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Jerry E. Mueller and C. R. Twidale

New Mexico Geology, v. 10, n. 4 pp. 73-79, Print ISSN: 0196-948X, Online ISSN: 2837-6420.
https://doi.org/10.58799/NMG-v10n4.73

New Mexico Bureau of Geology & Mineral Resources
New Mexico Institute of Mining & Technology
801 Leroy Place
Socorro, NM 87801-4796

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New Mexico GEOLOGY
• Science and Service
Volume 10, No. 4, November 1988

Geomorphic development of City of Rocks, Grant County, New Mexico

by *J.E. Mueller*, New Mexico State University, Las Cruces, New Mexico, and *C.R. Twidale*, University of Adelaide, Adelaide, South Australia

Introduction

City of Rocks is one of several intricately sculptured groups of volcanic rock outcrops in southern New Mexico. Located 2.6 km (1.6 mi) north of NM–61 and 4.3 km (2.7 mi) NNE of Faywood Hot Springs in southeastern Grant County (Fig. 1), City of Rocks has been developed as a State Park and tourist attraction. The rock complex has an average elevation of 1,600 m (5,250 ft) and occupies approximately 20 hectares (49 acres) of the 259–hectare (640–acre) State Park. The main assemblage of rocks is roughly hourglass in plan shape (Fig. 2) with an 800–m (2,600 ft) major axis trending NNE–SSW and a minor axis 240 m (790 ft) long aligned ESE–WNW. The City of Rocks complex consists of a group of pinnacles and boulders arranged in an orderly fashion on the crest of a low hill (Fig. 3). The evolution of these major forms and their associated minor features is discussed in this paper.

The lower sidewalls of the pinnacles are concave or flared, so much so that from a ground perspective these flared slopes constitute a dominant landscape feature (Fig. 4). Flared slopes occur also in other parts of the world in several different lithologic and climatic environments, though they are best and most widely developed in granitic rocks in southern Australia. It has been demonstrated there (Twidale, 1962, 1982) that the flares are of subsurface origin (etch form); they are, in fact, exposed sectors of former weathering fronts (Mabbutt, 1961). This paper suggests that many of the geomorphic forms developed at City of Rocks may be interpretated in similar terms: they are not a direct product of subaerial agencies, but rather have their origin in subsurface processes.

Geological background

City of Rocks is overlooked from the northeast by Table Mountain, a mesa underlain by flat-lying rhyolitic tuffs mapped as the Sugarlump Rhyolite by Elston (1957). Table Mountain is capped at an average elevation of 1750 m (5,750 ft) by a higher Sugarlump ash-flow-tuff unit whereas the City of Rocks complex is sculpted in the lowermost ash-flow-tuff unit of the Sugarlump. Until recently, there was no reliable radiometric date on the tuff exposed in the Rocks, though Clemons (1982) reported an age of 36.9 Ma for an ash-flow-tuff unit exposed in a road cut 5.5 km (3.4 mi) east of the Rocks that has also been mapped as lowermost Sugarlump. Now, paleomagnetic studies and ^{40}Ar/^{39}Ar dating by McIntosh (personal communication 1987) reveal an age of 35.12 Ma for City of Rocks and 33.32 Ma for the tuff unit at the top of Table Mountain. The tuff is clearly of Oligocene age. It consists of 20–25% phenocrysts of quartz, sanidine, plagioclase, biotite and hornblende in a devitrified matrix. Chemically, it contains approximately 74% silica, 14% alumina, and minor quantities of iron oxide, potash, and soda (Table 1).

The ignimbrite sheet in which City of Rocks is developed is more or less horizontal, with a few minor undulations and local dips. The same sheet extends to the southeast corner of the park where an outcrop of the tuff at the same elevation as City of Rocks displays similarly weathered rock forms.

An orthogonal fracture set subdivides the bedrock into columns and blocks. Discrete horizontal to subhorizontal fractures that are

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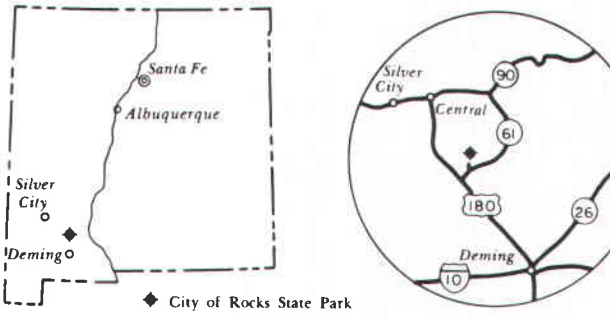

FIGURE 1—Location map (after Weber, 1980).

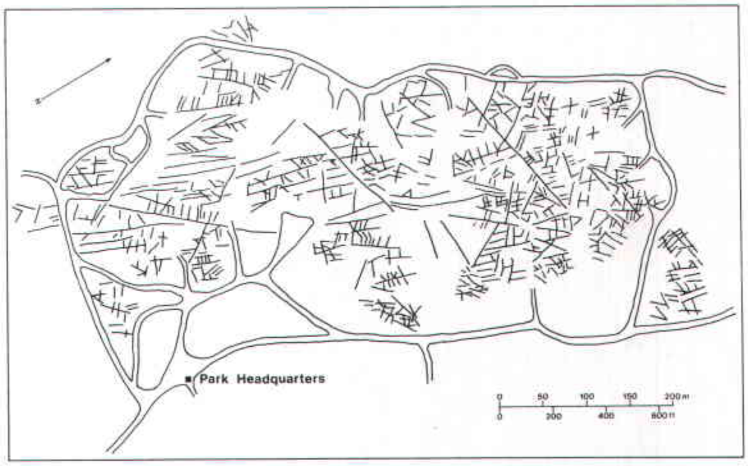

FIGURE 2—Plan of City of Rocks. Roads and vertical fracture pattern compiled from New Mexico Highway Department air photo taken March 15, 1968 at scale 1:10,600.

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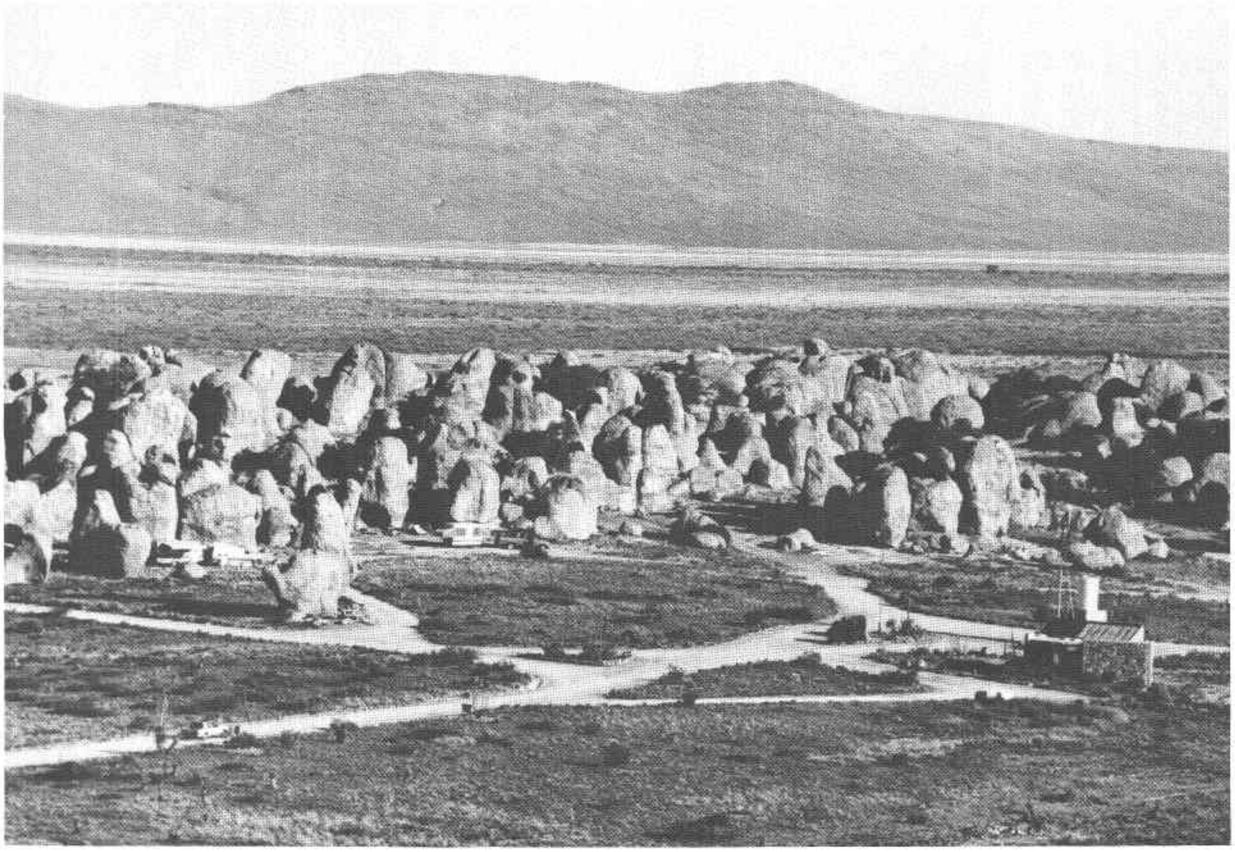

FIGURE 3—A portion of City of Rocks as seen from park observation point. Vehicles provide scale.

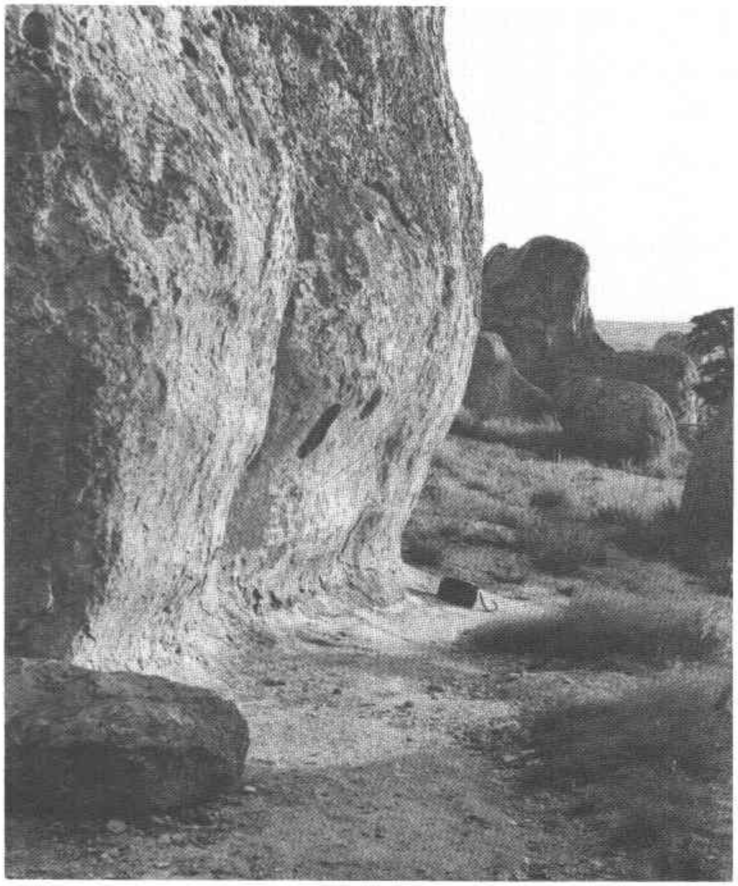

FIGURE 4—Large, bulbous-shaped pinnacle with flared sidewall. Note color contrast between upper and lower surfaces. Camera bag for scale.

New Mexico
GEOLOGY

• **Science and Service**
Volume 10, No. 4, November 1988
Editor: Carol A. Hjellming
Drafting assistance: Michael Wooldridge
Published quarterly by
New Mexico Bureau of Mines and Mineral Resources
a division of New Mexico Institute of Mining & Technology

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Circulation: 1,600

Printer: University of New Mexico Printing Plant

TABLE 1—Chemical analysis of Sugarlump ash-flow tuff at City of Rocks State Park; analysis by Michael O. McCurry, New Mexico State University.

Element	Weight (%)	Precision (±)
SiO_2	73.6	0.7
TiO_2	0.28	0.01
Al_2O_3	14.1	0.1
Fe_2O_3	1.89	0.02
MnO	0.03	0.002
MgO	0.32	0.01
CaO	1.34	0.01
Na_2O	3.8	0.05
K_2O	4.8	0.05

FIGURE 5—Pinnacle with discrete horizontal fracture. Camera bag to left of fracture provides scale.

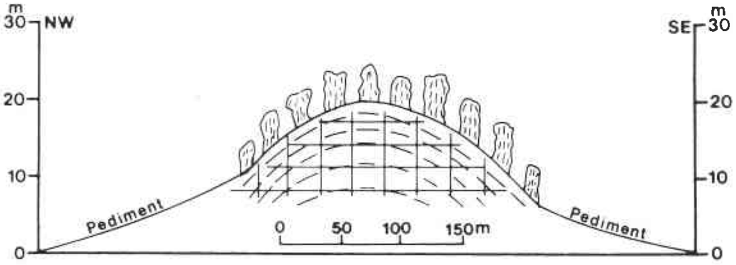

FIGURE 6—Diagrammatic section through City of Rocks. Vertical exaggeration is 6.2 times.

either related to sheeting fractures or are flat-lying members of the orthogonal set can be seen within many, though not all, pinnacles (Fig. 5). The orothogonal set also consists of vertical or nearly vertical fractures that subdivide the ignimbrite into rhomboidal, quadrangular, or triangular blocks. The major vertical fractures trend NNE–SSW, ENE–WSW and NW–SE (Fig. 2).

The origin and age of the fractures is unknown. Some fractures might be cooling cracks associated with thermal contraction of the ignimbrite sheet. Others could be associated with release of the gravitational load as overlying upper and middle units of the Sugarlump, as well as younger volcanics, were denuded. Another possibility is that certain fractures developed in response to reduction of lateral support in the rock complex that resulted from downcutting by adjacent drainage lines. That the fractures may have more than one origin might account for the fact that two adjacent vertical fractures, in some cases no more than a meter or so apart, have conspicuously different weathering and erosional histories: one is deeply and widely exploited by weathering and erosion; the other appears relatively fresh and closed, with no apparent influence on the morphology of the host rock. The fractures probably are not related to the release of compressive stress because City of Rocks is located in an area characterized by extensional tectonics. Nevertheless, these fractures certainly play a dominant role in the development of the morphology of the pinnacles and platforms.

Landforms

Between the main rock complex and the southeast corner of the park is a broad lowland occupied by an unnamed arroyo system. This system, along with another unnamed arroyo system to the northwest of City of Rocks, runs subparallel to the major axis of the rock complex and provides a local base level to which the extensive pediments of the park are graded (Fig. 6). Although the geomorphic surfaces within the park are not yet mapped in detail, it seems probable that periodic entrenchment of the arroyos and their tributaries may be responsible for the episodic stripping of the regolith and exposure of former weathering fronts within the rock complex.

Two major types of rock platform are recognized within the park. True rock pediments, with a thin veneer of gravel and an average slope of 3°, extend outwardly from the base of the main rock complex to adjacent arroyo systems. These pediments may have their origin in primarily surficial processes, or they might represent exposed sectors of a gently inclined weathering front (Twidale, 1981). Whatever their origin, the pediments on their upper margins give way rather abruptly to steeply sided (5°–10°) rock platforms within the rock complex. These upper rock platforms, unlike the pediments, may have a structural origin, because, in places, they appear to be developed along convex-upward sheeting fractures in the tuff. This interpretation is supported by the fact that the plane of the inclined platform, in some instances, continues as a basal fracture through the large rock columns. In addition, steep rock platforms associated with sheeting fractures are clearly evident at nearby Giant of the Mimbres, an area of isolated, tall rock columns also developed in the lowermost unit of the Sugarlump ash-flow tuff.

Major vertical fractures have been weathered, eroded, and thus enlarged to produce clefts or slots as large as 5 m (16 ft) wide. The long continuous rock corridors are the "streets" of the City referred to by Weber (1980). These corridors are best developed near the southeast and southwest margins of the rock complex. A few of the widest corridors are the result of complete evacuation of regolith between, as well as along, two adjacent and parallel fractures. In places, all that remains between adjacent fractures is a low rock mound or "traffic island" located just before a "street intersection." Some of the shorter corridors also link with others at an obtuse angle to form throughways. Others, however, terminate or "deadend" against rock walls.

Weathering and widening of fracture zones has caused the fracture-defined blocks to be reduced in area and to become rounded to a greater or lesser degree. The lower sidewalls of the rocks are markedly flared. In some instances there is a single flared zone, but commonly two or three such elongated and subhorizontal concavities can be distinguished on the sidewalls (Fig. 7). This marked basal weathering has produced pinnacles that are bulbous. Where maximum weathering occurs on midslope, the rocks resemble a dog bone or a dumbbell.

The upper surface and sidewalls of the rocks are dark gray, but the lower zones of flare development are cream colored with irregular patches of reddish brown. Although all the rock surfaces are scaly and rough, the lower flared zones are especially so, and many of the scales exposed in the basal areas are truncated. Finally, though small hollows ranging in diameter and depth between 1 and 25 cm are developed on the upper sidewalls, at several sites hollows are developed in zones coincident with the upper part of the basal concavity (Fig. 8).

Some of the vertical rock columns are cut by horizontal fractures that have been exploited by weathering to produce boulders resting on pedestals. The pinnacles and pedestals merge basally with gently sloping rock platforms that are narrow within the clefts (Fig. 7), but which are commonly several meters across where all remnants of the upper sheet structure have been eliminated (Fig. 9). The traces of vertical fracture sets are clearly visible in these platforms. Some have been deeply eroded to produce narrow gorge-like slots (Fig. 10). Remnants of the soil cover occur both within the clefts and on the broader platforms, though the soil is in the process of being stripped.

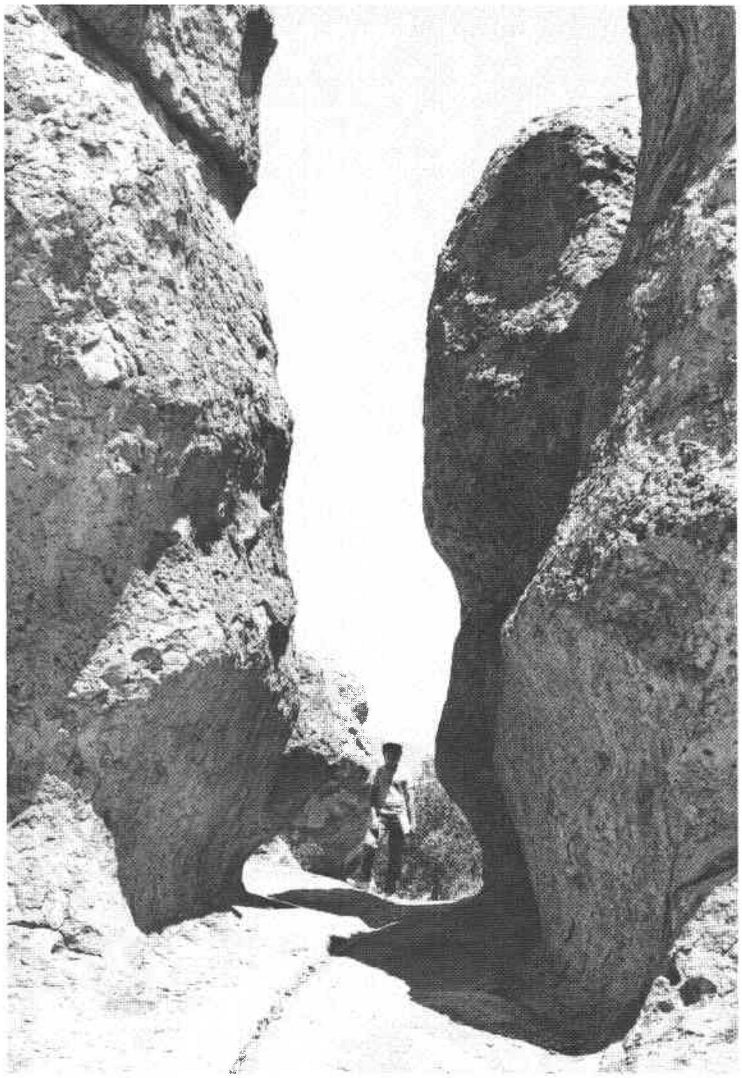

FIGURE 7—Cleft with flares on sidewalls and fracture trace in bedrock floor.

FIGURE 8—Markedly flared lower slopes and associated tafoni or rock hollows aligned along major fracture.

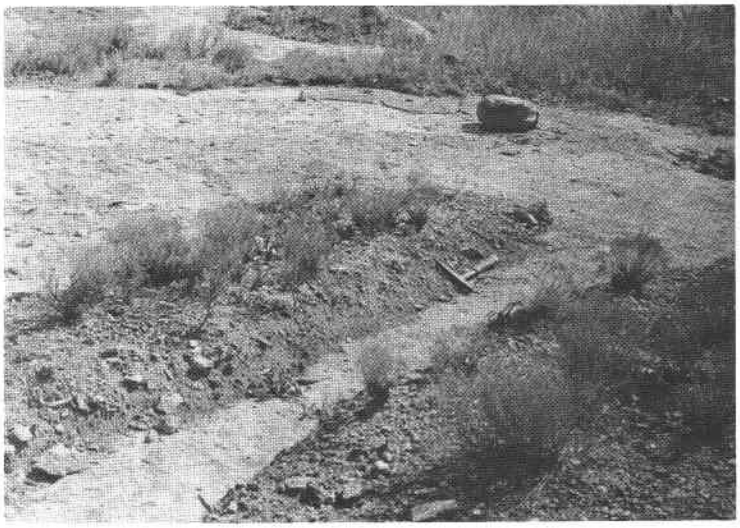

FIGURE 9—Rock platform partially covered with thin regolith. Hammer provides scale.

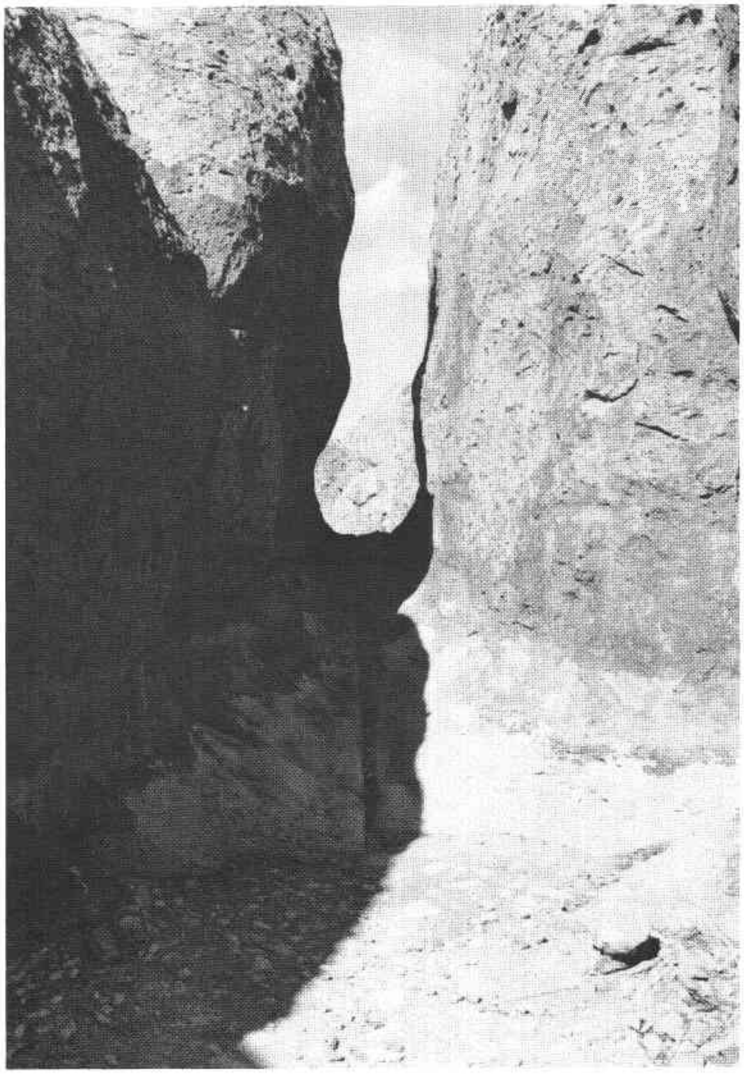

FIGURE 10—Deep, narrow cleft developed on vertical fracture. Hammer faintly visible on left sidewall.

Rock basins are found on the broader platforms, on pedestals, and also on the crests of several pinnacles. Many basins are the flat-floored "pan" variety (Fig. 11a) in the terminology of Wentworth (1944), but some, located within pans, are conical or hemispherical in shape ("pits"). Of the latter, fifteen are bedrock mortars (Indian grinding pits) located within 45 m (150 ft) of a rock shelter on the west side of the Rocks (Fig. 11b). The shelter formed when a large pinnacle toppled upslope and against two adjacent upright pinnacles. Three of the bedrock mortars, which probably date back at least to the Mogollon culture (pre-1400 A.D.) (S. Upham, personal communication 1987), retain their smoothly ground upper sidewalls. In others, however, deeply etched and roughened sidewalls indicate weathering by standing water.

Interpretation and conclusions

The development of flared slopes on the lower sidewalls of pinnacles strongly suggests that those zones were weathered by moisture beneath the land surface. Many lines of evidence and argument have been noted to demonstrate that flared slopes are a particular form of the weathering front developed in the piedmont zone of inselbergs, around the bases of boulders, and in fracture-controlled clefts (Twidale, 1962, 1982). The crucial evidence, however, is revealed in artificial excavations in which markedly concave weathering fronts are exposed at the base of the regolith. Perhaps the best-known site of this type occurs at Yarwondutta Rock, (Fig. 12a), near Minnipa, on northwestern Eyre Peninsula, South Australia, but others are known, and additional examples come to light from time to time (Fig. 12b). In a general way the upper extremity of the concavity marks the former hill–plain junction, the former upper limit of the regolith, the former stand of the land surface (Fig. 13).

Fracture-controlled clefts are especially prone to weathering and to the development of flared forms because run-off is concentrated there. Also, the fracture(s) allow infiltration of waters charged with chemicals and biota that react with the minerals of the bedrock. Once weathered, the permeability of the bedrock increases dramatically. The presence of water and altered rock allows colonization by plants that on decay supply humic acids that effect further chemical weathering. Thus, reinforcement effects come into play. The dry, exposed upper wall remains stable, but the sidewalls of clefts in contact with soil moisture may become markedly undercut and flared.

Each flare records a period of relative standstill during which subsurface weathering took place, followed by the stripping of the weathered mantle and exposure of the concave weathering front.

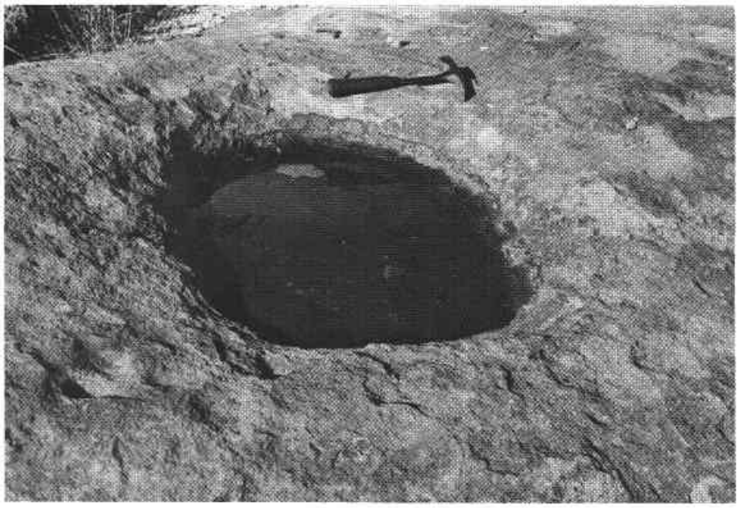

FIGURE 11—a. Solution pan developed in rock platform. Pan is 91 cm long, 66 cm wide, 10 cm deep.

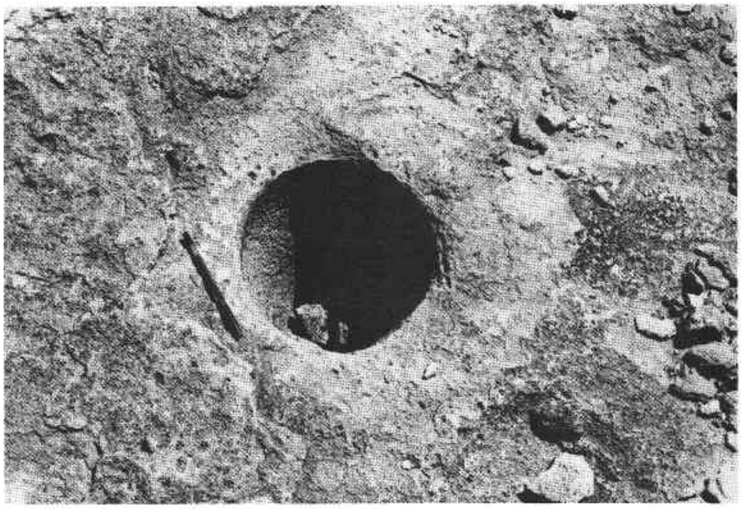

FIGURE 11—b. Indian bedrock mortar developed in rock platform. Pit is 25 cm wide, 31 cm deep.

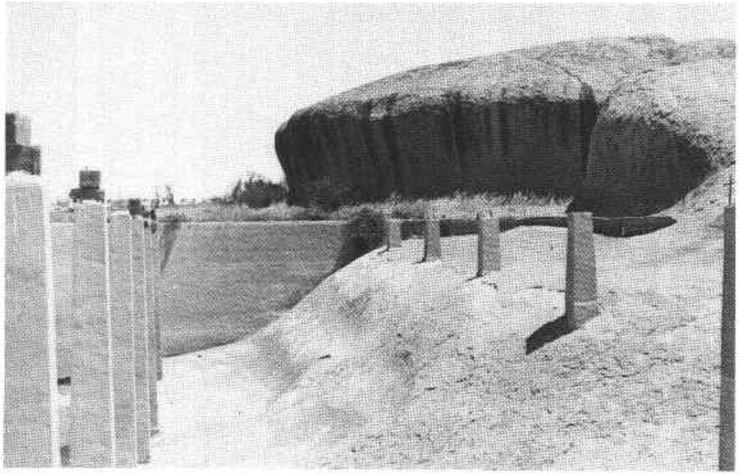

FIGURE 12—a. Yarwondutta Reservoir, near Minnipa, Eyre Peninsula, South Australia showing flared basal slope of inselberg and weathering front exposed in excavation. The row of posts to the right marks the upper limit of the former soil cover. Between the rows of posts and within 2 m of the former land surface is a freshly exposed, concave weathering front.

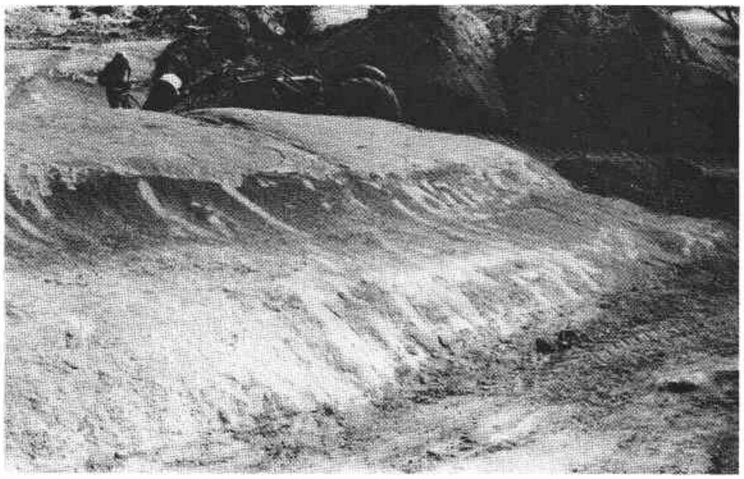

FIGURE 12—b. Small flare exposed in 1987 at Calca Quarry, west coast of Eyre Peninsula, South Australia.

The occurrence of multiple flares implies several alternations of weathering and erosion (Fig. 14). Such subsurface moisture attack could account for the contrasted characteristics of lower and upper sidewalls. Upper sidewalls have a distinctive gray color that develops from the accumulation of algae, lichens, and dark-colored oxides. The cream to reddish-brown color of the exposed weathering front, on the other hand, is due to bleaching of the feldspars and accumulation of iron oxides. The greater degree of roughness at the weathering front results from differential weathering of the rock at crystal scale to produce a pitted surface (Twidale and Bourne, 1976). The truncation of scales, which is probably related to proximity to the weathering front (Hutton et al., 1977; Twidale, 1986), is the result of especially intense attack by soil moisture.

The development of hollows or tafoni also is comprehensible in these terms, for here, as elsewhere, they are initiated in a zone of intense weathering just below the ground surface (Twidale, 1982). They are undoubtedly developed on weak zones or "softer spots" (Weber, 1980), the nature of which cannot be ascertained because the evidence has been evacuated. Like the flares, the associated tafoni have been developed primarily by subsurface moisture attack, though once exposed, the forms continue to evolve. At City of Rocks the coincidence of tafoni with the sloping zones of concavity provides especially persuasive evidence that tafoni are initiated at the weathering front (Twidale and Bourne, 1975; Twidale, 1978a, 1982).

The platforms, large and small, are also of etch type, as suggested by their continuity with flares, and by the fact that they are manifestly being exposed as the regolith is stripped (Twidale 1978b). Moreover, their surfaces are rough, scaly or platy, and stained with the same reddish-brown patina that characterizes the basal flares of the pinnacles. The upper limit of the stain on the pinnacles can be used to reconstruct the former land surface that once extended across the now-exposed platforms. Also of probable etch origin are the numerous rock basins located on top of rock platforms. These basins develop where points of weakness are exploited along the weathering front. Once exposed, the basins hold both detritus and water and continue to evolve (Twidale and Corbin, 1963; Twidale and Bourne, 1975). Thus, the lower flared sidewalls of pinnacles and the development of platforms can reasonably be interpreted in terms of subsurface moisture attack guided by and concentrated in the vertical fractures that subdivide the rock mass. The rounded crests of the pinnacles, however, can as readily be explained in terms of subaerial weathering. Assuming that the fracture-defined blocks were originally angular, the corners and edges of such blocks are, as many writers from MacCulloch (1814) onwards have pointed out, more rapidly attacked than the plane faces, so that blocks are eventually converted to boulders: nature *mutat quadrata rotundis*.

Two features suggest that the upper zones of the clefts, like the lower, have been exploited by water percolating along fractures and that they are the result of subsurface moisture attack. First, the general configuration of the complex of pinnacles is suggestive of a former thick sheet of ash-flow tuff that has been broken into its constituent blocks. That the City of Rocks complex is preserved on the crest of a hill can be explained by the disintegration of rock downslope by the increased volume of waters that run and infiltrate there. Similarly, platforms within the complex presumably reflect weak zones of, perhaps, greater fracture density. If surface runoff alone were responsible for the preferential lowering of the lower slopes, this would surely have produced alternating valleys and divides. Subsurface flow and weathering, however, could produce destruction of the entire mass.

Second, many pinnacles have deep pits or basins on their crests (Fig. 15). It is unlikely that such forms would develop initially at such sites, for water would tend to run off the crests of convex rocks. On the other hand, rock domes are noted for the development of basins and gutters (*Rillen*), and the City of Rocks' forms can be interpreted as basins formed on a topographic dome, possibly under a weathered mantle, and now fortuitously preserved on especially large and resistant blocks or pinnacles. Similar remnant blocks with gutters and a basin are found near Mannum in South Australia (Centeno and Twidale, 1988). If this interpretation is correct, two major phases of weathering and erosion are implied (Fig. 14). During the first, the upper sectors of clefts were formed and exposed. The second phase involved one, two, or possibly three minor alternations of subsurface weathering and erosion during which one, two, or three basal concavities were developed, exposed, and preserved.

The latest and continuing phase of soil erosion and exposure of the weathering front probably relates to recent entrenchment of the two nearby arroyos that serve as a base level for the numerous, though generally poorly defined, drainage lines that encroach upon the Rocks from the southeast and northwest. Because the stripping of the regolith is so nearly complete, even at the highest levels of the rock platforms along the major drainage divide, a long period of erosion is implied. Corroborative evidence for a long interval of erosion is provided by the bedrock mortars that apparently have a minimum age of 600 years. Therefore, the impact of settlement of the region in the last century and the use and abuse of the Rocks by tourists and vehicles may have accelerated the rate of stripping of the regolith, but certainly did not initiate it.

The major and minor landforms so beautifully developed and displayed at City of Rocks originated not at the surface after the exposure of the tuff, but in the shallow subsurface as a result of structurally controlled moisture attack.

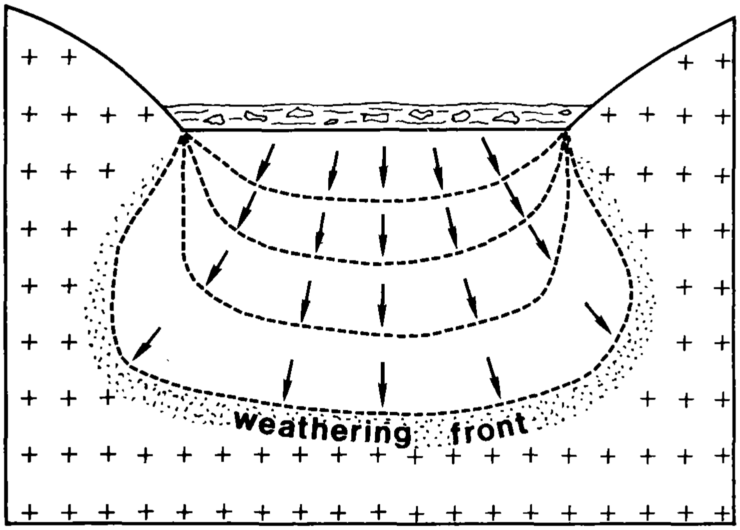

FIGURE 13—Progressive lowering of the weathering front and the development of flared sidewalls.

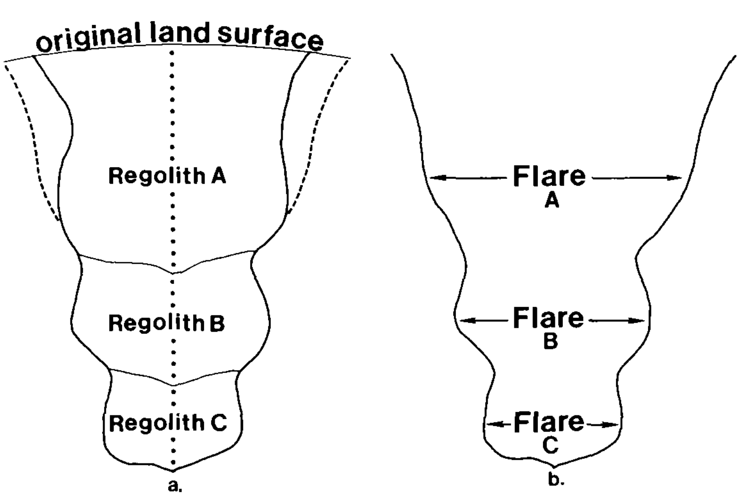

FIGURE 14—Episodic development of regolith and flared slopes along a deeply weathered vertical fracture (dotted line).

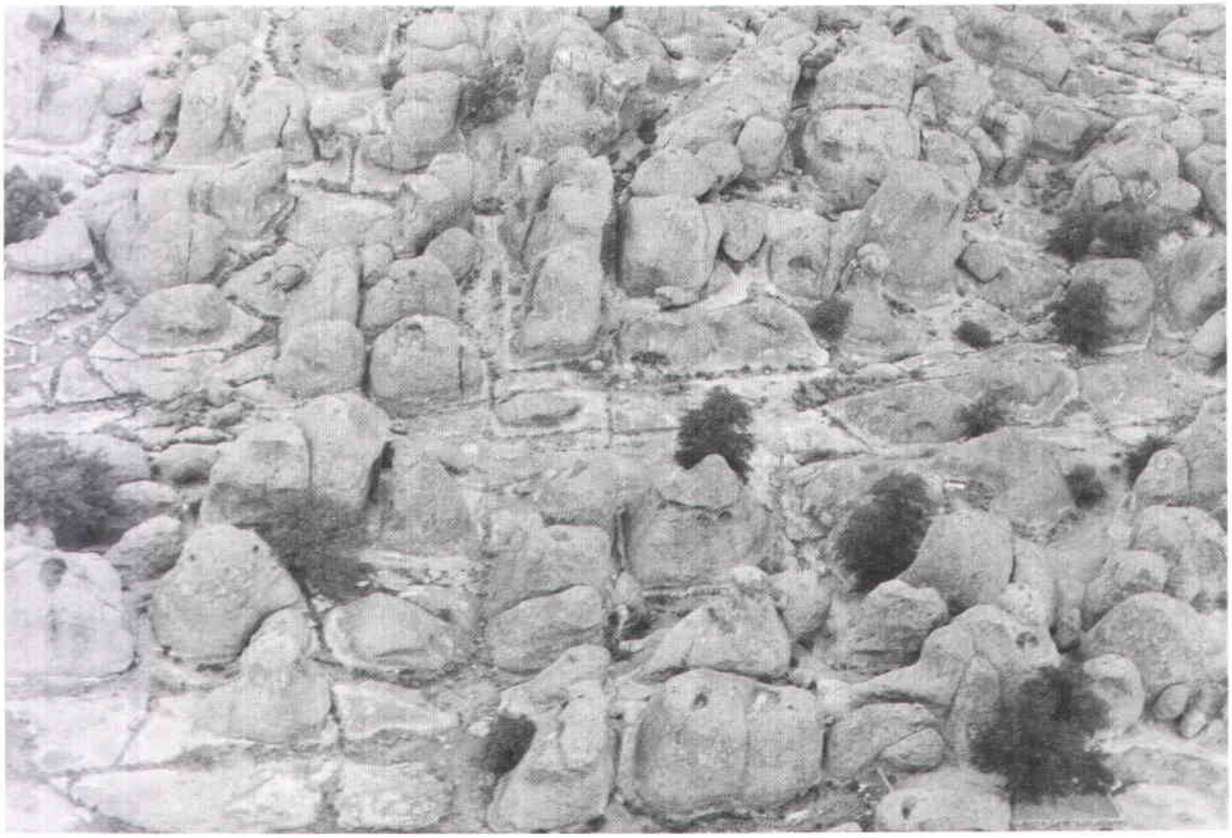

FIGURE 15—Oblique air view of rock complex with basins developed on top of several pinnacles in foreground. The vertical fractures and their expression as clefts and corridors are apparent.

ACKNOWLEDGMENTS—The authors appreciate the helpful reviews of Russ Clemons, Rick Giardino, Dave Love, Mike McCurry, and Bob Weber. Russ Clemons and Mike McCurry visited the field area and helped with the geological interpretation. Wayland Mueller served as field assistant and offered many helpful insights to the identification and interpretation of the forms discussed in this paper. Rowena Gilstrap typed the manuscript. Research support for Dr. Mueller was provided by Minigrant 1–3–43848 of the College of Arts and Sciences at New Mexico State University.

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