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Using morphospaces to understand tafoni development

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ABSTRACT

Tafoni research has tended to focus on issues around definition and differences rather than trying to develop general concepts for understanding the nature of tafoni. This paper uses the concepts of fitness landscapes and morphospaces to develop a standardized and dimensionless phase space within which to represent, visualize and analyse a dataset of 800 tafoni collected from Antarctica. Within this phase space it is possible to identify clustering of tafoni forms and to illustrate how tafoni development is constrained by a relational hierarchy of rock structure, processes and geometry or form.

1. Introduction

Tafoni have been the source of debate in geomorphology since the first identification and proposed explanation of this distinctive form (see Groom et al., in press). Unfortunately, key issues arise again and again in the literature as the supposed 'distinctiveness' of this form eludes definition. This elusiveness means that any definitive statement on the characteristics and diagnostic processes of this form are almost impossible to delineate. Specifically, the debate hovers around issues of scale (are 'small' tafoni the same as 'large' tafoni?), development (do small tafoni become large tafoni and is there a distinct developmental sequence to tafoni formation, do they represent self-organization?), and process-form relationships (is there a diagnostic set of processes that cause tafoni to develop and maintain the form?). Research tends to focus on either one or all of these issues. The underlying assumption of form indicating process and changes in form indicating changes in process is at the heart of the measurement and analysis of tafoni.

1.1. What are tafoni?

There appears to be a number of terms relating to 'hollows' developed in bedrock, the most common of which (in English) are 'honeycomb' or 'alveolar' weathering and 'tafoni' (e.g. Evelpidou et al., 2010); the whole often being referred to as 'cavernous weathering' (e.g. Turkington and Phillips, 2004; Viles, 2005). The terms 'honeycomb weathering' and 'cavernous weathering' seem to be the catch-all terms for the creation of "small caves" (Evelpidou et al., 2010) or "caverns" (Turkington and Phillips, 2004) developed by differential weathering in rock. In many of these studies the distinction between form terminology appears to be almost solely related to size rather than to actual form or process (Groom et al., in press). This, thus, leaves the question as to whether alveolar weathering is but a precursor of tafoni and/or whether the size distinction is simply a product of the host lithology. According to Evelpidou et al. (2010, p. 34), following Penck (1894), "honeycomb weathering formations bigger than 0.5 m are defined as Tafoni, whereas formations smaller than 0.5 m are defined as Alveoles"; seemingly the whole defined as 'honeycomb weathering'. Mustoe (1982) provides extensive information regarding nomenclature and some of the confusion resulting from non-standardization of terminology. Cavernous weathering is often used to encompass all the other terms (e.g. French and Guglielmin (2000) refer to tafoni as an attribute of cavernous weathering) but may also be considered as an entity in its own right (e.g. Dragovich, 1967). Thus, the question arises as to quite what **are** tafoni and where, if at all, do they fit within the spectrum of other associated terms?

To some extent, many of the background components of this discussion have been covered by Viles (2005) and the reader is directed towards this excellent review. Key within the study of Viles (2005, p. 1471) is the opening statement: "Understanding the initiation, development and significance of landforms remains a central issue in geomorphology." Indeed, the whole issue regarding initiation of these weathering forms remains an enigma (Boxerman, 2005, p.79). However, to the above points must also be added the caveat that 'terminology' (see Hall et al., 2012) requires we all understand the same thing through the use of specific terms; this does not appear to be the case with respect to the terms used here. In part, this may well underpin the observation by Turkington (2004, p.128) that "as more information has been presented their (tafoni and alveoli) possible origins, rather than being clarified, seem to have become more confused." Perhaps some of this confusion

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is related to our use of terms and that perhaps the forms these terms refer to are either a continuum (rather than discrete) or **are** discrete and not part of a continuum (see Inkpen, 2005, for a discussion on these issues within geomorphology).

Viles (2005) clearly uses the term 'cavernous weathering' to encompass a number of forms (notably tafoni and alveoli – see her Fig. 1) as too do Turkington and Phillips (2004). Here it is argued, much as discussed elsewhere for other processes (see Hall et al., 2012), that the foundational terminology 'cavernous weathering' itself creates confusion – is it (cavernous **weathering**) the 'process' (as actually implied by the term) or the product (the 'cavern') and if it is the 'cavern' then quite what does this encompass; or is it implying (as does appear to be the case) both process **and** form? Where, as it would appear here, both process and form are included within the term, then this creates many issues (much as it has in nivation – see Thorn and Hall, 2002) as to the conflating of process and form within one term. Thus, whilst Viles (2005) makes an excellent case for the advances made regarding 'cavernous weathering', notably the self-organizational attributes of form development, the very real problems of both terminology and process remain. Indeed, Viles (2005, p. 1472) alludes to this very issue where it is stated that the overall outcome "rather than providing a consensus viewpoint or indicating a clearly developing research field, seems to be 'mine are different to yours'." This may, though, be either the very issue or that various workers, simply because the terminology is failing us, do not recognize that they are indeed dealing with comparable forms.

1.2. Form and process relationships

There clearly is much confusion regarding the nature of the formative weathering (or, rather 'rock decay': see Hall et al., 2012) – essentially everything from chemical to physical to physico-chemical processes, and almost any combination thereof. This, in itself, need not be a problem as this paper argues. Indeed, the very extent and variety of suggested processes is not necessarily unexpected given that cavernous weathering is azonal in occurrence (Turkington and Phillips, 2004) and found in a variety of lithologies (see Mustoe, 1982, Table 1). Given the variety of identified causative processes, the product appears to be a classic 'convergence of form', as already noted by Turkington and Phillips (2004, p. 666). That being the case, then perhaps the question is one of why do these different processes produce the same end result?

In turn this may beg the question, as to whether the processes are any different in their **effect** on the rock; the effect is to solely disassociate the constituent materials. The **nature** of that disassociation may well be controlled more by lithology than process. In other words, if 'flaking' (the effect) is the outcome, it can be the product of a variety of causes (wetting-drying, thermal stresses, salt weathering, freeze-thaw, chemical processes, etc.) acting alone or in combinations. If that were the case then it may be less important as to what the formative process was and, in turn, suggests rock properties may play the key role (see Hall et al., 2012). It may also be, however, that it is the relations between the form and process and the factors that control these relations, rather than the dominance or otherwise of any particular component, that is the essential aspect to understanding any generalized conceptualisation of tafoni evolution.

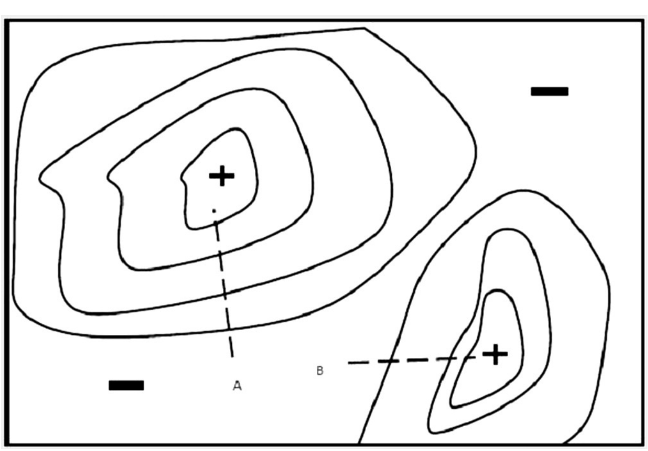

Fig. 1. Illustration of fitness landscape (modified from Wright, 1932).

Burridge and Inkpen (2015) highlight this in the mathematical model of tafoni development. In this paper rock properties provide the context within which process operate to produce the tafoni form. One might argue that, given convergence of form resulting from a multitude of identified processes, then maybe the focus of research should be on underlying factors such as rock properties that can constraint development or, in a more subtle conceptual framework, the relations between factors that may be canalizing development.

This paper suggests that this seemingly unsatisfactory state of affairs may help in developing a novel conceptual framework within which to interpret tafoni. This paper suggests that viewing tafoni within the conceptual framework of fitness landscapes and morphospaces permits 'fuzziness' in definitions within the context of the factors that constrain development and which define the parameter phase spaces for tafoni development. In order to advance this argument we first outline the nature of fitness landscapes and morphospaces. Secondly, we identify the three key factors and their parameter phase spaces that constrain tafoni as derived from the existing literature. We highlight the importance of a relational view of these factors for defining the canalizing outcome in phase space. By canalizing we mean that the parameter spaces confine and guide the development of forms along specific pathways. As individual tafoni become increasingly embedded within these developmental pathways, the constraints imposed by these parameter spaces become increasingly difficult to overcome. Lastly, using this conceptual framework we illustrate how it might be used to interpret simple dimensional measurement of tafoni derived from Dronning Maud Land in the Antarctic. From this analysis we are able to show that tafoni inhabit a restricted area of the phase space and that the detailed analysis of dimensions within this zone may not yield any additional information about process and form relationships. If appropriate then this conceptual framework suggests which aspects of form-process relationships should be the focus of further research into tafoni development.

2. Fitness landscapes and morphospaces

Within the biological literature, as noted by McGhee (2007), the concept of 'adaptive landscapes' originates with Wright (1932) who used the concept to visualize the fitness of genes, although he coined the term 'fitness landscape' for his visualization (Fig. 1). The adaptive landscape represents all the possible combinations of genes that an organism might produce. From these possible combinations, those that actually existed could be identified and plotted. The fittest of the existing combinations could be thought of as peaks rising from the relatively unfit surface. In Fig. 1, for example, there are two possible 'fit' peaks and Wright proposed that evolution by natural selection would force gene combinations to climb the nearest peak, always moving gene combination towards fitter variants. Movement is also informed by local conditions, so even if a nearby peak is lower than the lowest peak globally, variants will move towards that nearest, lower peak. The topography of a fitness landscape provides a roadmap of possible evolutionary pathways. Adaptive landscapes have also been defined in hyperdimensions by Kaufmann (1995), Gavrilets and Gravner (1997) and Gavrilets (2003) and with the latter suggesting that the complex and multiple nature of parameters affecting adaption result in a relatively flat but multidimensional landscape covered with holes. The holes represent locations where planes of fitness intersect