulting structures are robust, buffering or masking environmental change (Liu et al., 2012). Third, in “self-organized criticality,” subtle perturbations can trigger abrupt shifts, risking misattribution to external forcing. Recognizing self-organization thus provides a framework for understanding autogenic origins of stratigraphic variation.

DATA AND METHODS

Reefal carbonates, whether built by scleractinian corals or their more ancient predecessors, have frequently been shown to display coherent spatial patterning - an important hallmark of spatial self-organization. Globally, about 30% of atolls show a degree of spatial coherence of their lagoonal reefs and 15% show well-developed elongated ridges and polygonal networks, termed as reticulated or

'polygonal' reefs. Highly reticulated reefs occur in all three major oceanic basins and are spatially clustered (Fig. 1). Such patterning was once considered to be a product of antecedent topography related to karst during the lowstands (Purdy & Bertram, 1993). However, the combination of later drilling and seismic data suggest many reticulated reefs actually develop on a smooth and flat substrate (Schlager & Purkis, 2015), ruling out the karst hypothesis and suggesting another biotic self-organization possibility.

As reefs reach sea-level, lateral growth and coalescence between adjacent patch reefs can create ridges and polygonal networks. Formation of such complex networks can have real ecological consequences to the health of reef builders by increasing water residence time, which in turn increases water turbidity, anoxia, and risk of thermal stress. Similar reef morphology is also widely observed in Paleozoic, Mesozoic, and Cenozoic reefs (Purkis *et al.*, 2015), suggesting self-organization is an important process in geological time.

In this study, we built a library of global coral reef patterns from 60 sites (Xi *et al.*, 2025). We downloaded satellite imagery from PlanetScope, extracted bathymetry models, and deployed edge-detection algorithms to create binary maps of reefal ridges.

We then analyzed the various aspects of reef patterning including directional connectivity (Larsen *et al.*, 2012), anisotropy, and periodicity (Renshaw & Ford, 1984; van de Koppel & Crain, 2006) using binary images for each of the 60 sites. We further developed a process-based numerical model to test the self-organization hypothesis and compared the modeled reef patterns with those mapped in the real world. Our model consists of a 2D depth-averaged hydrodynamic model and three partial differential equations describing the dynamics of reef biomass, sedimentation, and elevation.

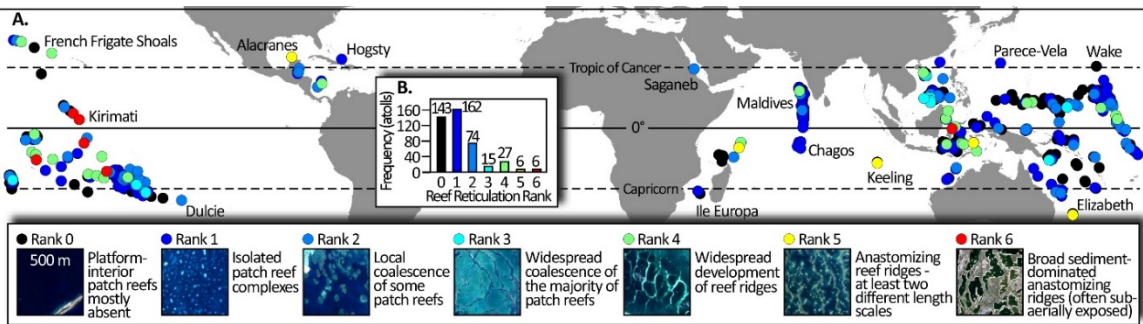


Figure 1. Geographic (A) and frequency (B) distributions of reticulation ranks for Goldberg's 433 'Atolls of the World' (Goldberg, 2016). The rank spans 0 for the case of a lagoon in which platform-interior patch reefs are mostly absent, through 6 where the patch reefs have organized into a densely-packed anastomizing network of reticular ridges.

RESULTS

Using the three morphometric indices from the pattern analysis, all 60 global reef patterning can be clustered into seven classes using the standard k-mean method, from sparse small patch reef in Class 1, through larger patch reefs in Classes 2 and 3, to elongated ridges in Classes 4 and 5, and finally well-connected reticulated reefs in Classes 6 and 7.

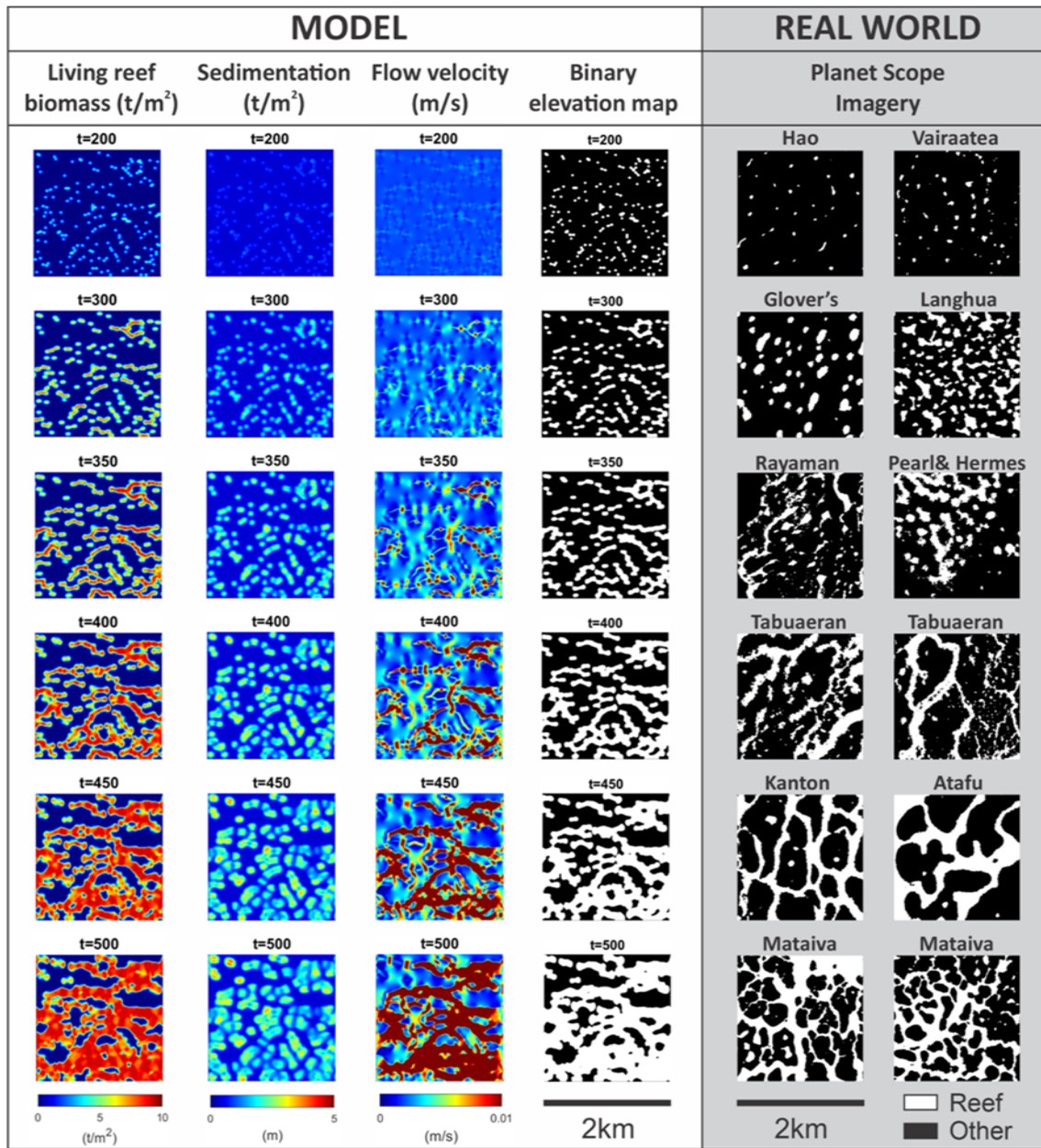


Figure 2. Comparison between real world reef patterns in our library and model simulations at selected time steps (year). The modeled flow direction is from bottom towards the top. Note the smooth transition from small isolated patch reefs to elongated ridges and eventually reticulated morphology where the position of the initial patch reefs can no longer be discerned.

The model results share striking similarities to real-world processes and products, suggesting the model is realistic and provides at least one possible explanation for emergent patterning of platform interior reefs. Initially, reefs grow vertically, and sediments are deposited around them (Fig. 2). As they approach the sea surface, lateral growth increases and adjacent reefs start to coalesce (Fig. 2). The reefs are elongated perpendicular to the flow direction, mimicking a key observation from modern Alacranes Reef (Purkis et al., 2016; Xi et al., 2025).

IMPLICATIONS

Spatial self-organization describes how ordered patterns emerge from initially disordered conditions through internal, or autogenic, interactions. Levin and Segel (1985) defined “spatial patterns” as heterogeneous but coherent structures, commonly appearing as stripes, bands, or labyrinths. Importantly, not all autogenic processes are self-organizing; here we reserve the term for processes that produce patterned outcomes.

Rietkerk and van de Koppel (2008) summarized three main models of ecosystem self-organization, which also extend to abiotic systems.

- **Type I – Scale-dependent feedbacks.** Local positive and broader negative feedbacks between organisms, often mediated by water or nutrients, create regular patch patterns. Well-studied examples include banded vegetation at the Sahara margin, peatlands in Siberia and Canada, pine stands in the Rockies, and biofilms or seagrass meadows in estuarine settings (Rietkerk et al., 2004; Weerman et al., 2012).
- **Type II – Self-organized criticality.** Local disturbance-recovery processes generate scale-invariant patchiness, with power-law distributions marking proximity to thresholds. Small environmental changes can trigger abrupt shifts, as seen in tidal channel networks (Fagherazzi, 2008), coral reef patchiness (Purkis et al., 2007; Xi et al., 2025), and arid vegetation (Kéfi et al., 2007). Here, loss or persistence of power laws signals closeness to a critical transition.
- **Type III – Consumer–resource oscillations.** Interdependent predator–prey dynamics can produce spiral waves, recognized in ecological and physiological models (Rohani et al., 1997; Gray et al., 1995). Such oscillatory patterns may leave cyclic signatures in the rock record.

While these models explain a wide range of natural patterning, pattern form alone cannot diagnose mechanism. Nor is self-organization the only pathway to structure in the sedimentary record. Still, in systems such as bivalve beds, tidal channels, reefs, and microbial buildups, self-organization provides a powerful lens, and further modeling and experimental work are needed to refine its application.

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