CONTROLS OF TAFONI DEVELOPMENT IN CASTLE ROCKS, IDAHO

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INTRODUCTION

Tafoni (singular tafone) are concave erosional features that can be found in a variety of rock types and locations (Fig. 1). They have been documented in sandstone, granite, dolerite, limestone, rhyolite tuff, and metamorphosed conglomerate. They are abundant in locations spanning diverse climatic zones including the cold arid climate of Antarctica, the coastal island of Corsica, semi-arid regions of the Southwestern US, and even on Mars (Cooke et al., 1993).

Despite the widespread distribution of tafoni, trends have been noted in both the rock type and climate in which tafoni occur. Tafoni are most commonly found in crystalline and granular rocks (Conca and Rossman, 1985; Smith, 1978). Environments that host tafoni tend to possess a saline moisture (Martini, 1978). It is therefore likely that tafoni development is controlled by both rock type and salinity, but also a variety of other factors relating to rock composition, rock structure, and climate. The goal of many recent studies have been to determine the relative importance of these controls in tafoni formation.

This study focuses on the distribution of tafoni in the granite of the Almo pluton in Castle Rocks State Park, Idaho. Primary foci for the field study include the aspect of tafoni initiation, the slope of the underlying soil or rock, tafoni dimensions, and the proximity of tafoni to jointing and features associated with older and higher ground levels. Field observations are compared to environmental factors to determine which established models of tafoni development contribute to tafoni formation in the region.

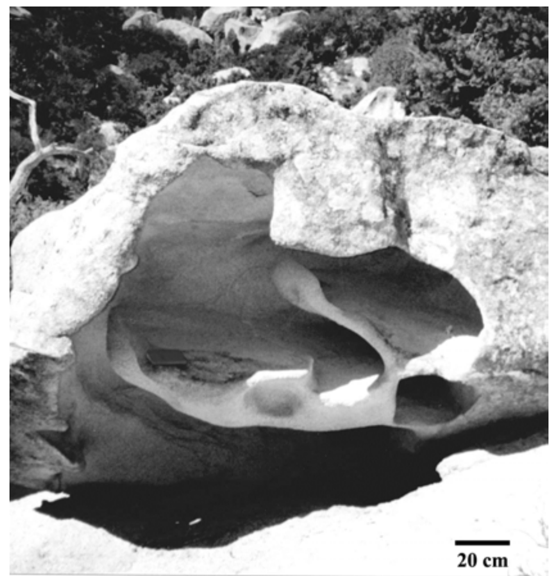


Figure 1: Tafone on the underside of a boulder in Castle Rocks State Park.

Models of formation

Tafoni initiate in zones of differential weathering on a rock surface (Dragovich, 1969). These zones include variations in lithology, structure, composition, texture, or biota (Dragovich, 1969). The degree of differential weathering across a surface can be further enhanced by differences in the environment that affect weathering rate (i.e. wind and water flow, exposure to insolation, proximity to a moisture-rich base level).

Generally, weathering will exploit these variations and once a site has been initiated the rock will degrade at a faster rate than adjacent unweathered regions, forming a tafone. The depths of the tafone interior weather at a faster rate than the walls, this has been attributed to 1) preexisting internal variations in the lithology of the host rock (Conca and Rossman, 1985; Schattner, 1961) and/or 2) variations in the microclimate (i.e. humidity and salinity) between the interior and exterior of the rock (Dragovich, 1969; Schattner, 1961; Smith, 1978).

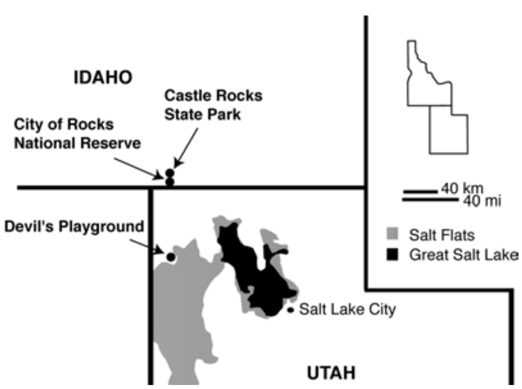
The first explanation is characterized by an exterior that is more lithified than the interior as a result of either case hardening or core softening; these processes are related to differential precipitation and dissolution of minerals in a solid rock (Conca and Rossman, 1985). Crystalline rocks like granite tend to core soften (Conca and Rossman, 1985). In core softened rocks, the softer interior weathers at a faster rate than the exterior.

In the second explanation, weathering is enhanced by wet-dry cycling: during wet periods water is retained in the protected interior of the cavern, during dry periods capillary water is drawn to the tafoni wall and evaporates in conjunction with interstitial salt crystallization (Martini, 1978; Rodriguez-Navarro et al., 1999). During both wet and dry periods the environment created in the deepest recesses of a tafone promotes weathering in a positive feedback cycle.

METHODS

Study area

The primary study area, Castle Rocks State Park, is located approximately 55 km northwest of the Great Salt Lake in a semi-arid climate (Fig. 2). The park is largely composed of coarse grained granite cut by orthogonal cooling joints and surface parallel exfoliation joints (Hereford, 2001; Levine, 2001). Pegmatite dikes and xenoliths are found throughout the pluton.



Large scale joint controlled granite landforms in the adjacent City of Rocks National Reserve can be 500 m long and 150 m tall (Levine, 2001). Castle Rocks exhibits a similar landscape of comparably sized fins, tors, spires, and domes. Rock surfaces in the area can be covered with red-stained case hardening or lichen. The area also contains abundant small scale weathering features including polygonally cracked case hardening, panholes, flared slopes, and, most important to this study, tafoni.

Devil's Playground was selected as a secondary study area due to similarities in geologic history and landforms. In contrast to Castle Rocks, Devil's Playground is located in northwestern Utah approximately 65 km south of Castle Rocks State Park and 10 km north of the Great Salt Lake desert. This region was chosen for proximity to the Great Salt Lake and increased abundance of tafoni.

Methods

For this study, I identified tafoni and quantitatively recorded the dimensions, orientation, and position of the cavity, the aspect of the opening, the elevation of the tafone and the GPS location. The joint spacing and the slope and composition of the underlying material were also noted. Elizabeth Clarke performed ion chromatography analysis on samples of grus from the tafone floor and wall to detect the presence of salts.

RESULTS

A typical tafone has a flat floor where weathered granite (grus) collects, a curved upper wall, and an overhanging visor that encloses and protects the interior. Measured tafoni have volumes ranging from 0.003 to 56.7 cubic meters. In general, widths range from 0.13 to 5.0 m (mean= 1.4 m), depths range from 0.1 m to 5.0 m (mean= 1.3 m), and heights range from 0.2 m to 2.8 m (mean=1.1 m).

As a result of differential weathering rates, the interior dimensions are larger than those of the opening; on average, the openings are 67% of the maximum dimension. The tafoni interior is significantly lighter in color, rougher in texture, and more easily disaggregated than the exterior rock. The interior walls are often quite friable due to the action of both flaking and granular disintegration. Based on the relative degree of surface disentegration, the back walls of the deepest recesses are often the most active sight of weathering indicating that tafoni tend to deepen rapidly as they expand. Tafoni can also develop laterally when two adjacent tafone coalesce. Vertical growth, however, is often limited by prominent horizontal jointing. Measurements of individual tafone dimensions shows a general deepening and widening with increased volume.

Tafoni were observed in both boulders and jointed bedrock. In boulders, tafoni are most prominently developed on the underside of overhangs, whereas in bedrock walls they were often abundant in zones with high structural or compositional irregularities (i.e. joints, xenoliths, pegmatite vugs). In general, tafoni tend to develop in close proximity to a subhorizontal surface; tafoni were not observed that were greater than 2.5 m above either a joint surface or the ground level.

Tafoni were observed in outcrops with a large range of joint spacing; individual tafone typically enlarge only to the spacing of the jointing. In bedrock, a joint can either limit the growth of a tafone or it can serve as the point of initiation of new tafoni. Tafoni distribution is highly variable. The direction of opening measured for 79 tafoni showed no directional relationship to aspect, nor is there a constant relationship between this aspect and the inclination of the underlying slope. Though lichen cover is often present, I observed no distinctive variations in lichen cover associated with tafoni.

At Castle Rocks, areas with high levels of cavernous weathering are more common within the main cluster of spires as opposed to the more isolated inselbergs. In some regions of abundant tafoni, I observed tafoni associated with pegmatitic vugs or xenoliths. Furthermore, there is a noticeable lack of tafoni in sheltered regions where the entire boulders are never exposed to direct sunlight or rainfall (i.e. below large rock slabs).

Measured climatic variations between the interior and the exterior environment are unpredictable. In measurements of temperature and dewpoint in 22 tafoni, there were instances of both increased and decreased temperature and dewpoint within a tafone with respect to the outer environment. However, on average, the interior dewpoint was 1.2 degrees higher than outside. Temperature variations were much less extreme and the average much closer to zero (mean = 0.1)

Ion chromatography of anions in grus from both the ceiling and the floor show significant concentrations of fluoride, nitrate, and sulfate (Table 1). There are significant variations in anion concentration between both 1) the ceiling and floor and 2) Castle Rocks and Devil's Playground. The concentration of chloride in grus collected from the ceiling is approximately double that found in the floor. In general, anion concentrations are much higher in Devil's Playground than in Castle Rocks.

Table 1. Ion Chromatography results for anion concentrations in grus (ppm).

	Devil's Playground			**Castle Rocks**		
	Ceiling	Coarse grained floor	Silt-size floor	Ceiling exterior	Ceiling interior	Floor
Fluoride	**5.96**	**3.85**	**1.49**	**0**	**0.31**	**1.31**
Chloride	**18954.35**	**4016.90**	**7041.02**	**4227.96**	**2122.58**	**40.46**
Nitrate	**52.53**	**415.29**	**510.89**	**664.83**	**5698.50**	**198.5**
Phosphate	**11.54**	**0.0**	**33.83**	**8.87**	**0.0**	**12.12**
Sulfate	**1953.10**	**150.52**	**3250.20**	**723.26**	**909.67**	**92.32**

DISCUSSION

Tafoni initiation is determined by a unique combination of structural or compositional and environmental anisotropy. The tafoni have no general preferred orientation, so neither insolation, wind, nor rain are dominant tafoni weathering processes in Castle Rocks. However, tafoni initiation was observed in direct association with variations in the rock. Jointing, drip zones, pegmatites, xenoliths, and breached case hardening were all observed in association with tafoni. These features are therefore likely to promote tafoni initiation, therefore composition, texture, and structure of the rock are all important factors controlling tafoni initiation.

According to Dragovich (1969) the differential weathering can be further enhanced by environmental factors like moisture, temperature, or salts. However, if compositional or structural anisotropies are not present in the rock, less localized weathering features such as flared slopes will result (Dragovich, 1969). Tafoni initiation in the study area appear to be closely related to the proximity of moisture rich base levels (i.e. jointing or soil horizon) or protection from direct insolation, precipitation and evaporation. Ultimately, tafoni initiation is caused by a combination of environmental and structural controls; each tafone is the result of a unique combination of these factors that locally accelerates the weathering of the granite.

In contrast, tafoni development seems to be controlled dominantly by environmental variations. There is no evidence to either support or discount Conca's (1985) hypothesis that in granite, core softening controls the development of a tafone. However, data does indicate that the microclimate created within the tafoni plays a significant role in the caverning process. Tafoni are only present in unsheltered locations; Martini (1978) argues that sunlight is necessary to create a distinctive microclimate within a tafone. Data shows higher moisture within tafoni and higher salt concentrations in tafoni walls than floors.

The presence of increased concentrations of water and salts accelerates weathering rates inside of the tafoni relative to the exterior environment. Past studies have shown that the back wall of a tafoni weathers at the fastest rate in both wet and dry conditions. In a semi-arid climate, humidity is greatest in the deepest recesses of a tafone; this increased humidity will cause mineral hydration. During dry periods, evaporation is dominant and saline soil water drawn through the capillaries of a rock will evaporate upon exposure; this water is first exposed in the inner-most portion of a rock, or the deepest point of a tafone (Rodriguez-Navarro et al., 1999). As a result of the crystallization in the walls salt concentrations are highest in the interior recesses of the tafoni. The tafone wall disentegrates as a result of both salt crystallization and mineral hydration.

CONCLUSIONS

Tafoni develop in response to a variety of internal and external variations in climate, composition, and structure. At Castle Rocks, tafoni initiate at differentially weathered structural or compositional anisotropies. Initiation is encouraged in moisure rich regions with accelerated weathering. Tafoni enlarge due to presence of increased levels of moisture and salts in their sheltered interiors.

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