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A morphometric assessment and classification of coral reef spur and groove morphology

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ABSTRACT

Spurs and grooves (SaGs) are a common and important feature of coral reef fore slopes worldwide. However, they are difficult to access and hence their morphodynamics and formation are poorly understood. We use remote sensing, with extensive ground truthing, to measure SaG morphometrics and environmental factors at 11,430 grooves across 17 reefs in the southern Great Barrier Reef, Australia. We revealed strong positive correlations between groove length, orientation and wave exposure with longer, more closely-spaced grooves oriented easterly reflecting the dominant swell regime. Wave exposure was found to be the most important factor controlling SaG distribution and morphology. Gradient of the upper reef slope was also an important limiting factor, with SaGs less likely to develop in steeply sloping (>5°) areas. We used a subset of the morphometric data (11 reefs) to statistically define four classes of SaG. This classification scheme was tested on the remaining six reefs. SaGs in the four classes differ in morphology, groove substrate and coral cover. These differences provide insights into SaG formation mechanisms with implications to reef platform growth and evolution. We hypothesize SaG formation is dominated by coral growth processes at two classes and erosion processes at one class. A fourth class may represent relic features formed earlier in the Holocene transgression. The classes are comparable with SaGs elsewhere, suggesting the classification could be applied globally with the addition of new classes if necessary. While further research is required, we show remotely sensed SaG morphometrics can provide useful insights into reef platform evolution.

1. Introduction

Spurs and grooves (SaGs) are distinctive features of fore reef slopes worldwide. Spurs are parallel ridges of carbonate material (coral and algae) separated by regularly spaced channels (grooves) forming a characteristic "comb-tooth" pattern (Gischler, 2010). SaG systems have been documented in every global reef province (e.g. Weydert, 1979; Sheppard, 1981; Shinn et al., 1981; Kan et al., 1997a; Rogers et al., 2015). They represent one of the most biodiverse and productive zones of modern reefs (Perry et al., 2013) and are believed to act as natural breakwaters (Munk and Sargent, 1954), regulating the hydrodynamic energy and nutrients received by reef platforms and thus affecting reef biogeography (Odum and Odum, 1955). Despite their importance, the geomorphology, formation processes and eco-morphodynamics of SaG systems are poorly understood (Gischler, 2010; Rogers et al., 2013) particularly in the Great Barrier Reef (GBR), Australia (Duce et al., 2014). Their underrepresentation in the literature is likely due to the difficulties of working in these high-energy environments (Guilcher, 1988).

There is considerable debate as to whether the formation of SaGs is driven by predominantly erosional or constructional processes, or by a combination of both (Sneh and Friedman, 1980; Guilcher, 1988; Storlazzi et al., 2003; Gischler, 2010). Erosional processes include wave and current driven abrasion of grooves by rubble and/or sediment (Cloud, 1954); "pruning" of corals on spurs and spur walls by occasional hurricanes (Blanchon and Jones, 1997); and limestone solution of antecedent topography by fresh water flows during sea level low-stands to form grooves (Newell, 1954; Purdy, 1974). Constructional processes include water motion promoting aligned coral growth and eventual colony coalescence to form spurs (Shinn, 1963; Shinn et al., 1981; Kan et al., 1997a); and coral debris being washed together and rapidly cemented by robust, wave-resistant coralline algae forming spurs (Storlazzi et al., 2003; Blanchon, 2011; Littler and Littler, 2011). Which process dominates is thought to be a function of environmental factors (primarily wave energy) (Storlazzi et al., 2003; Shinn, 2011) and the rate of Holocene sea-level change (Gischler, 2010).

The morphology of SaG systems varies markedly both between and within reefs (Duce et al., 2014). However, comparison between the features globally is difficult as there is no standard definition of morphometric parameters and authors report different metrics. For example, Roberts et al. (1977) and Storlazzi et al. (2003) report "wavelengths"

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(i.e. distance between consecutive spur crests) and "amplitude" (i.e. the distance from spur crest to groove trough) while Roberts (1974) and Blanchon and Jones (1997) report "spur frequency" (i.e. number of spurs per 1000 m of reef) and; Munk and Sargent (1954) report the "width and spacing" of grooves. In addition, descriptions are frequently qualitative and adjective-based rather than quantitative (Duce and Janowicz, 2010). For example, adjectives such as "narrow" are used in place of quantitative values to describe groove width (Roberts, 1974; Blanchon and Jones, 1997; Hamanaka et al., 2015).

Understanding SaGs globally is further complicated by differing terminology. A comprehensive review of reef terminology within published literature identified 12 different terms used to refer to SaGs (Kuchler, 1986a). In fact, Stoddart (1978) suggested that much of the controversy surrounding "the nature" and formation of SaGs arose from the term being applied too broadly to a variety of features which differed in morphology and origin.

Meaningful classification and clear definition is critical to effective management of natural systems (Elliott and McLusky, 2002; Duce, 2009). The classification of geomorphic features is also an important step in understanding their formation, evolution and interactions with the environment. Two approaches to classification have been adopted by geomorphologists: those based on form and, those based on processes (Drăguţ and Blaschke, 2006). Several publications have described different types of SaGs based on observations of both form and processes. These SaG types and the formation processes suggested in the literature are summarized in Table 1.

As evidenced in Table 1 there are different types of SaGs, likely dominated by different formation processes, with different implications to reef ecology and reef platform evolution. Identifying and clearly defining these SaG types is important to understand and manage coral reefs into the future. Ideally this requires extensive hydrodynamic data and dating of sub-surface material from many sites. However,

Table 1
Types of spurs and grooves and their suggested formation mechanisms from the published literature.

Location (source)	Types and description	Data used	Suggested formation mechanisms
Caribbean, western Indian Ocean, French Polynesia (Gischler, 2010)	**Indo-Pacific** *Dimensions*: wide flat spurs. Narrow V-shaped grooves *Groove floor*: sparse sand and rubble *Spur cover*: coralline algae and few corals **Atlantic** *Dimensions*: U-shaped *Groove floor*: abundant sand *Spur cover*: high coral cover	Qualitative observations and literature review	**Indo-Pacific** - Erosion dominated **Atlantic** - largely constructive. Driven by differences in Holocene sea-level change (transgressive-regressive in the Indo-Pacific and transgressive in the western Atlantic)
Molokai, Hawaii (Storlazzi et al., 2003)	**Higher energy spur and groove** *Depth*: 5–10 m *Dimensions*: mean spur height 0.5 m, ~87 m between spur crests *Spur cover*: Lower total coral cover **Lower energy spur and groove** *Depth*: 15–20 m *Dimensions*: mean spur height 1.1 m, ~93 m between spur crests *Spur cover*: higher total coral cover	Quantitative bathymetric data and wave modelling	Waves are the primary control, light and antecedent topography plays a lesser role. **Higher energy spurs** constructed primarily by cementation of coral rubble. **Lower energy spurs** dominated by in situ coral growth.
Caribbean, Indo-Pacific (Blanchon and Jones, 1997; Blanchon, 2011)	**Shallow spur and groove (2 types)** *Depth*: to 15 m *Dimensions*: One spur every 6–10 m. Spurs 4–8 m wide, 2–8 m high with steep to overhanging sides. Grooves 1–3 m wide *Groove floor*: coral gravel *Spur cover*: ***1. Coralline algae dominated*** ***2. Coral dominated*** **Chute and buttress** *Depth*: ~25–60 m *Dimensions*: Buttresses ~100 m long, 10 m wide, tapering shoreward. One buttress every 30 m or more	Literature review, bathymetric data, short-cores and observations	Distribution and form controlled by wave energy. **Buttresses** and **coral dominated spurs** constructional and grow towards the reef shelf with "pruning" by storms. **Coralline algae dominated** spurs are similar but may (the age structure of these spurs remains unknown) grow seaward.
Grand Cayman Island (Caribbean) (Roberts et al., 1975; Roberts et al., 1977)	**Wave dominated spur and groove** *Depth*: to 8 m *Dimensions*: ~43 m between grooves *Groove floor*: little sediment *Spur cover*: moderate coral cover **Current dominated spur and groove** *Depth*: 8–22 m *Dimensions*: ~50 m between grooves *Groove floor*: extensive sediment *Spur cover*: abundant coral cover	Bathymetry, wave and current measurements	Associated with eustatic sea-level history. **Current dominated** SaGs initiated early in Holocene sea-level rise and have had longer to mature and continued to grow under less wave stress as water deepened.
French Polynesia (Battistini et al., 1975)	**Furrowed platform** *Dimensions*: ~30–40 m long **Buttresses and valleys** *Depth*: – to ~12 m *Dimensions*: ~60 m long *Groove floor*: bare or covered in reef detritus **Outer slope spur and grooves** *Depth*: ~12–27 m *Dimensions*: ~100 m long *Groove floor*: bare or covered in reef detritus	Qualitative observations	**Furrows** "cut in the direction of the slope".