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 analyze 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.

Keywords: tafoni, development, fitness landscapes, morphospaces

Highlights

- Morphospace of tafoni defined
- Clustering of tafoni suggest potential developmental paths
- Key factors are rock structure, processes and form geometry
- Relational hierarchy of key factors constrains tafoni development

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.

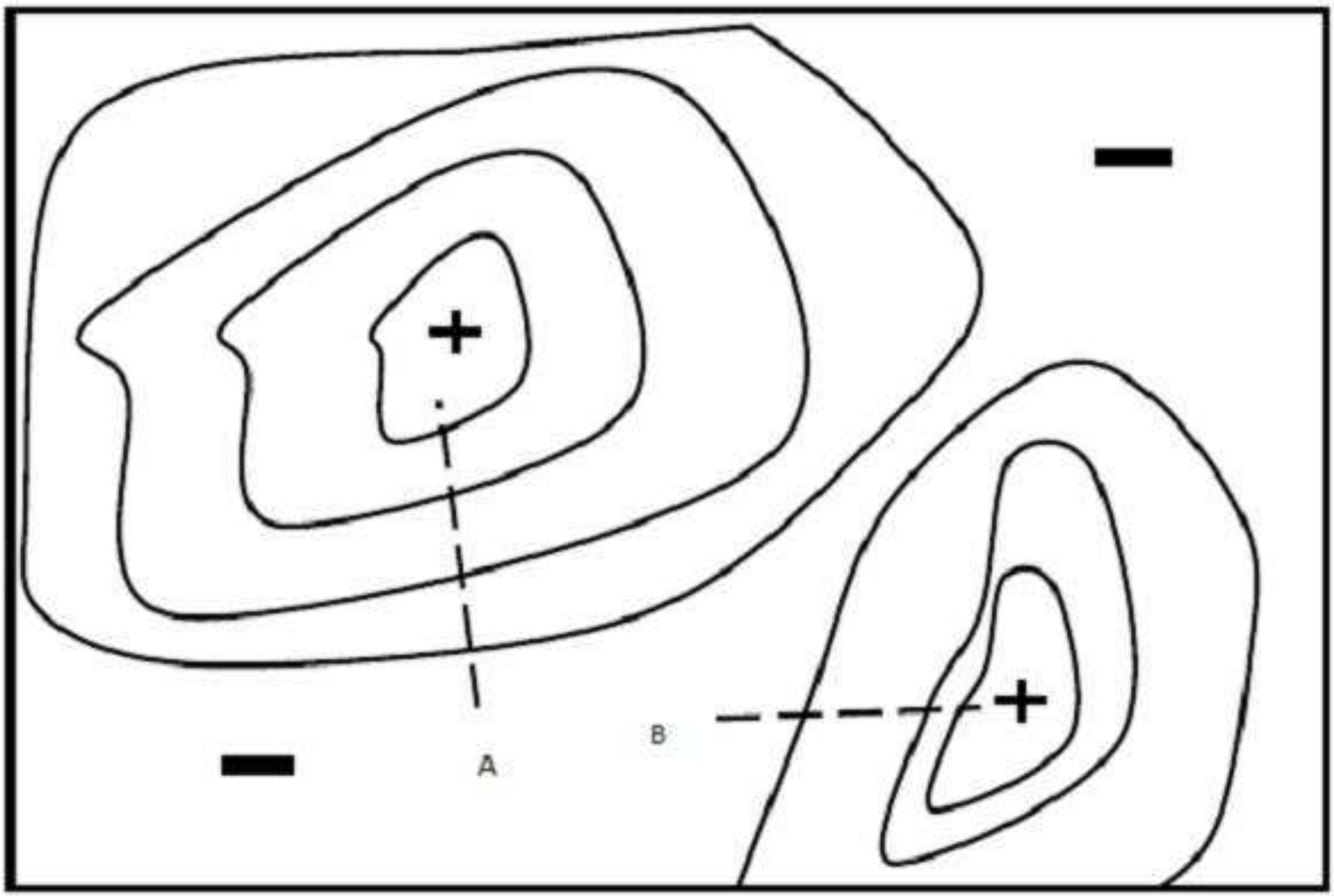
1.1 What are tafoni?

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 (Boxermann, 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 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, while 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.

Figure 1 Illustration of fitness landscape (Modified from Wright, 1932)



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.

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.

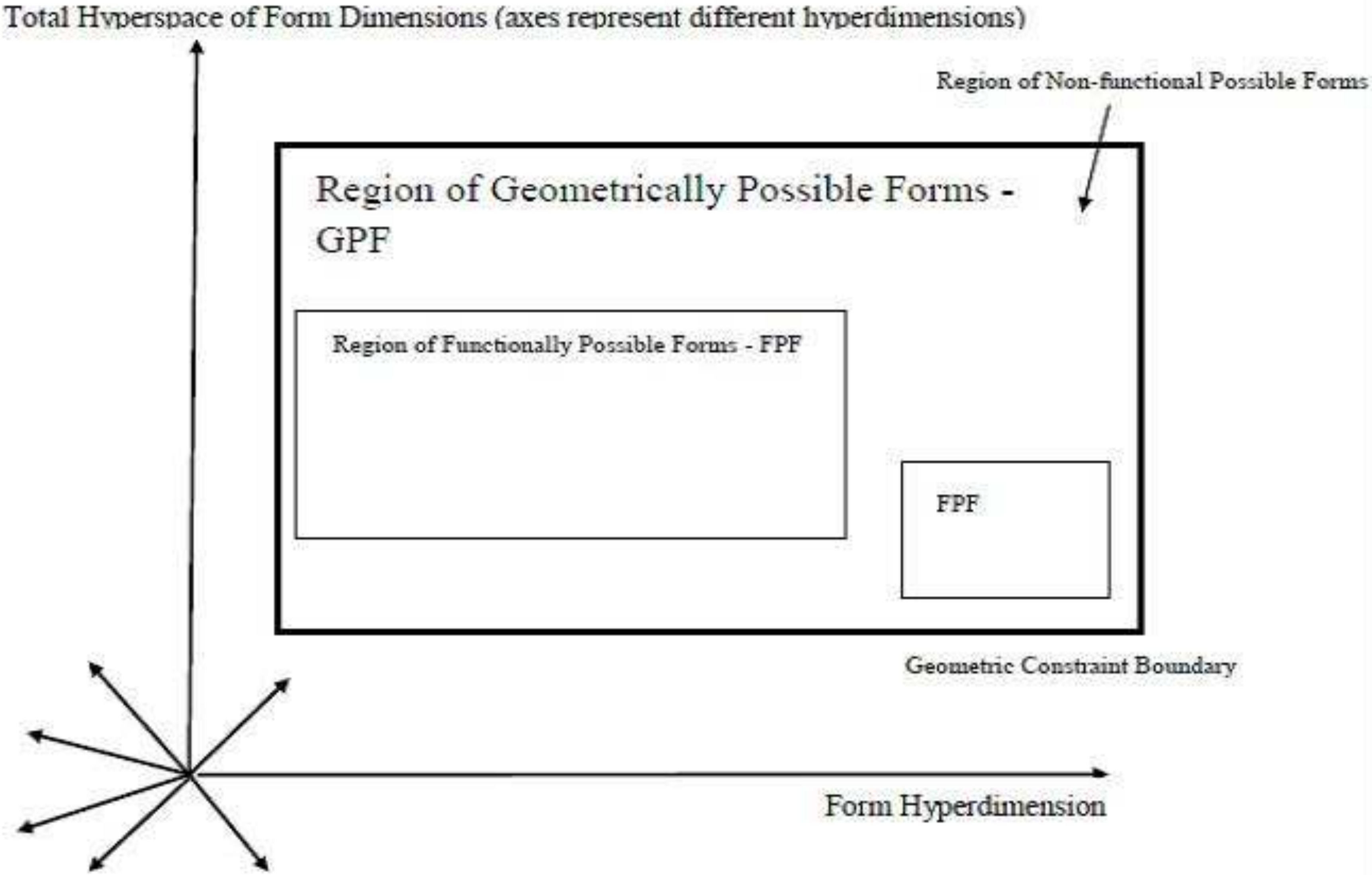
2. Fitness Landscapes and Morphospaces

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), Gaverilets and Gravener (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 and so are regions or clusters of hyperspace where fit gene combinations can occur. In the above author’s landscape, evolution can be ‘smooth’ within the clusters but ‘jumpy’ as gene combinations move from one cluster to another through ‘extradimensional bypasses’ (Gavrilets (1997, p.311). Within geomorphology Phillips (2009) outlined a similar vision of landscape evolution with his concept of Landscape Evolution Space (LES), an n-dimensional space or hypervolume representing the resources, energy, and the parameters available for landscape development. Conceptually, any landscape should be capable of being located within this hypervolume and its trajectory or development mapped out in the same space. Inkpen and Petley (2007) offer something similar in their analysis of landform development.

Theoretical morphospaces are not the same as adaptive landscapes but are related to them (McGhee, 2007). Developed by Raup (1966, 1967), a morphospace can be described as a hyperspace of geometries, with axes representing different morphological traits, that represent all the forms possible if these traits are systematically altered. Within a morphospace the axes represent dimensions and form; the resulting surface is a representation of how frequently that form appears. The morphospace provides an indication of the forms that occur in reality, and importantly, those that do not. The two types of space can be linked if the distribution of forms in the morphospace have adaptive significance. Raup (1966), for example, studied the form of ammonoids and identified that there was a distinct pattern to this distribution in morphospace. Chamberlain (1976, 1981) through experimental work on models, found that the two regions of morphospace created by ammonoid forms were those where swimming efficiency was maximised. Form was linked to adaptation. Regions of morphopsace do not necessarily match to peaks that optimise a specific function, but rather, as in the research into plant morphospaces by Niklas (1997, 2004), the peaks represent geometries that minimize several functional problems. This highlights that fitness is always a concept that needs to be thought of in multidimensional terms.

Combining the two spaces, McGhee (2007) develops an argument that they can be used to explore the constraints that exist upon development. Fig. 2 illustrates the concept that development is constrained by a series of factors; geometric, functional, phylogenetic and developmental in the case of organisms. McGhee defined the geometric and functional constraints as extrinsic, being imposed by the laws of physics and chemistry, whilst phylogenetic and developmental constraints were intrinsic, imposed by the biology of specific organisms. Assuming a form can be defined by a set of measurements then the total possible set of forms will be defined by points in a hyperspace as in Fig. 2. Within this set of possible forms will be a subset of forms that represent all geometrically possible forms (GPF in Fig. 2). Co-ordinates outside of this region of hyperspace represent geometrically impossible forms. McGhee defines the boundary between these regions of hyperspace as the ‘geometric constraint boundary’. Nested within the GPF are two other regions, functionally possible forms (FPF) and functionally impossible forms (FIP). The result is a clearly defined subset of hyperspace that demarcates the region of possible forms given the nested series of constraints. Importantly, the extrinsic constraints remain constant and define rigid boundary conditions, whilst the intrinsic constraints vary with taxon and so are more flexible in the boundaries they prescribe. Recent work on the simulation of vegetated aeolian landscapes (Baas, 2007; Baas and Nield, 2007,

Figure 2 Illustration of concept of development within a morphospace constrained by series of factors (Modified from McGhee, 2007)



2010; Nield and Baas, 2008) provide illustrations of the clustering of forms in a simulated parameter space.

Brierley (2010), building upon Brierley and Fryirs (2005), identifies a structuring of explanations concerning landscape development in a similar manner: identifying geologic, climatic and anthropogenic memory. Brierley views these three types of memory as imposing differing limits upon landscape development. Geologic memory imposes boundary conditions within which contemporary landscape-forming processes continue to operate, whilst climatic memory controls the nature and effectiveness of geomorphic processes. Anthropogenic memory alters the fluxes of sediment and flows in the landscape. Brierley (2010) is at pains to point out that these factors operate collectively and variably across different time frames despite the temptation to view them as hierarchical. This suggests that explanation in geomorphology is structured around sets of parameters that continually constrain the possible forms and the potential pathways of their development.

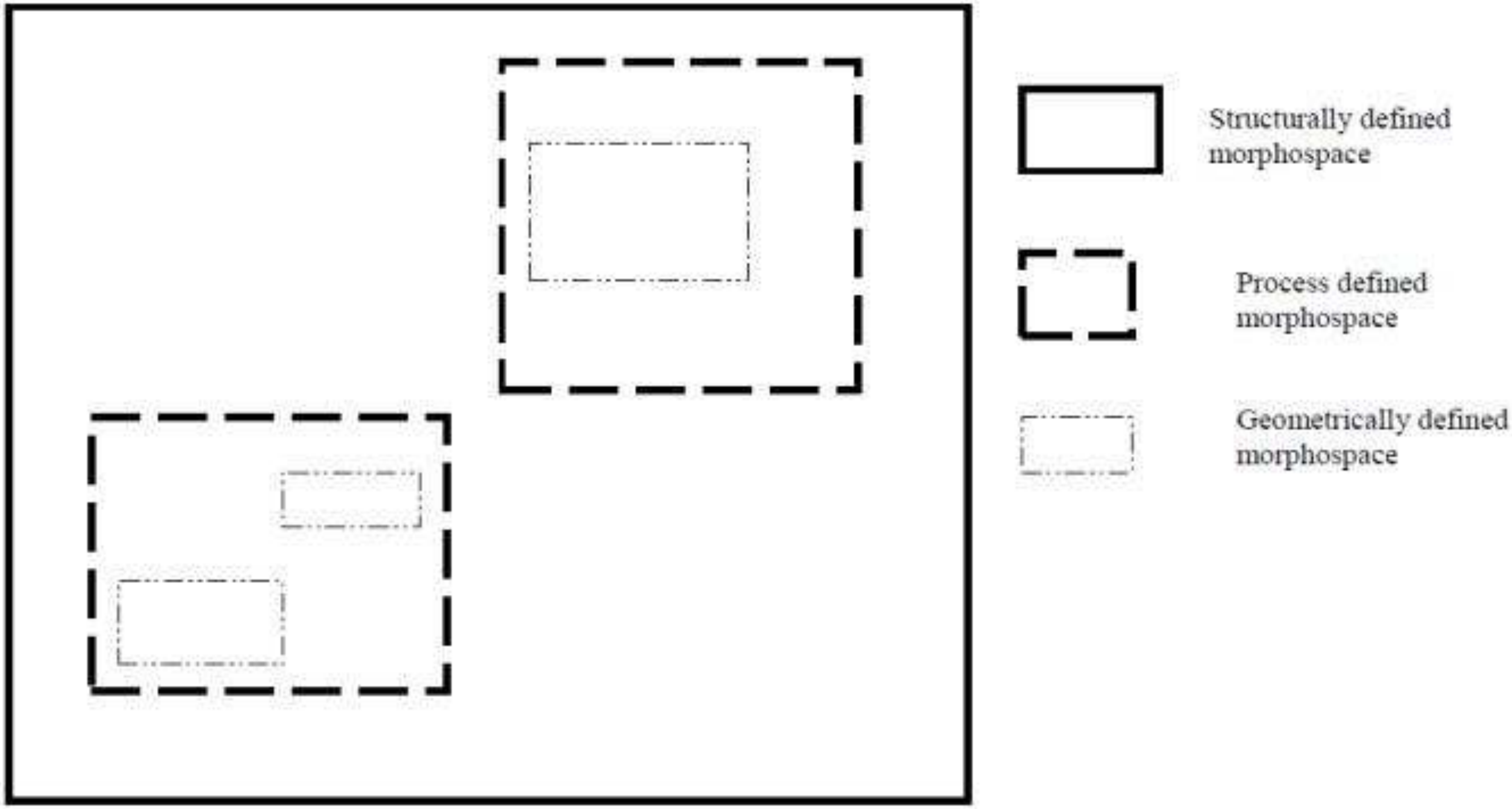
There may be a basis for seeing a conceptual analogy between morphospaces and fitness spaces and the concept of strange attractors (Phillips, 1999, 2003). Both sets of concepts discuss mapping system properties in a phase space within which certain portion of space are more likely to be populated than others. Within Phillips' discussion, strange attractors are areas of phase space to which evolutionary trajectories are drawn. In the language of morphospaces this means that the zone of the attractor will define a region of particular form characteristics. Within this region there will be a highly proportion or percentage of measured individuals. The attractor need not represent an evolutionary basin but rather the range of forms that can be taken given variations in constraining properties. The most frequent forms represent the most common outcome but other forms nearby could represent the manifestation of slightly different relations between constraining properties and yet still define a basin of attraction.

Application of both concepts to geomorphology does, however, face key problems that mirror those found within biology. Fitness spaces need to be defined in relation to some concept of fitness that then needs to be translated into empirical, measurable terms for defining the extent of morphospace. Identifying ‘fitness’ implies having a clear concept of the expected trajectory of a form and a clear understanding of the basis for this trajectory. Similarly, the plotting of individuals within a morphospace requires the identification and quantification of important characteristics of form. Our traditional ways of thinking about tafoni form affect what forms we identify in the field and what we deem important to measure. Likewise, technical constraints such as the type of equipment available, its measurement resolution and the ability to consistently measure a highly variable natural phenomenon will all impact upon the nature and quality of data available to characterise forms.

3. The Spaces of Tafoni

Combining fitness landscapes and morphospaces it is possible to analyse the parameters that define the morphospaces of tafoni and then the manner in which these forms change as tafoni form clusters and developmental sequences. The morphospaces that combine to constrain tafoni formation, development and form are structural, process-based and geometric. These three morphospaces are related to each

Figure 3 Relationship between structural, process-based and geometric factors in morphospaces as a nested hierarchy



as in Fig. 3, in a nested hierarchy with each additional space constraining the potential location of tafoni in the morphospaces. It is important to bear in mind that the figure is a representation of multidimensional spaces of rock structure, process and geometry and their relations in two-dimensions; it is a visual aid to interpretation. Fig. 3 illustrates that tafoni development is constrained by rock structure but rock structure itself is not sufficient to determine whether tafoni develop. Rock structure instead defines a section of morphospace within which tafoni could develop. Potential tafoni development in this morphospace is further constrained by other factors as discussed below. Collectively these form the hierarchy of constraining factors as illustrated in the figure. Burridge and Inkpen (2015) outline a similar hierarchical structure to modelling tafoni development. Rock properties provide the context within which processes operate to produce a geometry of form which then feedbacks to process and affects rock properties.

Structural or rock property constraints refer to the various parameters associated with rock properties that have been identified in the past as being associated with tafoni formation. These include inherent weaknesses in the rock, fractures, cracks, as well as porosity, permeability and rock composition. It is within this structurally defined constrained morphospace that processes of weathering and erosion operate and, importantly, interact with each other and with the structural parameters. Structural morphospace may constrain the potential for tafoni to develop but it is not sufficient on its own to determine whether tafoni will develop.

Tafoni are inherently about the relations between parameter spaces. For process-defined morphospace it is not the specific processes that are important but rather the nature of the relations between these processes and between these processes and structural parameters. Processes capable of inducing stresses in the near-surface of the rock, which then result in the differentiation of the surface and subsurface properties, are how process-defined morphospace and structural morphospace interact. This means that a range of processes can be vital for tafoni formation. It is not a specific process that causes tafoni to develop but rather it is the result of process relations, in conjunction with rock properties, that produces surface and subsurface differentiation and near-surface stress. Further, this is not a static relationship. Processes and structure interact and in so doing change the nature of that interaction. This means that the morphospaces evolve as well. The structural constraints are initially set very broadly. Adding the process relations produces a refinement of which parts of the spaces are able to develop tafoni. The ongoing interaction between the two further refines this space of potential development and can even expand the spaces of potential as structural properties are altered at the micro-level to become increasingly conducive to tafoni development.

An outcome of the complicated relationship between structure and process is the development of a distinct geometry to the resultant form. This is the geometric space, a further constraining morphospace. Once the characteristic tafoni form begins to develop there is an interaction with the processes causing surface and subsurface differentiation. The nature of this relationship determines the development of the geometry of the form that in turn affects the dynamics of the structural and process relationships. This further constrains the spaces of tafoni development as well as altering the nature of structural and process spaces to redefine the locations of potential tafoni development. Combined these three spaces produce a nested hierarchy of potential spaces for tafoni.

Conceptually, the interaction of the three spaces creates broad regions or clusters where tafoni could develop. These clusters need not be contiguous. This means that tafoni of different sizes and shapes are all tafoni formed through the relations between these three parameter spaces, just formed at different intersections of these parameter spaces. This also means that there is not necessarily a developmental sequence from small through middle-sized to large tafoni. The size distribution need not represent a developmental sequence but rather a different combination of relations.

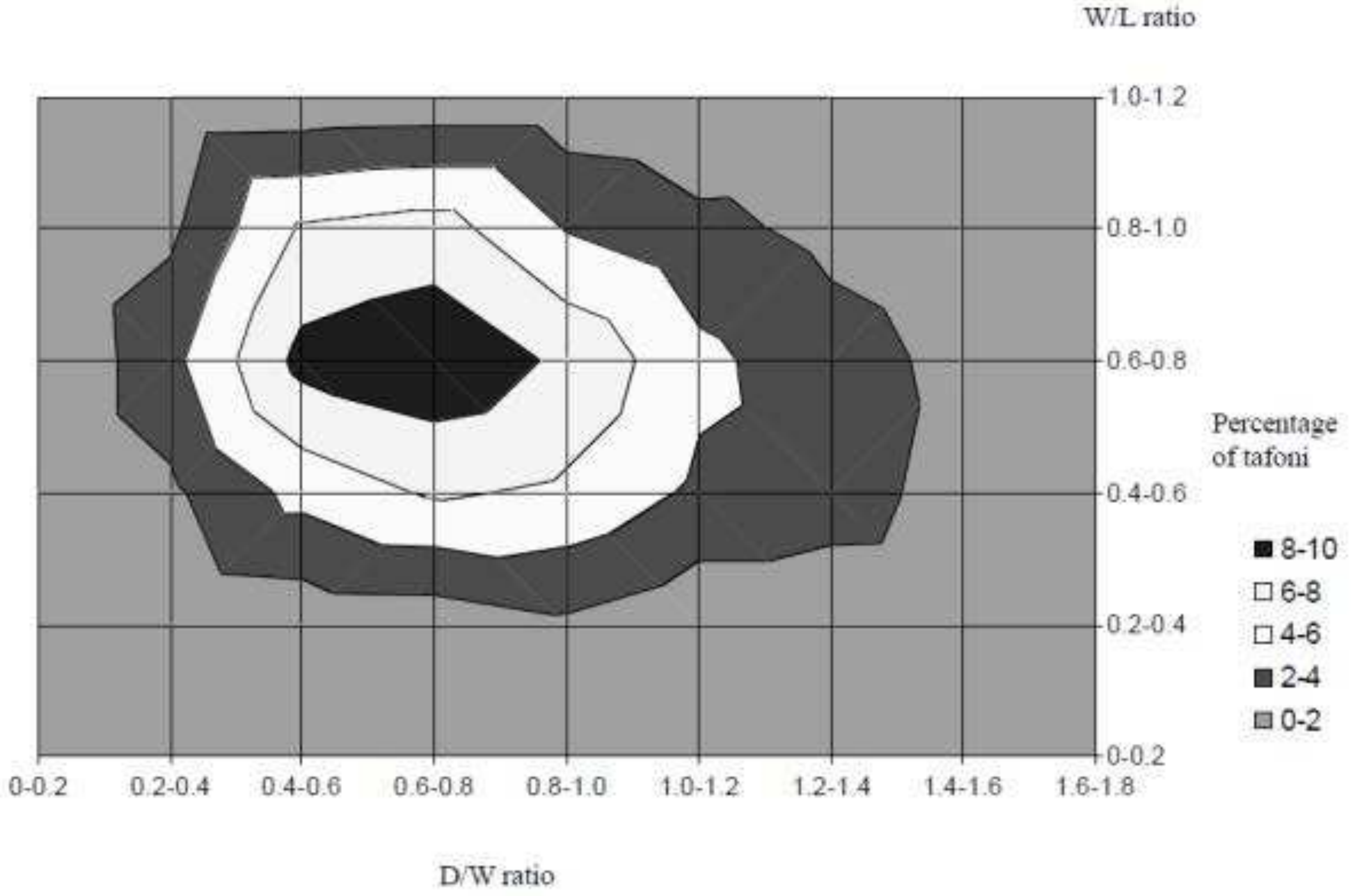
This means that it could be that different studies have revealed different clusters of tafoni and so different locations of potentiality in the relations between these parameter spaces. Once tafoni are initiated then they will develop into forms constrained by the morphospace. Although the potential forms may be varied there will be limits, boundaries, to these forms. It may be that small tafoni will always remain small as their development is confined within a specific region of tafoni morphospace. Small tafoni can not suddenly jump across morphospace and explore the region inhabited by large tafoni. Likewise large tafoni may initially develop rapidly as the relations between structure, process and geometry permit the rapid exploration of potentiality in that region of morphospace. Once trapped along a particular developmental pathway, however, it may be that the rate of growth slows as the limits to that particular pathway are reached. A deep cavern, for example, may be too deep for differentiation between surfaces to occur as weathering products can not be removed to permit further erosion. Conceptually this is limiting the space of potential development for a tafoni as it develops and alters the relations between the morphospaces of the three parameters.

4. Illustration of Interpretation of Tafoni Space

Tafoni were measured in Dronning Maud Land, Antarctica in the Austral summers of 2008/08 and 2010/11. Tafoni were measured on nunataks on the Ahlmannryggen (Ahlmann Ridge), specifically on nunataks, Vesleskarvet (Northern Buttress; 71^{o}40'S, 2^{o}51'W), Lorenzenpiggen (71^{o}45'S, 2^{o}50'W), Grunehogna (72^{o}02'S, 2o48'W), Flarjuven Bluff (72^{o}01'S, 3^{o}24'W) and Robertskollen (71^{o}27'S, 3^{o}15'W). The rock in the area is Precambrian in origin and the exposures measured were of the Borgmassivet Intrusives comprising doleritic and dioritic sills. Measurements were made on 40 rock faces, starting sampling at the central point of each rock face and then measuring the dimensions of the tafoni away from the centre of the rock face until 10 tafoni had been measured. Dimensions were measured using a set of callipers and undertaken by the same observer to ensure consistency in the field definition of length, width and depth.

The tafoni dataset was converted to dimensionless values using width/length and depth/width ratios and a phase space constructed using these dimensionless parameters as axes. The data were converted to dimensionless values to analysis form changes within the phase space rather than focusing on changes in the size of the tafoni. If the form of the tafoni, i.e. the relative dimensions of length, width and depth, did not change as it grew then more and more tafoni would occupy the same area of phase space. Fig. 4 illustrates the distribution of tafoni in this dimensionless phase space with cells along the x and y axes of 0.2 units. The contours represent the

Figure 4 Morphospace of percentage frequency of tafoni occurrence for specific width/length and depth/width ratios



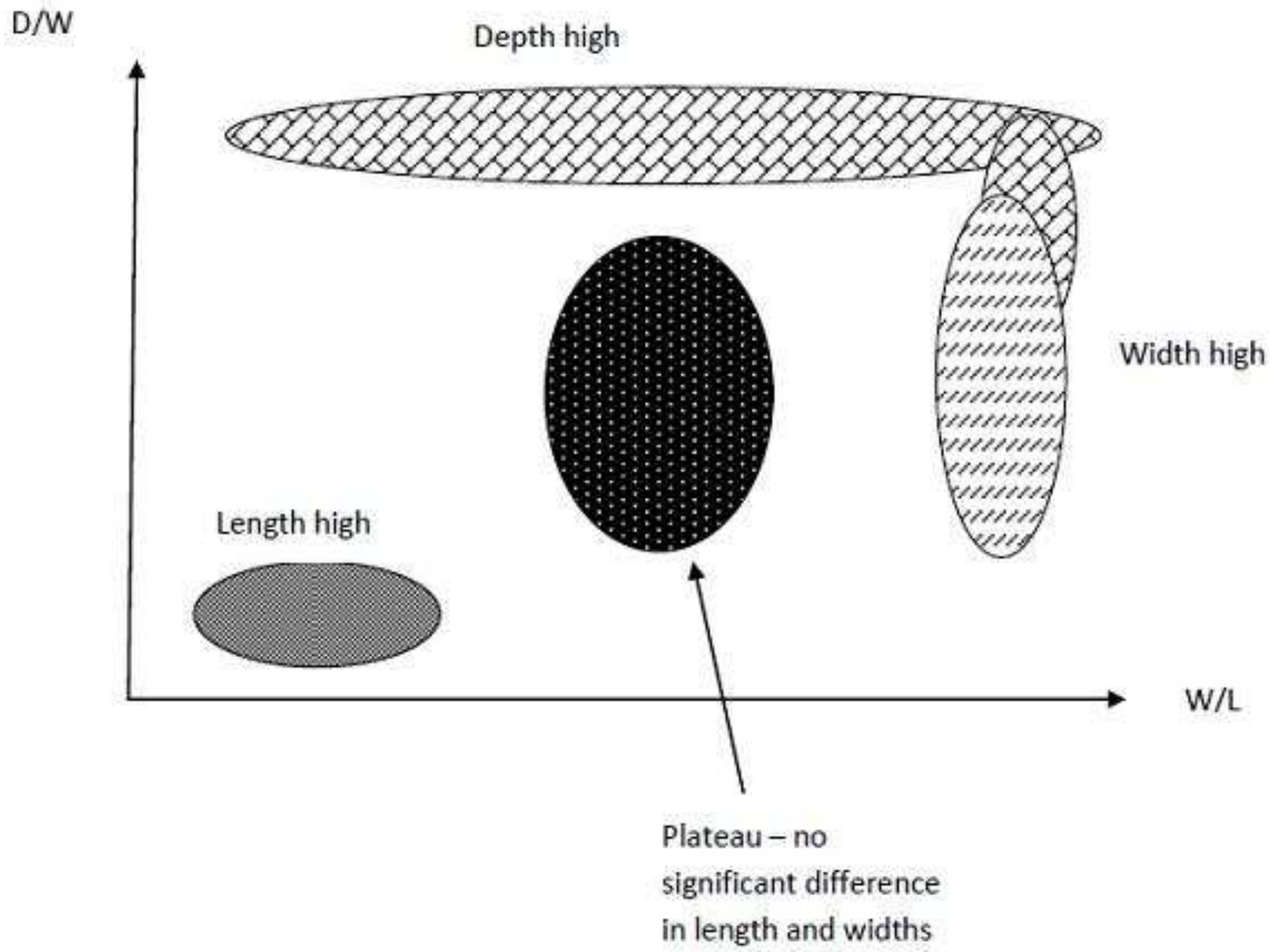
percentage of the tafoni in the dataset of 800 individuals occupying specific areas of the phase space. Although these dimensionless ratios have been used in tafoni research before they have not been used to map the distribution of tafoni in such as phase space. Fig. 4 shows a single peak to the distribution of tafoni at around 0.6-0.8 units of both the width/length and depth/width axes with a relatively smooth and continuous decrease around this peak in the occurrence of tafoni. There seems to be a tail in the distribution in the direction of higher depth/width ratios suggesting that there are a number of tafoni becoming deepening whilst retaining a form consistent with those tafoni in the peak area. The single peak and the relatively even spread of tafoni away from it might imply the peak represents the end point of an evolutionary or developmental sequence for tafoni. The relative frequencies of tafoni in the phase space would, if this were the case, represent the stages in tafoni evolution with the peak being the most frequent and final stage. Tafoni not in the peak might represent individual tafoni that had not yet developed to their final form or tafoni where the relations between rock structure, process and geometry in this environment were not as fully expressed as in the peak.

The contiguous nature and relatively plateau-like nature of the frequency surface in phase space may, however, suggest that the differences between a tafoni at the peak and one in the sub-peak areas may not mean that different processes are at work or that tafoni are at different stages of development. Rather the different zones represent the differing expression of the same set of rock structure, process and geometry relationships. This means that differences in form can not necessarily be interpreted to mean differences in how the tafoni form, only differences in the relative importance of each factor. This means that the exact position of an individual tafoni in the phase space need not reflect major changes in constraining factors nor in the relations that produce its final form. A cloud of individual tafoni positions may reflect the same relations just expressed slightly and insignificantly differently.

Analysis of variance suggests that there is no statistically significant difference between the tafoni in the three cells forming the plateau region in terms of length and width but depth increases significantly between these cells (analysis of variance with an F value of 0.8 for length and 0.69 for width, both statistically not significant and an F value of 9.43 for depth statistically significant at $\alpha=0.01$). Moving away from the plateau there are statistically significant differences in length, width and depth as might be expected as the ratios change. The nature of the change is consistent in that length, width and depth increase alone in specific areas of the morphospace so significant changes result from the increase in size of a single dimension rather than decreases in size.

Fig. 5 illustrates the variation in statistically significant increases in length, width and depth of tafoni in the morphospace. Tafoni in this dataset have a limited depth of 10-15 cm whatever the form of the tafoni. This implies that there is a vertical limit to tafoni development, suggesting that the relations between the three key factors only operate within a 10-1cm depth from the rock surface. This depth-limit to relationships between factors was also found in the mathematical modelling of tafoni in Burridge and Inkpen (2015) and may suggest that tafoni development is a depth-limited process. The bottom left of the phase space is dominated by tafoni with high average lengths compared to tafoni in every other part of the phase space. This suggests that tafoni in this section of the phase space are elongated and may represent either

Figure 5 Illustration of changes in tafoni length, width and depth across morphospace



controls on shape trough rock structure or the coalescence of tafoni lengthwise. The right-hand side of the phase space at mid D/W ratios has high average widths for tafoni compared to tafoni across the rest of the phase space. This suggests that tafoni move to this portion of phase space through widening rather than overall growth in dimensions, as the average tafoni length is not significantly different from the tafoni in the rest of the phase space.

The morphospace produced illustrates the constraining nature of the three parameters. Rock properties form the common context within which the tafoni develop and the single peak in morphospace implies that this constraint usually produces a single, characteristic set of forms. Process is constrained to the process specific to this environment and the geometry of form seems to be highly constrained to a limited set of ratios between the dimensions measured. The morphospace produced represents the range of tafoni form produced within this rock type, in this weathering environment and provides a template against which to map other tafoni from other environments as well as tafoni of lager and smaller dimensions. If the tafoni from other environments map into a similar zone then this implies that the relations between rock properties, process and geometry are consistent across environments and so forms converge into a specific region of morphospace. If, however, tafoni from other environments map to a different region of morphospace then this implies that there are significant differences in how the relationships between the factors are expressed in different environments. In this case there is a basis for claiming some tafoni are different from others and to question the common terminology to describe them.

5. Conclusion

Expressing the data within a standardized and dimensionless phase space allows the researcher to visualize the forms within a common setting. This can help the researcher to identify patches of the phase space where forms cluster, and to provide a definition of the characteristics that define these clusters in terms of dimensional relationships. Comparing the location of clusters between studies could help to identify if there is a common pattern to clustering within this phase space or if the location and nature of the clusters vary with each study. This will help to distinguish and define tafoni that present common patterns in form relationships and tafoni whose form relationships express their site-specific nature. Making this distinction will help researchers define forms which could be classified as tafoni in any environment as opposed to forms that exhibit tafoni-like tendencies but which cluster in a different part of the phase space. ‘Mine is different from yours’ becomes less of a problem as here is a way of visualizing if and by how much mine is different from yours and if the difference might be significant.

The role of form and process, as well as the relative importance of other factors, can be analysed using the hierarchical model of morphospaces presented above. The central importance of rock structure defines the limits to the range of forms possible and so could be viewed as the overarching control on the potential for tafoni to develop. Whether tafoni develop or not is not solely determined by rock structure however. The relationships between rock structure and weathering and erosion are vital for determining if tafoni develop and which areas of the phase space the forms inhabit. Producing stress in the near-surface is the key outcome that affects tafoni production and the evolving relationships between processes and form, tightly constrained by structure, establishes the developmental and geometric relationships that are expressed by the forms measured. This could mean that different processes produce different clusters in phase space and so process identification may be aided by mapping these clusters. It may be, however, that the clusters are so broad, as in this example, that the differentiation between processes is not feasible. This could imply that the range of forms produced within the constraints of the morphospace defined by rock structure is potentially large as subtle variations in process-form relationships can be expressed by a wide range of dimensional outcomes. With only one set of data it is difficult to assess if this is a general characteristic of tafoni but setting the discussion within this common framework would enable these key hypotheses to be tested.

6. Acknowledgements

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