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Defining tafoni: Re-examining terminological ambiguity for cavernous rock decay phenomena

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Abstract

Cavernous rock decay processes represent a global phenomenon, ubiquitous to all environments, with the viewable-in-landscape form usually being the final descriptor (e.g. “alveoli”), sometimes alluding to the specific decay process (e.g. “pitting”), other times not (e.g. “honeycombing”). Yet, definitive terminology remains inconsistent, usually owing to variability in dimension, morphometry, distribution, and/or academic lineage. This lack of an established lexicon limits scientific collaboration and can generate scientific bias. With no official consensus on appropriate distinctions, researchers and scientists must either be familiar with all the possible terminology, or know the apparent distinction between “forms”—which can seem arbitrary and, even more frustrating, often differs from researcher to researcher, scientist to scientist. This article reviews the historical and contemporary progression of scientific inquiry into this decay—and, arguably, erosional—feature to identify lexical inconsistencies and promote a singular unifying term for future scholars. Ultimately, the authors support using “tafoni” (singular: “tafone”) as the non-scalar universal term—the *form* created by numerous *processes* involved in cavernous decay features—and strongly suggest researchers adopt the same vernacular in order to promote collaboration.

Keywords

cavernous weathering, honeycombing, tafoni, terminology, rock decay

I Introduction

Characterized as cavities or hollows of various sizes in stone surfaces, cavernous rock decay is a globally occurring phenomenon that has

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been under scientific exploration for centuries and yet definitive terminology remains inconsistent. Publications on the enigmatic rock decay features vary considerably from qualitative interpretations (e.g. Bryan, 1928; Tschang, 1974) and temporal modeling of cell growth (e.g. Norwick and Dexter, 2002; Sunamura, 1996), to meticulous laboratory analyses (e.g. McBride and Picard, 2004; Rodriguez-Navarro et al., 1999) and complex multidisciplinary field studies (e.g. Brandmeier et al., 2010; Martini, 1978). However, variability in dimension, morphometry, and distribution of these decay features has resulted in the adoption of assorted terms such as alveoli, stone lace, honeycombing, caverns, pitting, and so forth. All of these refer to cavernous decay features with a generally accepted assumption that each term is somehow scale dependent (e.g. alveoli refer to smaller cells). However, no apparent consensus exists on the appropriate distinctions between terms. At what point is alveoli confidently alveoli and not honeycombing? Or, what is the definable difference between tafoni and stone lace? Some argument has been made that the distinction between such terms could depend on cell depth vs. width vs. clarity of separating ridges (e.g. Tschang, 1974), but even then what are the defining thresholds of these values? For example, when is a cell deep enough to be considered honeycombing instead of pitting? This lack of established lexicon restricts scientific collaboration and future research through terminology disconnects or misunderstandings, as evidenced throughout the history of cavernous decay research.

Despite, or perhaps spurred-on by, fluctuating scientific interest in cavernous decay research, different distinctions and terminology for decay features emerged seemingly autonomous from each other (Smith, 1982). Martini (1978) defined tafoni as "a landform and refers to weathering conditions and processes that lead to formation and maintenance of the morphological form" (Martini, 1978: 46), but this definition is ambiguous and open to multiple interpretations. Scientific confusion is continually perpetuated as researchers use different terminology to describe analogous decay phenomena. The significance of this situation is not lost on the rock decay research community, who have recently struggled with a similar conundrum advocating "rock decay" as a more accurate and encompassing replacement terminology for the widely used "weathering" to define stone deterioration (e.g. Dorn et al., 2013; Hall et al., 2012). Likewise with Bracken and Wainwright's (2006) contention of ambiguity over the term "equilibrium," especially in geomorphology, and Berthling's (2011: 98) argument that process (the usual "morphological definition") should not necessarily be the primary consideration when defining geomorphological features (in this case specifically rock glaciers). Related to tafoni specifically, in his 1982 *Nature* article, "Why Honeycomb Weathering?," Smith (1982: 121) aptly describes the situation: "With so many independent observations of so many examples in so many different places, it is perhaps not surprising that it has come to have a variety of names."

There have been previous attempts to standardize the nomenclature, but few such pleas have been successful and terminological inconsistency remains. In *The Geomorphology of Rock Coasts*, Trenhaile (1992) writes "the lack of a precise definition of honeycombs, tafoni, and other related forms makes it difficult ... to determine the meaning of the terminology as it is used by different workers" (Trenhaile, 1992: 31). At some point during the late 1900s, researchers began designating large, meter-sized cavities as tafoni and smaller, similarly shaped, millimeter- to decimeter-scale cavities as honeycomb, honeycomb weathering, alveoli, alveolar weathering, and small tafoni, but with no official clarification of scale-dependence (e.g. Kelletat, 1980; McBride and Picard, 2000; Smith, 1982; Turkington and Paradise, 2005; Figure 1). Despite this

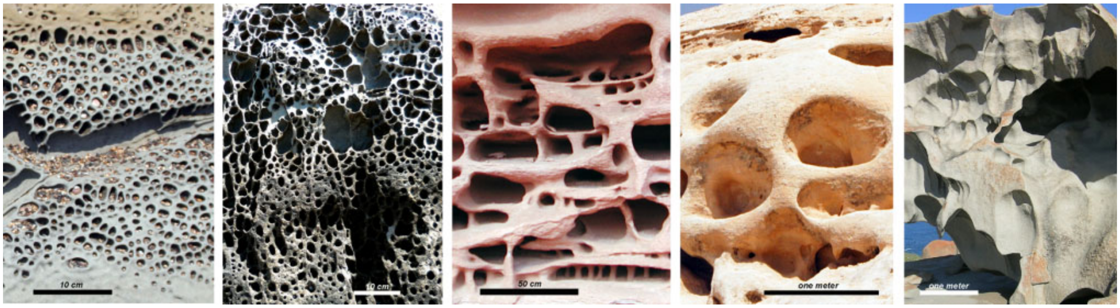

Figure 1. Tafoni of various sizes with scale bars for reference. Locations from left to right: Bean Hollow State Beach, CA; Bean Hollow State Beach, CA; Moenkopi Formation in Wupatki NM, AZ; DISI formation in Beidha, Petra, Jordan; and the Remarkable Rocks in Flinders Chase NP, Australia. Photographs by T.R. Paradise.

pseudo-collaboration, established distinctions between the myriad of terms, whether based on size, shape, or cavity frequency per rock surface, are still absent and many studies continue to use varied terminologies (e.g. Andre and Hall, 2005; Young and Young 1992). However, this begs even more complex questions: are they the same feature, just at different scales, and, thus, require a universal term, or are all the various distinctions warranted? Are honeycombing, tafoni, and other cavernous decay features' geomorphology synonymous despite historically observational and lexical differences? What are the scientific implications inherent to inconsistent terminology and how might moving towards a single, common terminology benefit future research? With such questions left unaddressed, it has become difficult to establish basic processes such as the influence of salts, micro-climate, air circulation, mineralogy, and case hardening, to name a few, if scholars cannot even agree on the form being studied. As the eventual aim of cavernous decay research is to establish overarching processes causing similar features in different lithologies and environments, then adopting common terminology allows significantly more efficient comparison within the literature.

To address these key issues, this article outlines a number of instances where this consensus is not reached and fluid terminologies are used despite researching very similar forms. This is accomplished through a temporal and thematic approach in discussing pertinent questions to gain a better evolutionary understanding of nomenclature ambiguity in cavernous decay research. Significant eras of tafoni literature are outlined in detail, chronologically from oldest to most recent. The first research period spans the late 1800s to the early 1900s, when systematic tafoni research and terminology were first beginning to emerge. The second era focuses on cavernous decay investigations following geography's so-called "Quantitative Revolution" (~1960s to 1970s, cf. Barnes, 2009; Burton 1963; Livingstone, 1992: chapter 9). Finally, the most recent cavernous decay studies from the 1980s into the 21st century are examined for terminology, definitions, and other significant findings. The purpose of this review is to outline the progression of tafoni and cavernous decay research and, by doing so, identify terminological inconsistencies that may be hindering future scientific discoveries and research. By offering an alternative through a structured terminology framework, we can move forward, perhaps finding overarching processes within tafoni development rather than creating disconnected literature "islands" of case studies.

II The scientific beginning of cavernous decay features

Descriptions of tafoni and cavernous decay features have been recorded for thousands of years, the earliest being 3500-year-old intricate Minoan fresco paintings (Boxerman, 2005). Early explorers and scholars, such as Charles Darwin (1839) and James Dana (1849), offer casual reflections in their journal, but hardly more than curious observation. Much of the earlier studies on cavernous features come from the Mediterranean region by scholars such as Casiano de Prado (1797–1866), who first described tafoni in the Sierra de Guadarrama, Central Spain (De Prado, 1864). In fact, the earliest printed uses of the term "tafoni" (singular: tafone)—stemming from the verb *tafonare* meaning "to perforate"—referring to cavernous decay features were by Hans Henrik Reusch in 1882 and later by Albrecht Penck in 1894, both of whom researched tafoni cells in Corsica.

Cavernous decay was not given any serious scientific attention in the Americas until the early 1900s. During this era of exploratory science, two of the founding reports on tafoni not only present different formation hypotheses, but also, unfortunately, initiated the habit of arbitrary terminology and categorization for the decay phenomena. These authors were Kirk Bryan (1888–1950) and Eliot Blackwelder (1880–1969). Bryan and Blackwelder's successive articles on tafoni and cavernous decay in the southwestern United States laid the groundwork for future research, though they contained throughout them numerous arbitrary terms.

Pioneering empirical tafoni research, Bryan's 1928 article "Niches and Other Cavities in Sandstone at Chaco Canyon, New Mexico" introduced various terms and designations for cavernous decay features. Suggesting larger than average tafoni cells, Bryan defined many of the cavities at his site as "desert niches" (though he also mentioned a contemporary scholar who would have defined these larger voids as "caves") and the smaller cells "nests" (Bryan, 1928). Additionally, Bryan labeled intricate bands of smaller cells as "stone lace" or "stone lattice." Despite his variety of categories, Bryan acknowledged a fundamental resemblance in forms and processes: "The holes of stone lace have, therefore, the same origin as the small niches which they closely resemble in form" (Bryan, 1928: 137). While the main purpose of Bryan's article was to support differential physical processes producing tafoni, he also recognized the complexity of cavernous decay and the potential for polygeneity: "There are many kinds of holes and cavities and many valid means by which they may have been formed" (Bryan, 1928: 125). Although Bryan founded many of the underlying theories in tafoni formation, he admittedly adopted dissimilar terms to define features of similar forms.

Conversely, Blackwelder (1929) supported a chemical approach to cavernous decay and added his own terminology into the mix. While he acknowledged Bryan's designation of "desert niches," Blackwelder primarily used more general and utilitarian terminology such as "cavities," "pockets," or simply "cavernous decay." Blackwelder disagreed with Bryan's conclusions that the primary formation processes behind cavernous decay were physical and this disparity might explain his reluctance to adopt his terminology. In fact, despite being two of the earliest and most influential scientific explorations of cavernous decay, neither used any of the same designations or nomenclature. Additionally, both Blackwelder and Bryan's blatant rejections of other scholars' designations for similar forms without proposing the establishment of a singular, universal definition for cavernous decay features denotes a poor lack of foresight for future studies. This inconsistency resulted in an unfortunate acceptance of personalized terminology from researcher to researcher that is still perpetuated today.

Besides Bryan and Blackwelder, cavernous decay research and continuity within tafoni terminology remained scarce until the Quantitative Revolution in the 1960s. The term "desert niches"

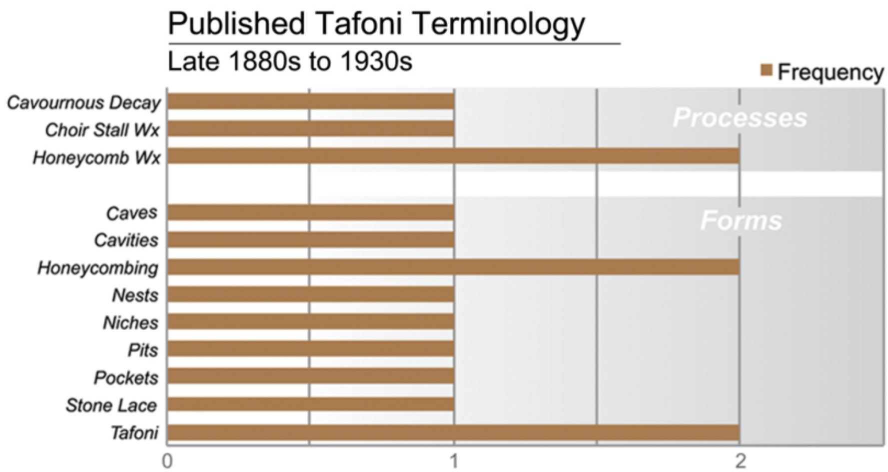

Figure 2. Diagram of prominent tafoni terminology for both form and process published from the late-1880s through the 1930s. For brevity "Wx" represents "Weathering." K.M. Groom.

never really caught on and by the 1930s designations ranged from ''honeycomb weathering'' (Bartrum, 1936) to ''decay pits'' (Palmer and Powers, 1935; Figure 2; Appendix 1). It was not until later in the century when Penck's and Reusch's term ''tafoni'' began to gain popularity outside of Corsica.

III The quantitative revolution and cavernous rock decay research

During the 1960s the world's technological and intellectual advancements opened new opportunities for studying the universe's mechanisms and science thrived, including rock decay science and tafoni research. By end of 1980s, tafoni research had been conducted across the globe in sites as varied as Antarctica (e.g. Calkin and Cailleux, 1962; Prebble, 1967), Hong Kong (Tschang, 1974), Southern Australia (e.g. Dragovich, 1967; Winkler, 1979), Northwest Sahara (Smith, 1978), and Italy (Martini, 1978). By its own nature, the Quantitative Revolution also prompted more empirically based approaches to tafoni formation hypotheses. During this era, tafoni researchers gained a greater understanding of the roles of salt crystallization (Bradley et al., 1978; Winkler, 1979), biochemical decay (Mustoe, 1971), and flaking (Dragovich, 1967) connected to environmental influences on rock decay rates. Contradicting the historic chemical *or* physical standpoint as posed by Bryan and Blackwelder, respectively, some authors during this era suggested a more polygenetic approach where multiple processes could have been the source of the same landforms (e.g. Martini, 1978).

With this surge in cavernous decay research came an array of divergent terminology (Figure 3; Appendix 2). Part of the inconsistency that arose during this time was due to continued disagreement on what tafoni *were* and how they should be defined. Jennings (1968: 1103) defined tafoni as ''forms of cavernous weathering, chiefly found in medium and course grained, acid to intermediate crystalline rocks, but also occurring in other rocks such as sandstone, limestone, and schist.'' This definition was less ambiguous than earlier suggestions, but, as tafoni research increased, exceptions to these parameters were discovered. Martini (1978) added another component into the equation by trying to define both form and process: ''Tafone is a term that has

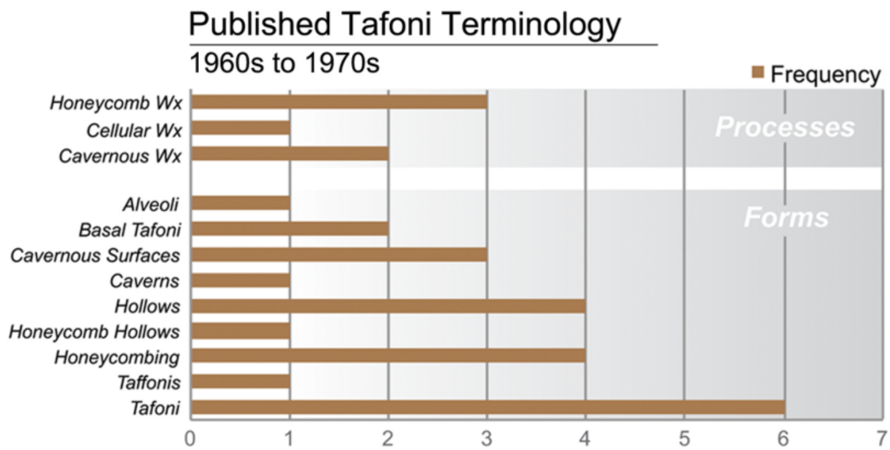

Figure 3. Diagram of prominent tafoni terminology for both form and process published from the 1960s through the 1970s. For brevity "Wx" represents "Weathering." K.M. Groom.

been used both to describe a landform, and to refer to weathering conditions and processes that lead to formation and maintenance of the morphological form'' (Martini, 1978: 46). As tafoni literature expanded, these decay conditions and processes became as varied as the terms used to describe them, so attempting to define tafoni by the host rock's geology *and* decay processes were inadequate.

This era also marked the beginning of conceptualizing size as a contributing factor in cavernous decay terminology. Larger voids were known as "caverns" (Dragovich, 1967) or "caves" (Grantz, 1976), even though the decay processes and research questions for these studies are arguably synonymous to contemporary tafoni research (Turkington and Paradise, 2005). Similarly, the names for smaller cells ranged from "hollows" (Cailleux and Calkin, 1963) to "honeycombing" (Mustoe, 1971). There are also several publications that use the terms "cavernous weathering" and "tafoni" exclusively, despite scale, such as Bradley et al. (1978) and Wilhelmy (1964). Although the understanding that cavernous decay terminology is scale dependent has remained relatively acceptable, the thresholds at which terms become more or less appropriate than others are poorly defined.

The Quantitative Revolution did witness a push for common nomenclature (e.g. Jennings, 1968; Tschang, 1974), but to no avail. The range of sizes, locations, and types of cells prompted scholars to create more ambiguous adjectives or classification systems, yet very few seemed to catch on for any significant amount of time. For example, Tschang (1974) attempted to create different classes and subclasses of tafoni based on their shape and location on the stone surface. His main classes included miniature tafoni, side tafoni, basal tafoni, horn tafoni, and pseudotafoni. These classes were then divided into sub-categories by formation directions and processes: horizontal extension type, curved extension type, vertical extension type, oblique extension type, lotus petal type, mixed type, ruined type, and a miscellaneous type for cells that did not fit into any of the other subclasses (Tschang, 1974). Representing an acknowledged need for an overarching terminology, Tschang's distinctions appear to be relatively arbitrary and unnecessarily complicated.

IV Modern scientific discoveries and tafoni terminology

With even more advances in technology and scientific exploration, tafoni research continued expanding from the 1980s to the present, both geographically and evolutionarily. By the end of the 20th century, cavernous decay studies had extended regionally to include Japan (e.g. Matsurkura et al., 1989; Suzuki and Hachinohe, 1995), the United Kingdom (Pye and Mottershead, 1995), Spain (e.g. Mellor et al. 1997; Sancho and Benito, 1990), Scotland and Southern Greece (Kelletat, 1980), Northern Ireland (McGreevy, 1985), Finland (Kejonen et al., 1988), and even Mars (Rodriguez-Navarro, 1998). Continued research also emerged from previously researched locales such as Antarctica (e.g. Conca and Astor, 1987), throughout the United States (e.g. Butler and Mount, 1986), and Australia (e.g. Twidale and Sved, 1978). The regional scope of cavernous decay studies continues to expand through the 21st century to include South Africa (Mol and Viles, 2010), Jordan (Paradise 2013a; Viles and Goudie, 2004), and Southern India (Achyuthan et al., 2010).

Formation hypotheses and foci of study are still greatly varied during this era— though the roles of salt and moisture have become common themes. Previous research has shown that accelerated cell growth can be tied to intensified rates of salt crystal accumulation and movement, which, in turn, have been associated with multiple extrinsic variables such as higher evaporation rates for perpendicular surfaces to dominant wind direction (Rodriguez-Navarro et al., 1999) and crystalline salts and calcites deposition and migration via precipitation (McBride and Picard, 2000). In addition, the salts in themselves can act as decay catalysts (Young, 1987), for example through repeated and extended drying and wetting cycles (Huinink et al., 2004). A general pattern emerges from these studies: a particular climatic variable influences the accumulation or evaporation of moisture, which then determines the rate of salt crystallization promoting tafoni evolution, often intensified when combined with high porosity and permeability (McBride and Picard, 2004). Surface and sub-surface moisture, acknowledged variables in mechanical rock decay, were associated with cell development through transporting salts and other dissolved minerals (e.g. Mustoe, 1983) as well as destabilizing pressure fluctuations through internal water movement and expansion (e.g. Conca and Astor, 1987). Water circulation, autonomous from salt accumulation, was also directly correlated with several hydro-geomorphological processes leading to cavernous decay features such as ice micro fractures (French and Guglielmin, 2000; Kejonen et al., 1988) and joint-determined moisture patterns (Conca and Astor, 1987). Mol and Viles (2010) related higher internal moisture content with reduced stone hardness and elevated rates of decay. They later employed similar methods to assess moisture in tafoni cells and comparable processes seem to effect cell development (i.e. higher moisture = greater cell growth, see Mol and Viles, 2012).

Yet for all the advances, terminology and cavernous decay labels have remained inconsistent during this time (Figure 4; Appendix 3). Popularized by Mustoe (1983), terms such as "honeycombing," "stone lace," "alveolar weathering," and "fretting" began to appear interchangeably in cavernous decay research. The distinction provided by Mustoe (1983) was that tafoni were "large cavities [that] may reach diameters of several meters" (Mustoe, 1983: 517) and the rest of these terms describe "patterns consisting of many small cavities" (Mustoe, 1983: 517). This arbitrary separation has been perpetuated through countless citations, and many articles have adopted the term "honeycombing" in their titles (e.g. Andre and Hall, 2005; Butler and Mount, 1986; Rodriguez-Navarro et al., 1999). However, not all tafoni literature accepted Mustoe's varied terms and definitions, as exemplified by Pestrong (1988): "No such distinction is made in this paper, however, for sufficient similarities in formation mechanisms appear to exist" (Pestrong, 1988: 1049).

Much of the current literature admits cavernous decay is widely varied in geographies,

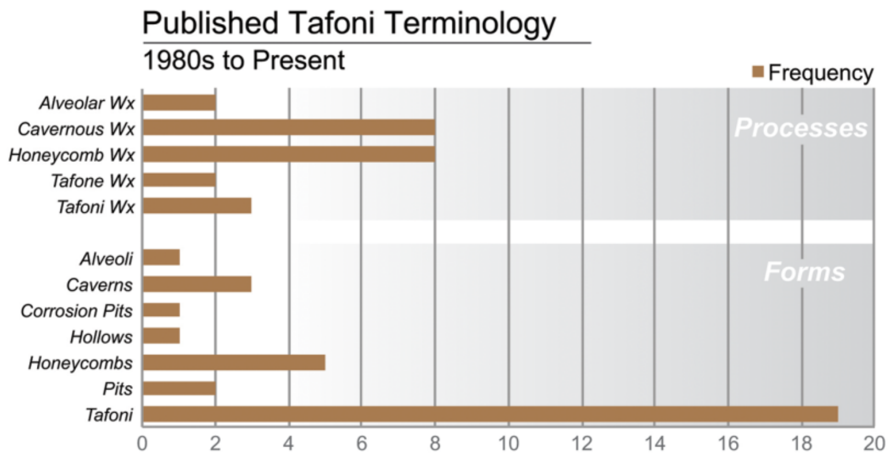

Figure 4. Diagram of prominent tafoni terminology for both form and process published from the 1980s to current. For brevity "Wx" represents "Weathering." K.M. Groom.

geologies, and decay processes, but, unfortunately, terminology has become a widely ignored issue. In their exploratory article, Brandmeier et al. (2010) examined the history of tafoni and discussed new challenges and unanswered questions for future research. Among many pertinent statements on the condition of cavernous decay research is a comment given in passing, but speaking volumes: "the term is not strictly defined in the literature" (Brandmeier et al., 2010: 839). In other words, this article tackled the history and formation hypotheses for decay features with little concern that they still lack a universal definition. Unfortunately, this kind of treatment towards the status of tafoni terminology is not uncommon in modern literature. Siedel (2010), used "alveoli," "pits," and "honeycombs" interchangeably even after recognizing the existence of "some terminological confusion in the use of 'alveolar' or 'honeycomb weathering'" (Siedel, 2010: 12). Other abstracts and introductions from numerous publications include statements such as "a multitude of terms have been used to describe such features" (McBride and Picard, 2000: 869) or "the nomenclature for pitted and cavernous weathering was not harmonized throughout most of the twentieth century" (Norwick and Dexter, 2002), but no such study explicitly calls for a unified lexicon. The latter example cited Sunamura (1996) as the official foundation of using "tafoni" as a non-scalar term, but the exact passage cited was simply a disclaimer for that particular study: "These two cavernous forms are, however, collectively called 'tafoni' in this paper, unless otherwise stated" (Sunamura, 1996: 741). Despite some confusion within the scientific community, there are scholars who are actively trying to define tafoni through further research of their formation processes—such as Owen's (2013) research on pseudokarstic tafoni in the Bahamas—as a possible avenue for tafoni definition, or through literary reviews, such as this manuscript and Uña Alvarez's (2008) terminological examination of granite tafoni nomenclature.

V Defining tafoni: Finding a terminological solution

Perhaps the irregular use of terminology throughout the history of cavernous decay research has deeper epistemological and ontological roots. Indeed, *The Scientific Nature of Geomorphology* (Rhoads and Thorn, 1996) discusses at length the philosophy behind geomorphology

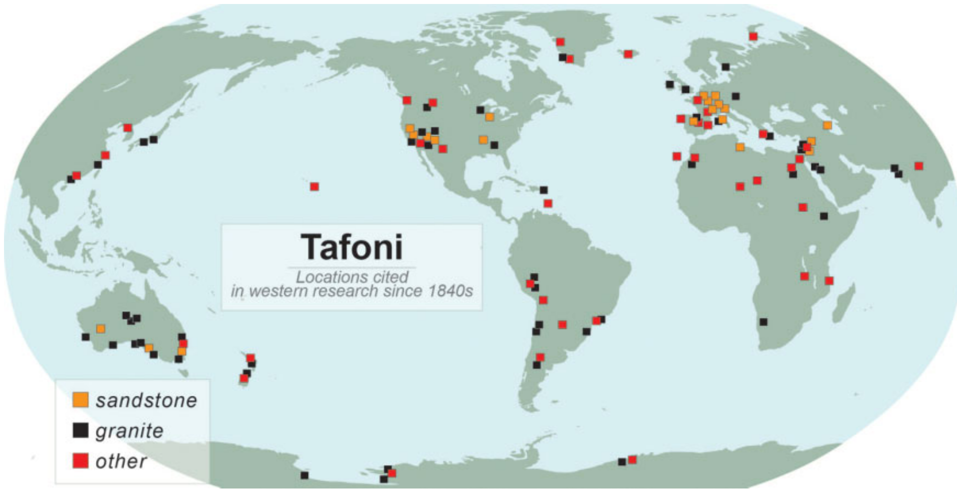

Figure 5. World map showing the diverse geographical settings of documented tafoni research in English, French, German, and/or Italian languages since 1840. Icons separated by color to indicate researched lithology. T.R. Paradise.

as a discipline, yet barely touches on naming conventions even though landform literature remains littered with terminological ambiguity. A few decades ago, Haines-Young and Petch (1983) put forth a geomorphologically example-rich study associated with the concept of equifinality and its relationship to Chamberlin's (1890) theory of multiple working hypotheses, noting the use of method and process for landform naming might actually generate more vagaries. Two decades later, Smith and Mark (2003) provocatively questioned whether mountains even exist. Their argument, bolstered by an ontological context (what a mountain *is*), supports the notion that the form itself (the mountain) is what gives it meaning, not necessarily the process(es) that created it. More recently, Brierley et al. (2011: 1981) remind geomorphologists that, while official bodies exist for naming places, geological time periods, and biological species,

> no formal procedures have been established for landscape types. In geomorphology, an inevitable outcome of this local naming process is that overlapping or identical features are given names in different languages (e.g. terms such as kamenitza, vasque, pia, Opferkessel and gnamma all describe small pans in rock surfaces).

Some of these ontological and philosophical dilemmas have translated from a wider geomorphological context into cavernous rock decay research, furthering terminological disagreement through a series of unaddressed inconsistencies: azonality, polygenetic processes, size variance, and lithological constraints—each of which would benefit from collaborative terminology.

1 Azonal distribution

One major variance within tafoni development research and, as an extension, tafoni terminology is the diverse geographic, geologic, and environmental contexts in which they can be found (Figure 5). As demonstrated in this review, cavernous decay features have been observed worldwide in environments ranging from coasts (e.g. Suzuki and Hachinohe, 1995) and river basins (e.g. Sancho and Benito, 1990) to subzero deserts (e.g. Selby, 1971) and other dryland regions (e.g. Wilhelmy, 1964). The variety of landscapes accommodating tafoni development, both physical and climatological, discourages assuming any single evolution hypothesis as the primary cause for all cavernous decay (and source of terminology), but, instead, insinuates a multifaceted connection between polygenetic formation processes and geographic setting, geology, and climate (Inkpen and Jackson, 2000). Paradise (2013b) demonstrates this variance in cavernous decay mechanisms by emphasizing the interconnectedness of principle decay processes to lithological and environmental settings—discouraging any kind of terminology based on setting alone.

In addition, the spatial breadth of tafoni and cavernous features has also hindered international collaboration through poor dissemination and language barriers, especially in the earlier literature. To avoid ambiguous nomenclature, scholars may be tempted to employ simple and utilitarian terms such as "void" or "hollow" (as seen in Blackwelder, 1929) or even "cavernous features," but such terms would vary linguistically and would not bridge the language barrier, leaving the research isolated from the international scientific compendium (e.g. De Prado, 1864). Therefore, a universal term—valid in all languages, locales, and environments – would provide the continuity necessary for further global research.

2 Polygeneity and process

Notwithstanding substantial academic attention, scientific understanding of the principal driving mechanisms for cavernous decay remains yet to be discovered. Throughout the history of tafoni research, numerous postulations have been offered ranging from the physical (e.g. Mottershead and Pye, 1994) versus chemical (e.g. Campbell, 1999) process dichotomy begun by Blackwelder and Bryan, to biological decay influences (Andre and Hall, 2005; Mol and Viles, 2012), to some unidentifiable mix of all three (Martini, 1978). Pope et al. (1995: 38) appropriately portrayed the complexity of decay processes in the terms of "synergy" by saying, "variability in weathering [rock decay] involves synergistic interactions of biological, chemical, and physical factors." For tafoni, the mere existence of so many different supported formation theories supports the concept of polygeneity—where a single form can be the result of a multitude of processes (Dorn et al., 2012).

Cavernous decay research has only recently incorporated multifaceted approaches to cell evolution (Brandmeier et al., 2010; Turkington and Phillips, 2004). In a recent textbook, Paradise (2013b: 112) embraced the polygenetic complexity and defined tafoni as "lace-like, honeycomb, bowl, or pan-shaped cavities occurring in a variety of rock types and locations that show a commonly unique assemblage and morphology." This definition took a different approach than previous endeavors in that it excluded exact formation processes all together. As tafoni research expands, there is increasing recognition that tafoni are, in fact, polygenetic and actually the result of multiple, if not simultaneous, decay processes varying case to case (e.g. Achyuthan et al., 2010; Brandmeier et al., 2010; Mol and Viles, 2012). It is, then, not difficult to understand how a multifaceted and polygenetic decay feature such as tafoni could accumulate such a diverse assortment of names despite sharing analogous characteristics. Perhaps appropriate terminology can only be reflective of the form, discarding the process, in cases when the forms are homogeneous but the formative processes are not? But are the forms the same? Observationally, regardless of formation processes, location, and lithology, all cavernous features share a universal progression: intense localized differential decay *and* removal of decayed material leaving a hollowed surface (Achyuthan et al., 2010; Figure 6). It could be argued, then, that the variety in tafoni appearances are dependent on location, lithology, and environment—not individual processes—and therefore an umbrella term for these features completely disassociated from process would provide greater inter-study communication.

3 Size

Another inconsistency impacting ambiguity in tafoni science has been the long-standing

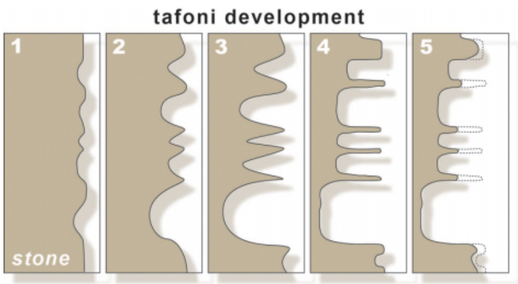

Figure 6. Cross section diagram showing a generalized progression of tafoni development. T.R. Paradise.

assumption that cell size can be used as the qualifying feature to define lexicon. While many scholars adopted the concept of scale-dependent terminology, the exact thresholds at which size distinguishes one term from another are subjective and arbitrary. This has resulted in various studies employing different designations for cells of the same size, thus completely defeating the purpose of threshold terminology. Exemplifying this discourse, contemporary studies such as Andre and Hall (2005), Paradise (2013a), and McBride and Picard (2004) each assessed cavernous features 1–4 cm in diameter, but use different terms (Figure 7). The notion that size justifies differential terminology is not only difficult to moderate without definitive thresholds, but also cognitively separates features that could otherwise be assessed homogeneously—thus limiting further scientific exploration.

So why has a more rigorous threshold definition system for cavernous features not yet been established? A primary issue with this solution is that, in many cases, decay rates, shapes, and sizes of tafoni are largely a function of lithology so not all cells will follow the same formation patterns (Hall et al., 2012), rendering a universal size-based categorization useless. Additionally, the concept of grouping terminology by size—or any single characteristic—is also restrictively simplistic. Scholars may inadvertently end up grouping together several-millennium old sandstone cells in a weathering-limited desert environment with century old tropical limestone cells simply because they appear to be the same size. To offer a medical analogy, this would be congruent with naming a similar disease by different names depending on the height of the patient. What information might the doctors be missing by not collaborating with each other?

4 Lithological restraints

Lithology, the last inconsistency, accounts for much of the variability in both size and process, but is rarely addressed beyond identification. The working relationship between intrinsic (internal) and extrinsic (external) influences on rock decay and geomorphology has been explored for decades. GK Gilbert (1843–1918) described landscape change as a ratio between sheer strength and sheer stress quoting "solidity is not absolute but relative" (Gilbert and Dutton, 1880: 91). This notion can be easily adaptable to rock decay with "sheer strength" signifying intrinsic variables (e.g. mineralogy or lithification) and "sheer stress" denoting extrinsic variables (e.g. climate or anthropogenic activity). Both variables affect cavernous decay, but have been historically researched separately with significantly more attention given to exogenetic (external) influences. The irony in this is that lithology has an intense influence on the extent and methods of decay (Hall et al., 2012)—including the distribution and morphometry of cavernous features (e.g. Conca and Rossman, 1985) explaining the variety of cell shapes and appearances.

With that in mind, the variety of substrates on which tafoni can be found is astonishing. Cavernous decay features have been documented on a multitude of lithologies including volcanic tuff (e.g. McBride and Picard, 2000), intrusive granite and gneiss (e.g. Dragovich, 1967), various sandstones (e.g. Grantz, 1976), limestone (e.g. Rodriguez-Navarro et al., 1999), slightly metamorphosed conglomerate (Martini, 1978), and even manufactured materials such as concrete (Pestrong, 1988; Figure 8). The fact that

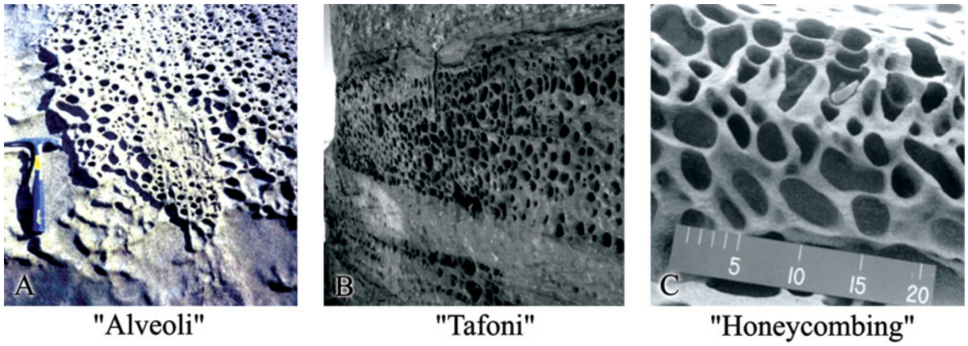

Figure 7. Examples of scalar discrepancies in modern tafoni literature. A: Andre and Hall (2004), B: Paradise (2013a), C: McBride and Picard (2004).

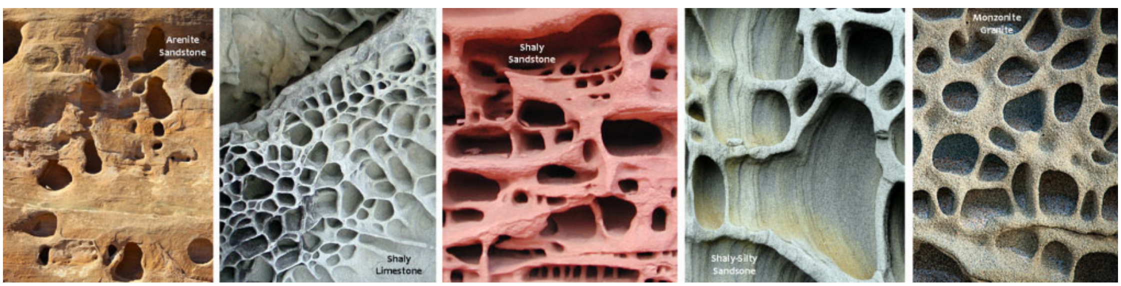

Figure 8. Tafoni development in various lithologies. Locations from left to right: Colorado National Monument, CO; Bean Hollow State Beach, CA: Wupatki National Monument, AZ; Bean Hollow State Beach, CA; and Eastern Slope Yosemite National Park, CA. Photographs by T.R. Paradise.

so many different rock types, with all of their inherent constraints on decay processes, can support the development of cavernous features demonstrates a profound continuity despite varying geologic settings that have been obstructed by ambiguous terminology. Ultimately, cavernous features are highly complicated with multiple constraints—none of which are suitable to singularly define terminology.

VI Discussion and conclusions

With cavernous decay features presenting themselves in so many different locations, lithologies, and appearances, scholars are left with the question: do the different terms exist for a reason? Are these features truly independent of each other and necessitate discrete terminology? The purpose of this article is to challenge previously held perceptions of separateness where it might not exist. As this paper vigorously argues, all cavernous decay features follow the same basic progression: localized differential decay and subsequent removal that leaves a hollowed surface (Achyuthan et al., 2010). Turkington and Phillips (2004) describe cavernous decay in terms of self-organization and feed-back processes within the rock decay system. This approach is applicable to all forms of cavernous decay regardless of which terminology is preferred. Unifying the terminology will most likely encourage alternate ways of thinking that can eventually lead to more process-focused investigations between what have been historically perceived as separate forms, potentially resulting in new and important understandings.

Obviously, appearances are not perfectly identical, but the fact that so many similarities exist despite the incredible variations in setting, climate, and lithology warrants more cohesive research—a unity that would be enhanced through shared terminology.

This review demonstrates how the inconsistency of tafoni terminology has limited intuitive scientific collaboration and hindered the ability of any scholar, novice or expert to research tafoni and cavernous decay holistically. Researchers interested in the formation of cavernous features must search each term individually to gain a universal view of existing literature using any number of prevalent academic search engines, such as Google Scholar™ or other online library achieves. A query for "tafoni" only surfaces a fraction of existing relevant research. An additional search for "honeycombing" might add more references, but this is still an incomplete representation of the existent literature. Exemplifying this disconnect, Honeyborne (1998) outlines some major effects of "alveolar" decay on masonry deterioration (an important, but under-researched, application of tafoni science), but is absent from any research query for either "tafoni" *or* "honeycomb weathering." In a recent cry for common terminology, Uña Alvarez (2008) describes some issues surrounding confused tafoni terminology: "The situation can generate a conceptual and a categorical uncertainty in the knowledge of the cavernous granite forms" (Uña Alvarez, 2008: 65). As insinuated by the quote, Uña Alvarez (2008) focused on granite features— a, perhaps, self-defeating constraint. As illustrated by the various inconsistencies of tafoni research, if an established terminology is to be appropriate, it must be devoid of any locational, process, size, and lithological limitations.

Therefore, we support "tafoni" (singular: tafone) as an overarching designation for cavernous features. The etymological origin of "tafoni" to define cavernous features is unspecified, but is thought to have substantial Mediterranean influence (Paradise, 2013b)—representing a significant provenance in the pioneering of cavernous decay science. One proposed origin of the term stems from the Greek word *taphos* meaning tomb or sepulcher (Battisti and Alessio (1957) in Trenhaile, 1992). Other sources suggest the Corsican (French) word, *taffoni*, meaning windows, or *tafonare* meaning to perforate (Wilhelmy, 1964). In Sicilian, *tafoni* means windows (Goudie, 2003). Ontologically, Brierley et al. (2011: 1981) point out that "there are some informal precedents in which locality names have become more widely used," such as "karst" – from the Kars Plateau in Slovenia where karst research was founded (Bezlaj, 1982). So while the "locality" of cavernous features is global, it would not be without precedence to adopt a universal term with a regional origin—i.e. the mostly-Mediterranean term, "tafoni."

"Tafoni" is nominated not only because of its global recognition and already popular use, but also because it bypasses many of the terminological inconsistencies found in the literature. Geographically, tafoni is non language-specific and, therefore, unaffected by translations so it can remain constant in international publication venues, further promoting more successful global dissemination. Purely descriptive or observational terminology such as cavernous features, hollows, or cells would be lost in translation. In terms of polygeneity, tafoni are the result of both decay *and* erosion, so any definitive terms based solely on decay processes, such as honeycomb weathering, tafone weathering, alveolar weathering, or even cavernous weathering/decay, are inadequate as they only acknowledge half of the process necessary for tafoni to exist. Tafoni is also a non-scalar term that could be comfortably applied to cells spanning a few millimeters to several meters in diameter. This cannot be said of other terms historically used to describe cavernous features, such as alveoli or honeycombing, which carry significant scalar baggage. Additionally, tafoni is not restricted to any one lithology or geologic context, unlike terms such as "pitting"—which is most commonly associated with limestone or karst landscapes. Ultimately, the term tafoni provides necessary terminological continuity within cavernous decay science without being limited by its own definition.

Science is a dynamic and adaptive process—as scientists and researchers should be in our search for knowledge. The terminology we use reflects upon how we think (Hall et al., 2012), for, as the Scottish philosopher Thomas Reid so eloquently stated, "There is no greater impediment to the advancement of knowledge than the ambiguity of words" (Reid, 1850: 1). In short, then, as science delves deeper into rock decay science, a common vernacular can enhance collegial endeavors and promote an alternative framework no longer hampered by ambiguity. An example of such a transition is the shift from "weathering," which was often cognitively associated to "weather" and environmental factors, to "rock decay," which encompasses the myriad of internal and external influences known to exist (Dorn et al. 2013; Hall et al., 2012). Similarly, adopting a standard nomenclature provides scholars with the universal lexicon vital to collectively promoting tafoni research worldwide.

Once consensus can be reached on terminology, scientists will be able to investigate inconsistencies in methodology, as well as address the schools of thought that favor, variously, salt, climate, and lithology as determining factors in cavernous decay feature development. As it stands, the majority of this research's current inconsistencies make it difficult to directly compare process and form of features variously labeled as "alveoli," "tafoni," and "pitting" when, in addition to terminological diversity, these have been investigated using differing methods and field sites. Certainly, more research is necessary to determine the exact constraints and causes for the various appearances of tafoni, but, as argued here, the collaborative benefits of researching a singular form, tafoni, vastly outweighs the benefits of keeping each cognitively separate. There is little denial that cavernous features are complicated, which is why the push for scientific consistency and terminological continuity is critical to ensure the effectiveness of global research collaboration today and in the future.

Appendices

Appendix 1. Table of authors and tafoni terminology used most organized by date from 1800 to 1959

Dominant cavernous decay terminology, late-1800s to 1930s		
Author(s)	Year published	Terms used
HH Reusch	1882	tafoni
FW Simonds	1888	nests, caves
A Penck	1894	tafoni
WF Hume	1925	choir stall weathering
K Bryan	1928	desert niches, niches, stone lace
E Blackwelder	1929	cavities, pockets, cavernous decay
HS Palmer and HA Powers	1935	pits
JB Mackie	1935	honeycomb weathering
JA Bartrum	1936	honeycomb weathering

Appendix 2. Table of authors and tafoni terminology used most organized by date from 1960 to 1979

Dominant cavernous decay terminology, 1960s to 1970s		
Author(s)	Year published	Terms used
P Calkin and A Cailleux	1962	cavernous weathering, taffonis
A Cailleux and P Calkin	1963	hollows, cavernous weathering
H Wilhelmy	1964	tafoni, hollows, cavernous rock surfaces
GT Bowra et al.	1966	honeycomb weathering
D Dragovich	1967	hollows, caverns, cavernous surfaces
JN Jennings	1968	tafoni, hollows
ED Gill	1972	honeycomb, cellular weathering
H Tschang	1974	lateral tafoni, basal tafoni, pseudo-tafoni, subordinate tafoni, relic tafoni
P Höllermann	1975	cavernous rock surfaces, tafoni
DA Robinson and RBG Williams	1976	honeycomb hollows, honeycombing
WC Bradley et al.	1978	tafoni, basal tafoni, sidewall tafoni
IP Martini	1978	tafoni, alveoli, honeycomb weathering

Appendix 3. Table of authors and tafoni terminology used most organized by date from the1980 s to current

Dominant cavernous decay terminology, 1980s to current		
Author(s)	Year published	Terms used
D Kelletat	1980	honeycombs, tafoni, cavernous weathering
ED Gill	1981	tafoni, honeycomb weathering
GE Mustoe	1983	tafoni, honeycomb weathering
JP McGreevy	1985	honeycomb weathering
PR Butler and JF Mount	1986	honeycomb weathering, corrosion pits
ARM Young	1987	caverns, cavernous weathering
JL Conca and AM Astor	1987	cavernous weathering
R Pestrong	1988	tafoni
A Kejonen et al.	1988	tafoni, cavernous weathering
C Sancho and G Benito	1990	tafoni weathering, tafonis
Y Matsukura and N Matsuoka	1991	tafoni weathering, tafoni
A Mellor et al.	1997	tafoni, hollows, cavernous weathering
C Rodriguez-Navarro et al.	1999	honeycomb weathering
SW Campbell	1999	tafoni, alveolar weathering
HM French and M Guglielmin	2000	tafoni, cavernous weathering

(continued)

Appendix 3. (continued)

Dominant cavernous decay terminology, 1980s to current		
Author(s)	Year published	Terms used
SA Norwick and LR Dexter	2002	tafoni
HP Huinink et al.	2004	tafoni, honeycomb weathering
EF McBride and MD Picard	2004	honeycomb cells, aberrant honeycombs
MF Andre and K Hall	2005	honeycombs, tafonis, alveolar weathering
AV Turkington and JD Phillips	2004	caverns, cavernous weathering
JZ Boxerman	2005	tafoni, tafone weathering
E Hejl	2005	tafoni, cavernous weathering, tafoni weathering
H Achyuthan et al.	2010	tafoni, pits
MJ Brandmeier et al.	2010	tafone weathering, tafoni
T Sunamura and H Aoki	2011	tafoni, honeycomb weathering
L Mol and HA Viles	2012	caverns, alveoli, tafoni
TR Paradise	2013a, b	tafoni, honeycomb weathering

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References

Achyuthan H, Kumar KA, Tiwari SK, et al. (2010) A reconnaissance study of tafoni development, exfoliation, and granular disintegration of natural and artificial rock surfaces in the coastal and lowland regions of Tamil Nadu, southern India. *Zeitschrift fur Geomorphologie* 54(4): 491–509.

Andre MF and Hall K (2005) Honeycomb development on Alexander Island, glacial history of George VI sound and palaeoclimatic implications (Two Step Cliffs/Mars Oasis, W Antarctica). *Geomorphology* 65(1): 117–138.

Barnes T (2009) Quantitative Revolution (geography of). In: Kitchin R and Thrifts N (eds) *The International Encyclopaedia of Human Geography*. Oxford: Elsevier, 33–38.

Bartrum JA (1936) Honeycomb weathering of rocks near the shore-line. *The New Zealand Journal of Science and Technology* 18(1): 593–600.

Berthling I (2011) Beyond confusion: Rock glaciers as cryo-conditioned landforms. *Geomorphology* 131(3): 98–106.

Bezlaj France (1982) *Etimološki slovar slovenskega jezika*, vol. 2. K–O. Ljubljana: SAZU, 82.

Blackwelder E (1929) Cavernous rock surfaces of the desert. *American Journal of Science* 17(1): 393–399.

Bowra GT, Holdgate MW and Tilbrook PJ (1966) Biological investigations in Tottanfjella and central Heimefrontfjella. *British Antarctic Survey Bulletin* 9: 63–70.

Boxerman JZ (2005) The evolutionary cycle of the tafone weathering pattern on sandstone at Bean Hollow Beach, northern California. *Geological Society of America Sectional Meeting*. Abstract. Salt Lake City, UT.

Bracken LJ and Wainwright J (2006) Geomorphologic equilibrium: Myth and metaphor? *Transactions of the Institute of British Geographers* 31(2): 167–178.

Bradley WC, Hutton JT and Twidale CR (1978) Role of salts in development of granitic tafoni, south Australia. *Journal of Geology* 86(5): 647–654.

Brandmeier M, Kuhlemann J, Krumrei I, et al. (2010) New challenges for tafoni research: A new approach to understand processes and weathering rates. *Earth Surface Processes and Landforms* 36(6): 839–852.

Brierley G, Huang HQ, Chen A, et al. (2011) Naming conventions in geomorphology: Contributions and controversies in the sandstone landscape of Zhangjiajie Geopark, China. *Earth Surface Processes and Landforms* 36(14): 1981–1984.

Bryan K (1928) Niches and other cavities in sandstone at Chaco Canyon, New Mexico. *Zeitschrift fuer Geomorphologie* 3(1):125–140.

Burton I (1963) The quantitative revolution and theoretical geography. *The Canadian Geographer* 7(4): 151–162.

Butler PR and Mount JF (1986) Corroded cobbles in southern Death Valley: Their relationship to honeycomb weathering and lake shorelines. *Earth Surface Processes and Landforms* 11(4): 377–387.

Cailleux A and Calkin P (1963) Orientation of Hollows in Cavernously Weathered Boulders in Antarctica: Biuletyn Peryglacjalny, 12: 147–150.

Calkin P and Cailleux A (1962) A quantitative study of cavernous weathering (taffonis) and its application to glacial chronology in Victoria Valley, Antarctica. *Zeitschrift fuer Geomorphologie* 6(1): 317–324.

Campbell SW (1999) Chemical weathering associate with tafoni at Papago Park, central Arizona. *Earth Surface Processes and Landforms* 24(3): 271–278.

Chamberlin TC (1890) The method of multiple working hypotheses. *Science* 15(92): 281–293.

Conca JL and Astor AM (1987) Capillary moisture flow and the origin of cavernous weathering in dolerites of Bull Pass, Antarctica. *Geology* 15(2): 151–154.

Conca JL and Rossman GR (1985) Core softening in cavernously weathered tonalite. *Journal of Geology* 93(1): 59–73.

Dana JD (1849) *Manual of Geology*. 1st ed. New York, NY: Ivison, Blakeman, Taylor and Company.

Darwin C (1839) *The Voyage of the Beagle*. New York, NY: Collier and Son Company.

De Prado C (1864) Descripción física y geológica de la provincia de Madrid. *Col. Ciencias, Humanidades e Ingeniería* 2: 60–76.

Dorn RI, Dorn J, Harrison E, et al. (2012) Case hardening vignettes from the western USA: Convergence of form from a divergence of hardening processes. *Association of Pacific Coast Geographers Yearbook* 74: 1–12.

Dorn RI, Gordon SJ, Allen CD, et al. (2013) The role of fieldwork in rock-decay research: Case studies from the fringe. *Geomorphology* 200: 59–74.

Dragovich D (1967) The origin of cavernous surfaces (tafoni) in granitic rocks of southern South Australia. *Zeitschrift fuer Geomorphologie* 13(2): 163–181.

French HM and Guglielmin M (2000) Cryogenic weathering of granite, northern Victoria land, Antarctica. *Permafrost and Periglacial Processes* 11(4): 305–314.

Gilbert GK and Dutton CE (1880) *Report on the Geology of the Henry Mountains*. US Government Printing Office: Washington, DC.

Gill ED (1972) The relationship of present shore platforms to past sea levels. *Boreas* 1(1): 1–25.

Gill ED (1981) Rapid Honeycomb Weathering (Tafoni Formation) in Greywacke, S.E. Australia: Earth Surfaces Processes and Landforms, 6: 81–83.

Goudie A (2003) *Encyclopedia of Geomorphology*. London: Routledge, 1200.

Grantz A (1976) *Sandstone Caves (tafoni) in the Central Santa Cruz Mountains, San Mateo County*. Sacramento, CA: California Division of Mines and Geology, 51–54.

Haines-Young RH and Petch JR (1983) Multiple working hypotheses: Equifinality and the study of landforms. *Transactions of the British Institute of Geographers* 8(4): 458–466.

Hall K, Thorn C and Sumner P (2012) On the persistence of "weathering". *Geomorphology* 149: 1–10.

Hejl E (2005) A pictorial study of Tafoni development from the 2nd Millennium BC. *Geomorphology* 64: 87–95.

Höllermann P (1975) Formen kavernöser Verwitterung ("Tafoni") auf Teneriffa. *Catena* 2: 385–409.

Honeyborne DB (1998) Weathering and decay of masonry. *Conservation of Building and Decorative Stone* 1: 153–184.

Huinink HP, Pel L and Kopinga K (2004) Simulating the growth of tafoni. *Earth Surface Processes and Landforms* 29(10): 1225–1233.

Hume WF (1925) Geology of Egypt. Egyptian Geological Survey: Cairo. 73.

Inkpen RJ and Jackson J (2000) Contrasting weathering rates in coastal, urban, and rural areas in southern Britain: Preliminary investigations using gravestones. *Earth Surface Processes and Landforms* 25(3): 229–238.

Jennings JN (1968) TAFONI, tafone, taffoni Tafoni. In: Fairbridge RW (ed) *Geomorphology*. Heidelberg: Springer Berlin, 1103–1104.

Kejonen A, Kielosto S and Lahti SI (1988) Cavernous weathering forms in Finland. *Geografiska Annaler* 70A: 315–322.

Kelletat D (1980) Studies on the age of honeycombs and tafoni features. *Catena* 7(4): 317–325.

Livingstone DN (1992) Statistics don't bleed: Quantification and its detractors. In: Livingstone DN (ed) *The Geographical Tradition: Episodes in the history of a contested enterprise*. Oxford, UK: Blackwell, 304–346.

Mackie JB (1935) The geology of the Glenomaru survey district, Otago, New Zealand. *Transactions of the Royal Society of New Zealand* 64: 275–302.

McBride EF and Picard MD (2000) Origin of development of tafoni in Tunnel Spring Tuff, Crystal Peak, Utah, USA. *Earth Surface Processes and Landforms* 25: 869–879.

McBride EF and Picard MD (2004) Origin of honeycomb and related weather forms in Oligocene Macigno sandstone, Tuscan coast near Livorno, Italy. *Earth Surface Processes and Landforms* 29: 713–735.

McGreevy JP (1985) A preliminary scanning electron microscope study of honeycomb weathering sandstone in a coastal environment. *Earth Surfaces Processes and Landforms* 10: 509–518.

Martini IP (1978) Tafoni weathering, with examples from Tuscany, Italy. *Zeitschrift fur Geomorphologie* 22(1): 44–67.

Matsukura Y and Matsouka N (1991) Rates of Tafoni Weathering on Uplifted Shore Platforms in Nojima-Zaki, Boso Peninsula, Japan: Earth Surfaces Processes and Landforms, 16: 51–56.

Matsurkura Y, Matsuoka N and Yano N (1989) A preliminary study on tafoni and honeycombs in Nojima-Zaki, Boso Peninsula, Japan. *Annual Report. Institute of Geoscience, University of Tsukuba* 25: 29–32.

Mellor A, Short J and Kirkby SJ (1997) Tafoni in the El Chorro area, Andalucía, southern Spain. *Earth Surfaces Processes and Landforms* 22: 817–833.

Mol L and Viles HA (2010) Geoelectric investigations into sandstone moisture regimes: Implications for rock weathering and the deterioration of san rock art in the Golden Gate reserve, South Africa. *Geomorphology* 118: 280–287.

Mol L and Viles HA (2012) The role of rock surface hardness and internal moisture in tafoni development in sandstone. *Earth Surface Processes and Landforms* 37: 301–314.

Mottershead DN and Pye K (1994) Tafoni on coastal slopes, south Devon, UK. *Earth Surfaces Processes and Landforms* 19: 543–563.

Mustoe GE (1971) *Biochemical Origin of Coastal Weathering Features in the Chuckanut Formation of Northwest Washington*. Washington State: Western Washington State College, 1–85.

Mustoe GE (1983) Origin of honeycomb weathering. *GSA Bulletin* 93: 108–115.

Norwick SA and Dexter LR (2002) Rates of development of tafoni in the moekopi and kaibab formations in meteor crater and on the Colorado plateau, northeastern Arizona. *Earth Surface Processes and Landforms* 27: 11–27.

Owen AM (2013) Tafoni development in the Bahamas. In: Lace MJ and Mylroie JE (eds) *Coastal Karst Landforms*. The Netherlands: Springer, 177–205.

Palmer HS and Powers HA (1935) Pits in coastal pahoehoe lavas controlled by gas bubbles. *Journal of Geology* 43(6): 639–643.

Paradise TR (2013a) Assessment of tafoni distribution and environmental factors on a sandstone djinn block above Petra, Jordan. *Applied Geography* 42: 176–185.

Paradise TR (2013b) Tafoni and other rock basins. In: Shroder JF (ed) *Treatise on Geomorphology*, Vol 4. San Diego, USA: Elsevier, 111–126.

Penck A (1894) *Morphologie der Erdoberflache*, translated by Englehorn John (ed). Verlag: Stuttgart, Germany.

Pestrong R (1988) Tafoni weathering of old structures along the northern California coast, USA. In: Marinos PG and Koukis GC (eds) *Engineering Geology of Ancient Works, Monuments, and Historical Sites*, Balkema: Rotterdam, 1049–1053.

Pope GA, Dorn RI and Dixon JC (1995) A new conceptual model for understanding geographical variations in weathering. *Annals of the Association of American Geographers* 85(1): 38–64.

Prebble MM (1967) Cavernous weathering in the Taylor dry valley, Victoria land, Antarctica. *Nature* 216: 1194–1195.

Pye K and Mottershead DN (1995) Honeycomb weathering of carboniferous sandstone in a sea wall at Weston-Super-Mare, UK. *Quarterly Journal of Engineering Geology* 28: 333–347.

Reid T (1850) Explanation of words. In: Walker D (ed.) *Essays on the Intellectual Powers of Man*. Cambridge, UK: Cambridge University Press, 1–9.

Reusch HH (1882) Notes sur la géologie de la Corse. *Bulletin de la Société Géologique de France* 11: 53–67.

Rhoads BL and Thorn CE (1996) *The Scientific Nature of Geomorphology*. Chichester: John Wiley & Sons.

Robinson DA and Williams RBG (1976) Aspects of the geomorphology of the sandstone cliff s of the Central Weald. *Proceedings of the Geologists Association* 87: 93–100.

Rodriguez-Navarro C (1998) Evidence of honeycomb weathering on Mars. *Geophysical Research Letters* 25(17): 3249–3252.

Rodriguez-Navarro C, Doehne E and Sebastian E (1999) Origins of honeycomb weathering: the role of salts and wind. *GSA Bulletin* 111(8): 1250–1255.

Sancho C and Benito G (1990) Factors controlling tafoni weathering in the Ebro Basin (NE Spain). *Zeitschrift fur Geomorphologie* 34: 165–177.

Selby MJ (1971) Salt weathering of landforms and an Antarctic example. In: *Proceedings of 6th New Zealand Geography Conference, Christchurch, New Zealand*, 30–35.

Siedel H (2010) Alveolar weathering of cretaceous building sandstones on monuments in Saxony, Germany. *Geological Society, London, Special Publications* 333(1): 11–23.

Simonds FW (1888) The Geology of Washington County, Arkansas. Annual Report for 1888. Arkansas Geological Survey: Little Rock, 72–82.

Smith B and Mark DM (2003) Do mountains exist? Towards an ontology of landforms. *Environment and Planning B: Planning and Design* 30(3): 411–427.

Smith BJ (1978) The origin and geomorphic implications of cliff foot recesses and tafoni on limestone hamadas in the northwest Sahara. *Zeitschrift fuer Geomorphologie* 22: 21–43.

Smith PJ (1982) Why honeycomb weathering? *Nature* 298: 121–122.

Sunamura T (1996) A physical model for the rate of coastal tafoni development. *The Journal of Geology* 104(6): 741–748.

Sunamura T. and Aoki H. (2011) Application of an S-shaped curve model to the temporal development of tafoni of salt-weathering origin. *Earth Surface Processes and Landforms* 36(12): 1624–1631.

Suzuki T and Hachinohe S (1995) Weathering rates in bedrock forming marine terraces in Boso peninsula, Japan. *Transactions, Japanese Geomorphological Union* 16: 93–113.

Trenhaile AS (1992) Chemical and salt weathering. In: *Geomorphology of Rock Coasts*. Oxford, UK: Oxford University Press, 31–58.

Tschang H (1974) Geomorphological observations on the tafoni forms of Hong Kong. *The Chung Chi Journal* 13(1): 32–54.

Turkington AV and Paradise TR (2005) Sandstone weathering: A century of research and innovation. *Geomorphology* 67(1): 229–253.

Turkington AV and Phillips JD (2004) Cavernous weathering, dynamical instability and self-organization. *Earth Surface Processes and Landforms* 29: 665–675.

Twidale CR and Sved G (1978) Minor granite landforms associated with the release of compressive stress. *Australian Geographical Studies* 16(2): 161–174.

Uña Álvarez E (2008) Description and nomenclature of the tafoni features (cavernous rock forms): Tesearch approaches in granite terrains. *Cadernos do Laboratorio Xeolóxico de Laxe: Revista de xeoloxía galega e do hercínico peninsular* 33: 65–82.

Viles HA and Goudie AS (2004) Biofilms and case hardening on sandstones from Al-Quwayra, Jordan. *Earth Surfaces Process and Landforms* 29: 1473–1485.

Wilhelmy H (1964) Cavernous rock surfaces (tafoni) in semiarid and arid climates *Pakistan Geographical Review* 19: 8–13.

Winkler EM (1979) Role of salts in development of granitic tafoni, South Australia. *Journal of Geology* 88: 119–120.

Young ARM (1987) Salt as an agent in the development of cavernous weathering. *Geology* 15(10): 962–966.

Young R and Young A (1992) *Sandstone Landforms*, 11. Springer Series in Physical Environment. Heidelberg: Springer Berlin.