Giant Sandstone Weathering Pits Near Cookie Jar Butte, Southeastern Utah

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Abstract. In arid southeastern Utah, giant weathering pits in the lower member of the Entrada Sandstone of the Middle Jurassic age are striking features of the landscape near Cookie Jar Butte in Glen Canyon. The pits are larger than most of those described in the geologic literature (as wide as 38 m and as deep as 16.5 m). Four pit types identified on the basis of cross-sectional form are cylinders (the most abundant type), bowls, armchairs, and pans. Sandy sediment commonly veneers the bedrock floor of all pit types. The sediment is similar in character to the adjacent sandstone and is probably locally derived. Many of the deeper pits retain water from months to years, and water temperature and pH values vary considerably by season. Vegetation in pits that are not periodically inundated with water differs by type and amount; pits with the thickest sediment tend to have the densest cover. Laboratory analyses of sandstone from pit walls, floors, and rims reveal a fine-grained ($\bar{x}$ diameter about 90–100 μ) arkosic sandstone that is weakly cemented with $CaCO_3$ (2.7–9.1% by weight) and lesser amounts of clay. Thin-section analyses of the sandstone cores reveal quartz, plagioclase, and potassium feldspars that are relatively unweathered, and examination using a scanning electron microscope indicates that most grains are coated with variable thicknesses (0–5 μ) of clays and iron oxides—interstitial clays constitute 1–6% of the total sample. Physical weathering such as spalling, salt crystal growth, and clay mineral hydration and dissolution of carbonate cement weaken the sandstone. The sediment produced by these processes is probably removed by wind, plunge-pool action, and perhaps dissolution and piping. The cause of the removal of pit sediment is unknown.

Key words: Entrada Sandstone, Glen Canyon National Recreation Area, pothole, tinaja, water pocket.

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Weathering pits are typically broad, shallow depressions formed on flat to gently-sloping outcrops of bare rock. They are commonly flat-floored, as wide as a few meters, and a few tens of centimeters deep. Theories on their origin usually propose a combination of physical, chemical, and biological weathering processes that promote mineral decomposition and the action of wind or water that removes the decomposed material. Little is known about the age of weathering pits.

Weathering pits have attracted special attention in arid regions, where they have been watering holes for people and animals for millennia. This accounts for many of the local names given to them, such as cisterns, tanks, caldrons, huecos, dew holes, potholes, water pockets, and tinajas. Pits develop on diverse lithologies; intermittent ponds have been reported on quartzite ridges in North Carolina (Reed et al. 1963), in limestone in Texas (Udden 1925), in arkose at Ayers Rock in Australia (Twidale 1982), and unusually deep (8 m) pits in granite–gneiss in Brazil (Twidale 1968). Weathering pits are nearly ubiquitous on gently-sloping outcrops of weathered granite and sandstone. Weathering pits are so abundant on friable sandstones of the Colorado Plateau that they locally create a distinctive dome-and-pit landscape.

Previous investigators focused on pits with high width-to-depth ratios and on processes that weather rock rather than those that remove the weathered material. The limited quantitative data on pit morphology indicate that pits are typically circular to elliptical in plan view, flat-floored, have widths of 0.5 to 3.0 or 4.0 m, depths of 5 to 60 cm, and average width-to-depth ratios of 6:1 to 10:1 (Udden 1925; Twidale 1982; Ollier 1984; Alexandrowicz 1989). Angeby (1951) and Jennings (1967) reported much deeper holes, but the origin of these depressions seems related to plunge-pool action at the base of waterfalls and to collapse into subterranean voids and not solely to weathering. Weathering processes proposed for pit development emphasize the role of water, which, partly because of reduced rates of evaporation, probably remains for progressively longer periods as the pit deepens. Reference is made to some combination of physical, chemical, and biochemical activity that accounts for weathering of pit walls and floors (Udden 1925; Matthes 1930; LeGrande 1952; Reed et al. 1963; Jennings 1967; Roberts 1968; Twidale and Bourne 1975; Godfrey 1980; Jennings 1983; Goudie 1986; Young 1987a; Howard and Kochel 1988; Alexandrowicz 1989). Authors do not agree, however, on the role and relative importance of specific weathering processes—salt crystal growth, spalling, hydration and desiccation, solution, hydrolysis, attack by organic acids, frost weathering, and colloidal plucking in pit initiation and growth. Although the existence of salts and calcite is frequently cited as evidence of crystal wedging (Bradley et al. 1978; Laity and Malin 1985), it is difficult to demonstrate that these minerals are the direct cause of grain dislodgement (Young and Young 1992). Howard and Kochel (1988) and others stated that solutions of calcite cement locally created karstic landforms on barren, smooth outcrops of friable sandstone (i.e., slickrock) slopes in the Glen Canyon region, but they provided little evidence to support their statement. Goudie (1991) summarized the most recent literature on pan development and supports the idea that the initial depressions are largely the result of solution. He also concludes that aridity contributes to pan development by limiting vegetation cover (permitting deflation), and by localizing salts (promoting rock disintegration).

Several mechanisms have been proposed to account for the removal of weathered sediment from pits (Barnes 1978). Wind deflation is thought by some to be effective, although Twidale (1982) de-emphasized its importance. Where pits are in or near intermittent water courses, fluvial action may abrade bedrock and remove sediment. In deeper pits, especially those that are not integrated into water courses, subsurface removal by dissolution or piping has been proposed, particularly for pits that are obviously connected to underground conduits (Twidale 1990). Extensive underground tubes and cavities in quartz sandstones have been reported in Venezuela and Australia (Jennings 1983; Young 1987b).

Some of the most conspicuous gaps in the literature concern the age and rate of development of weathering pits. Matthes (1930) noted that weathering pits in the Sierra Nevada are present on older glaciated surfaces but are absent on recently (less than 10,000 years?) glaciated surfaces. In the Colorado Front Range, incipient pits have developed on boulders in glacial deposits of Holocene age (Birkeland 1984; Birkeland et al. 1987). The Mistor Pan in Dartmoor, England, is a large, well known pit that was first described in 1291; its depth did not significantly change between 1828 and 1929 (Twidale 1982). The rate of pit growth may be highly variable, depending on factors such as climate, lithology, and rate of sediment removal.

Clusters of giant sandstone weathering pits are known at three sites in southeastern Utah; two are in the lower part of Glen Canyon, which is partially inundated by Lake Powell (Fig. 1). The pits near Cookie Jar Butte and Rock Creek Bay are formed in outcrops of the lower member of the Entrada Sandstone of Middle Jurassic age.

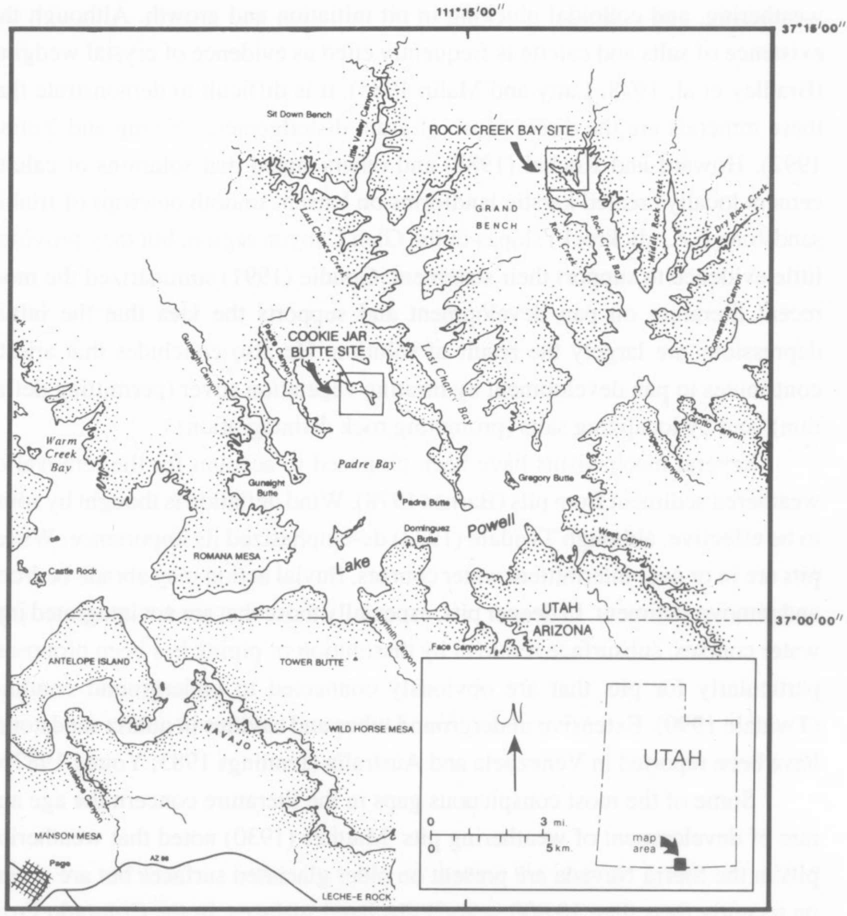

Fig. 1. Map of the giant weathering pits near Cookie Jar Butte and Rock Creek Bay, Utah.

Field and laboratory analyses of the pits near Cookie Jar Butte were done in 1992 and 1993. Measurements indicate that these pits are much deeper than typical weathering pits; they may be among the deepest in sandstone on earth (Netoff and Shroba 1993). They are of considerable geomorphological interest because of their immense size and because their origin is difficult to explain by conventional theories.

The major objectives of this report are to describe the geologic occurrence, dimensions, and geometry of the weathering pits at Cookie Jar Butte and to evaluate several hypotheses that might account for their origin.

Study Area

Cookie Jar Butte is on the north side of Padre Bay (Fig. 1; Sec. 7, T. 45 S., R. 6 E. of the Gunsight Butte 7.5-minute quadrangle, Utah) in an approximately 30-ha area of pitted terrain on gently to moderately-sloping surfaces. Clusters of giant weathering pits in the Entrada Sandstone also exist at two other sites: one is on a mesa top near the head of Rock Creek Bay, and the other is at Dance Hall Rock, about 30 km northeast of Cookie Jar Butte. Neither was examined in detail.

The bedrock of this part of the Colorado Plateau consists of horizontal to gently-dipping Mesozoic and Cenozoic sedimentary strata, locally deformed in monoclinal folds and broad upwarps and downwarps. Cookie Jar Butte lies along the southeastern margin of the Kaiparowits Downwarp, which has regional dips of about 1° toward the northwest (Hackman and Wyant 1973).

The bedrock at and near Cookie Jar Butte is described in detail by Peterson and Barnum (1973) and Sargent and Hansen (1982) and is briefly summarized here. From bottom to top, the rock units include the Navajo Sandstone (Lower Jurassic), the upper member of the Carmel Formation (Middle Jurassic), the lower member of the Entrada Sandstone, the middle member of the Entrada, the sandstone at Romana Mesa, and the Salt Wash Member of the Morrison Formation (Upper Jurassic).

The lower member of the Entrada Sandstone, in which all of the giant pits have formed, is an orange, reddish-brown to buff, very fine-grained sandstone that is thinly to thickly cross-bedded. It has been described as a quartz-rich sandstone (quartz arenite), composed predominantly of subrounded to subangular quartz grains (Harshbarger et al. 1957; Witkind 1964; Davidson 1967; Peterson and Pipiringos 1979). Our laboratory analyses, however, reveal abundant (20–29%) feldspars and lithic fragments (3–14%), indicating an arkosic sandstone. It is approximately 170 m thick near Cookie Jar Butte. Large, irregular masses of structureless sandstone exist locally at the study site, some of which are partially exposed in pit walls and rims. The lower member of the

Entrada is thought to be of eolian and nearshore marine origin (Peterson and Barnum 1973).

The layer-cake structure of the rocks in the Glen Canyon region and their deep dissection by the Colorado River and its tributaries have produced a stair-step landscape, including mesas, buttes, structural terraces, steep-walled canyons, and talus-mantled ledgy slopes at the base of steep slopes. The Salt Wash Member forms the resistant caprock on the mesas and buttes that rise above Cookie Jar Butte. Distinctive topographic features that have developed on both the Navajo and Entrada sandstones include alcoves, varnished cliffs with rounded shoulders, pitted uplands, and slickrock slopes (Fig. 2). These features are in marked contrast to the flat-topped bedrock terraces and sharp, angular cliffs that characterize the landforms on more competent units such as the Wingate Sandstone (Lower Jurassic) and the Dakota Sandstone (Upper Cretaceous).

The climate of the lower part of the Glen Canyon region is arid to semiarid and is characterized by considerable variations in temperature and precipitation that are caused by differences in elevation and aspect. The average July temperature at Wahweap, near Page, Arizona (Fig. 1), is 28° C, whereas the average January temperature is 0° C (National Park Service, 1958–80, unpublished data). Diurnal temperature variations are marked, especially during spring and summer when they often exceed 20° C. Mean annual precipitation at Wahweap is a meager 15 cm (National Park Service, 1958–80, unpublished data), with significant year-to-year variations. Prevailing winds are from the southwest and are commonly strongest during spring. Severe winds are often associated with thunderstorms and squall lines, which also commonly approach from the southwest.

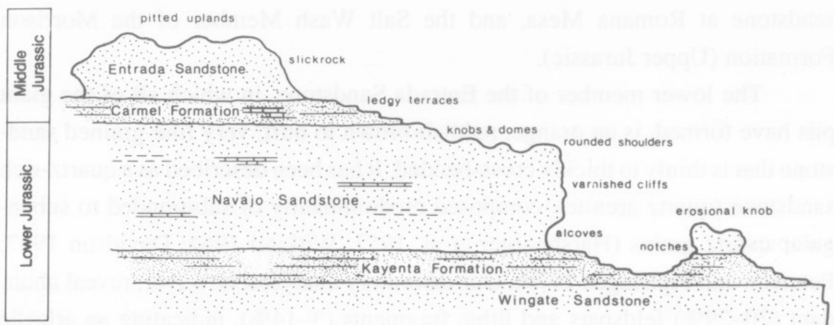

Fig. 2. Schematic diagram of erosional landforms that typically develop on the friable sandstones and mudstones in the lower part of the Glen Canyon region, Utah. The sandstone at Romana Mesa is only present locally and is not shown. At high pool (1,128 m), the surface of Lake Powell is just above the Carmel–Entrada contact at Cookie Jar Butte.

Vegetation and soils are sparse. They are limited to small areas where moisture is concentrated, such as along seeps and stream courses, and in weathering pits. Soil development is not only restricted by aridity and sparse vegetation but also by the meager amount of unconsolidated parent material.

Methods

Field and laboratory studies began in May 1992 with a reconnaissance of the Cookie Jar Butte site. Preliminary field maps (scale approximately 1:1,000) showing the distribution of weathering pits were prepared with the aid of 1:12,000-scale color aerial photographs provided by the Bureau of Reclamation, 1:24,000-scale topographic maps (U.S. Geological Survey), and 1:4,000-scale topographic maps prepared by the Bureau of Reclamation for the National Park Service. Thirty-one pits were described and measured, and 9 bedrock core samples were extracted. Loose sediment on the floors of selected pits was described and sampled for laboratory analysis. Additional bedrock cores and four pit water samples were collected in December 1992.

More detailed field investigations of the pits at Cookie Jar Butte were conducted during March 1993. The large, accessible pits were measured and described to determine the width and depth of closure (lowest part of pit rim to top of sediment or to bedrock floor in pit), pit-wall morphology, pit-floor sediments, pit-floor vegetation, and other pertinent site factors. Additional samples of bedrock cores, loose pit-floor sediment, weathered rock, and water in pits were collected for laboratory analyses. Visits to Cookie Jar Butte were made again in May and July 1993 to collect water samples and selected bedrock samples.

The laboratory analyses were conducted to determine the nature of the sandstone in which the pits formed and the nature of the pit-floor sediment and pit water. Thin sections of bedrock cores were examined by petrographic microscope to determine the mineralogy of grains, the type and amount of cement, and the percent pore space. Selected samples of weathered bedrock were examined with the scanning electron microscope and in thin section to determine the degree of alteration of the sandstone by diagenesis or near-surface weathering. The particle size of pit-floor sediments was analyzed, and selected samples were examined for the presence of distinctive tracer grains that were emplaced in December 1992. The $CaCO_3$ content of selected sandstone cores was analyzed to determine whether systematic variations in $CaCO_3$ content reflect selective dissolution of the calcite cement. Water samples from selected pits were collected in December 1992 and in March, May, and July 1993 to determine the magnitude of seasonal fluctuations in water temperature and pH.

Results

The giant weathering pits near Cookie Jar Butte are usually circular in plan view, cylindrical in shape, have low width-to-depth ratios, and depths of closure of as much as 16.5 m (Fig. 3). Single pits exist, but pits commonly exist

Fig. 3. Low oblique aerial photograph of a cluster of pits southeast of Cookie Jar Butte, Utah. Note the circular shape of most pits and the large mass of structureless sandstone *left* (south) *of center*. The pit at the base of the structureless sandstone (*at head of arrow*) is CJ-24, which has a diameter of 27.1 m and a depth of closure of 14.9 m (photograph by D. I. Netoff 1992).

in clusters; some are so closely spaced that they coalesce. Weathering pits exist on flat outcrops and on gentle to moderate slopes (30° or more) that face north, south, east, and west (Fig. 4). Some are on ridge crests and near isolated hilltops. Several are aligned along drainage courses.

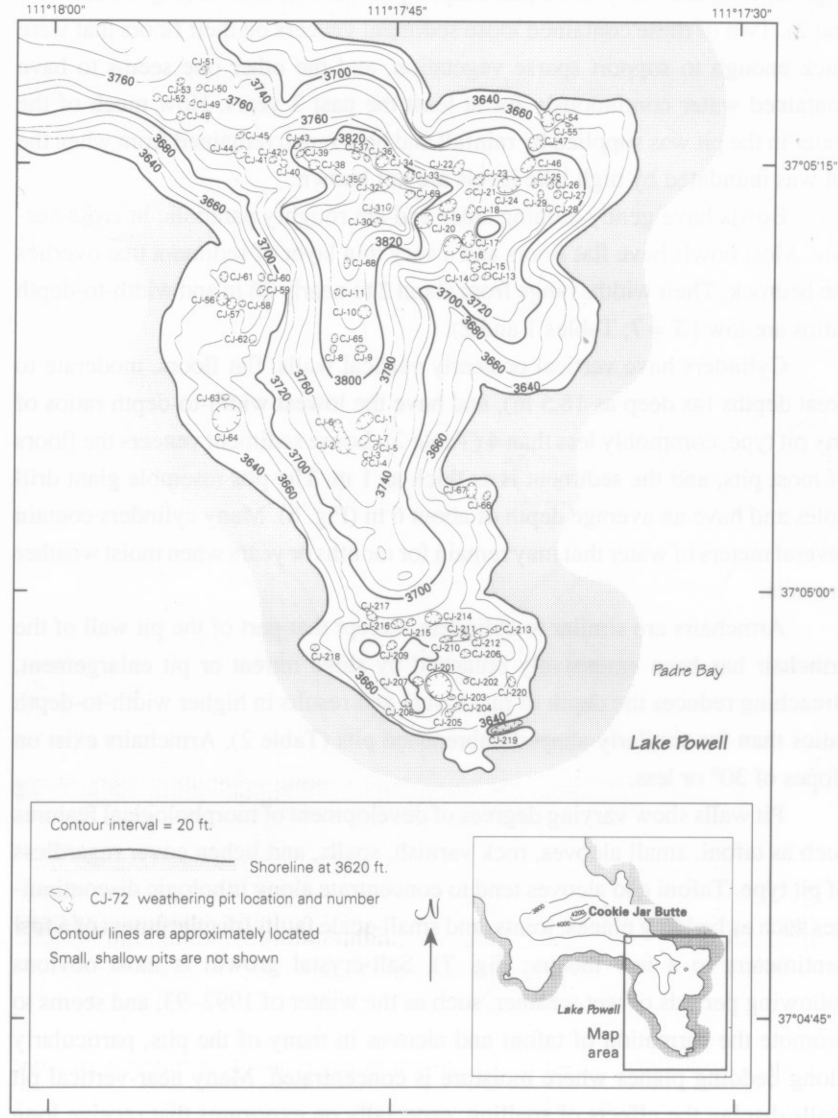

Fig. 4. Giant weathering pits southeast of Cookie Jar Butte, Utah.

Four distinct types of pits were identified on the basis of their cross-sectional form. The following nomenclature was modified from that of Twidale's (1982). Pans are broad, flat-floored, steep-sided, and have high width-to-depth ratios (Fig. 5; Tables 1 and 2). They are similar in form to pits commonly described in the literature but differ significantly from them because of their large dimensions. Only three pan-shaped pits were identified (Fig. 5; Tables 1 and 2). Two of these contained loose sediment veneers on their floors that were thick enough to support sparse vegetation, and the other one seems to have contained water continuously for at least the past 3 years. How much of the water in the pit was supplied by rainfall and how much remained from when the pit was inundated by high lake levels are not known.

Bowls have gently-sloping sides and are roughly parabolic in cross-section. Most bowls have flat floors and a very thin layer of sediment that overlies the bedrock. Their widths range from about 2 to nearly 26 m and width-to-depth ratios are low ($\bar{x} = 7$; Tables 1 and 2).

Cylinders have vertical or nearly vertical walls, flat floors, moderate to great depths (as deep as 16.5 m), and have the lowest width-to-depth ratios of any pit type, commonly less than 4 (Table 2). Loose sediment veneers the floors of most pits, and the sediment is as thick as 1 m. The pits resemble giant drill holes and have an average depth of about 6 m (Fig. 6). Many cylinders contain several meters of water that may remain for months or years when moist weather prevails.

Armchairs are similar to cylinders, except that part of the pit wall of the armchair has been extensively breached by slope retreat or pit enlargement. Breaching reduces the depth of pit closure and results in higher width-to-depth ratios than for similarly-shaped unbreached pits (Table 2). Armchairs exist on slopes of 30° or less.

Pit walls show varying degrees of development of morphological features such as tafoni, small alcoves, rock varnish, spalls, and lichen cover regardless of pit type. Tafoni and alcoves tend to concentrate along lithologic discontinuities such as bedding planes, joints, and small-scale faults (displacement of a few centimeters to a few meters; Fig. 7). Salt-crystal growth is most obvious following periods of wet weather, such as the winter of 1992–93, and seems to promote the formation of tafoni and alcoves in many of the pits, particularly along bedding planes where moisture is concentrated. Many near-vertical pit walls display the effects of spalling, especially on exposures that receive long periods of direct sunlight. Near-vertical walls on the north-facing sides of many

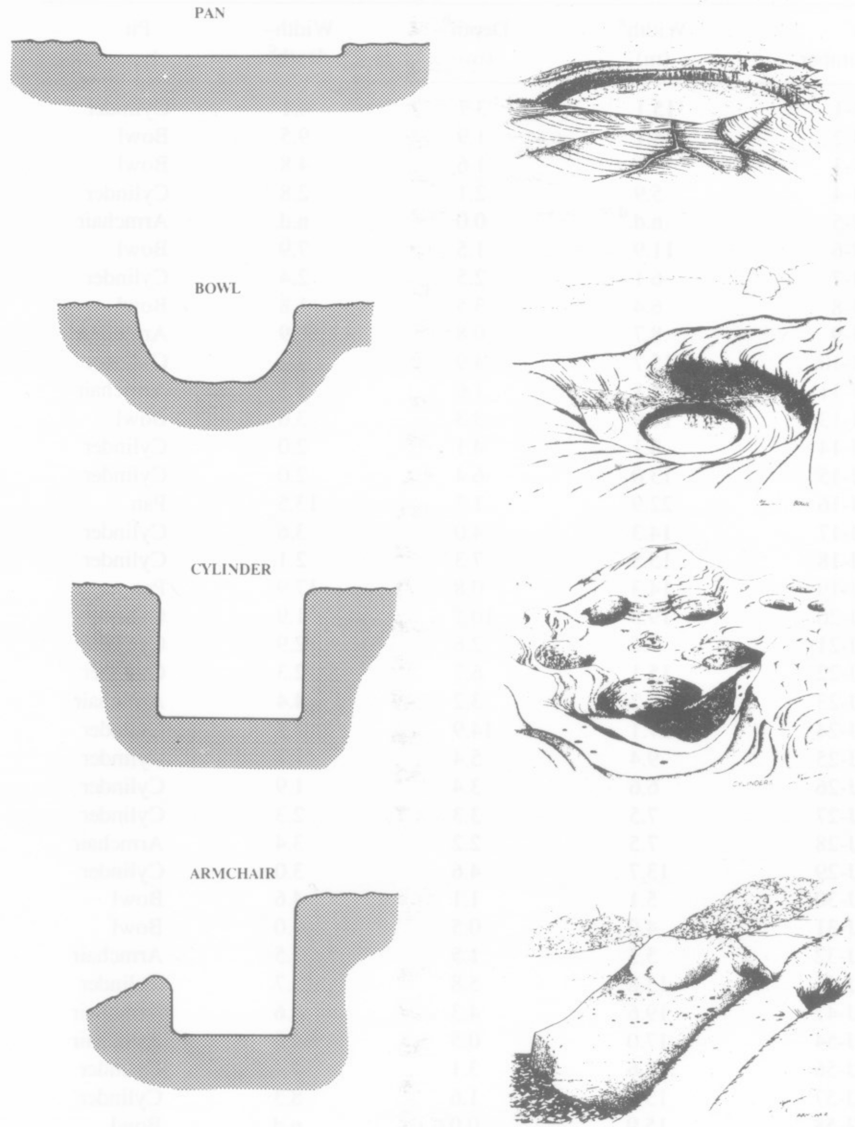

Fig. 5. Types of weathering pits near Cookie Jar Butte, Utah. Diagrams on the left are schematic cross sections; sketches on the right are oblique views of actual pits (sketches by Gary Durant).

Table 1. Summary of width, depth, width-to-depth ratio, and type of pit for the giant weathering pits near Cookie Jar Butte, Utah.

Pit number	Width[a] (m)	Depth[b] (m)	Width–depth[c]	Pit type
CJ-1	15.1	3.7	4.1	Cylinder
CJ-2	18.1	1.9	9.5	Bowl
CJ-3	7.6	1.6	4.8	Bowl
CJ-4	5.9	2.1	2.8	Cylinder
CJ-5	n.d.[d]	0.0	n.d.	Armchair
CJ-6	11.9	1.5	7.9	Bowl
CJ-7	6.1	2.5	2.4	Cylinder
CJ-8	6.4	3.5	1.8	Bowl
CJ-9	8.7	0.8	10.9	Armchair
CJ-10	15.7	4.9	3.2	Cylinder
CJ-11	8.8	1.6	5.5	Armchair
CJ-13	11.9	3.3	3.6	Bowl
CJ-14	8.1	4.1	2.0	Cylinder
CJ-15	13.0	6.4	2.0	Cylinder
CJ-16	22.9	1.7	13.5	Pan
CJ-17	14.3	4.0	3.6	Cylinder
CJ-18	15.5	7.3	2.1	Cylinder
CJ-19	14.3	0.8	17.9	Pan
CJ-20	19.5	10.1	1.9	Cylinder
CJ-21	7.6	2.6	2.9	Cylinder
CJ-22	15.1	6.7	2.3	Cylinder
CJ-23	14.2	3.2	4.4	Armchair
CJ-24	27.1	14.9	1.8	Cylinder
CJ-25	9.4	5.4	1.7	Cylinder
CJ-26	6.6	3.4	1.9	Cylinder
CJ-27	7.5	3.3	2.3	Cylinder
CJ-28	7.5	2.2	3.4	Armchair
CJ-29	13.7	4.6	3.0	Cylinder
CJ-30	5.1	1.1	4.6	Bowl
CJ-31	4.0	0.5	8.0	Bowl
CJ-32	5.3	1.5	3.5	Armchair
CJ-46	15.8	5.8	2.7	Cylinder
CJ-47	19.6	4.3	4.6	Armchair
CJ-54	17.0	0.5	34.0	Armchair
CJ-56	13.6	3.1	4.4	Cylinder
CJ-57	13.3	1.6	8.3	Cylinder
CJ-58	15.9	0.0	n.d.	Bowl
CJ-64	37.5	4.6	8.2	Pan
CJ-65	8.4	4.1	2.0	Cylinder
CJ-68	5.4	0.6	9.0	Bowl
CJ-100	22.6	15.5	1.5	Cylinder
CJ-101	14.0	1.3	10.8	Bowl

Table 1. *Continued.*

Pit number	Width[a] (m)	Depth[b] (m)	Width–depth[c]	Pit type
CJ-102	14.3	n.d.[d]	n.d.	Bowl
CJ-103	14.0	1.6	8.8	Bowl
CJ-104	8.1	0.0	n.d.	Bowl
CJ-105	6.9	n.d.	n.d.	Bowl
CJ-106	8.2	0.8	10.3	Bowl
CJ-107	9.4	0.0	n.d.	Pan
CJ-108	6.9	3.1	2.2	Cylinder
CJ-109	6.4	2.3	2.8	Bowl
CJ-110	7.3	0.4	18.3	Bowl
CJ-114	20.6	5.5	3.7	Cylinder
CJ-201	21.3	16.5	1.3	Cylinder
CJ-202	7.8	2.6	3.0	Cylinder
CJ-203	6.8	2.6	2.6	Cylinder
CJ-204	12.4	0.0	n.d.	Bowl
CJ-205	11.1	4.7	2.4	Armchair
CJ-206	15.2	9.4	1.6	Cylinder
CJ-207	19.5	8.6	2.3	Bowl
CJ-208	10.8	1.5	7.2	Armchair
CJ-209	9.3	4.6	2.0	Cylinder
CJ-210	14.2	9.4	1.5	Cylinder
CJ-211	12.0	4.4	2.7	Cylinder
CJ-212	19.5	n.d.	n.d.	Armchair
CJ-213	15.5	n.d.	n.d.	n.d.
CJ-214	19.4	8.2	2.4	Cylinder
CJ-215	12.4	1.8	6.9	Bowl
CJ-216	17.2	8.8	2.0	Cylinder
CJ-217	25.9	4.6	5.6	Bowl
CJ-218	10.4	2.4	4.3	Cylinder
CJ-220	9.6	0.3	32.0	Armchair

[a]Width = average of maximum and minimum diameters measured at the inner part of the pit rim.
[b]Depth of closure = vertical distance from the lowest part of the pit rim to the pit floor (bedrock or top of sediment).
[c]Width–depth = the ratio of width to depth of closure.
[d]n.d. = not determined.

of the pits seem to be the most stable; they display the least amount of granular disintegration, have the least amount of loose detritus at their base, and have by far the greatest percentage of lichen cover, which averages about 17% versus less than 1% lichen cover on pit walls that are not north-facing.

Table 2. Comparison of width-to-depth ratios of the four kinds of weathering pits at Cookie Jar Butte, Utah.

Cylinder		Bowl		Armchair		Pan	
Pit number	Width–depth	Pit number	Width–depth	Pit number	Width–depth	Pit number	Width–depth
CJ-1	4.1	CJ-2	9.5	CJ-9	10.9	CJ-16	13.5
CJ-4	2.8	CJ-3	4.8	CJ-11	5.5	CJ-19	17.9
CJ-7	2.4	CJ-6	7.9	CJ-23	4.4	CJ-64	8.2
CJ-10	3.2	CJ-8	1.8	CJ-28	3.4		
CJ-14	2.0	CJ-13	3.6	CJ-32	3.5		
CJ-15	2.0	CJ-30	4.6	CJ-47	4.6		
CJ-17	3.6	CJ-31	8.0	CJ-54	34.0		
CJ-18	2.1	CJ-68	9.0	CJ-205	2.4		
CJ-20	1.9	CJ-101	10.8	CJ-208	7.2		
CJ-21	2.9	CJ-103	8.8	CJ-220	32.0		
CJ-22	2.3	CJ-106	10.3				
CJ-24	1.8	CJ-109	2.8				
CJ-25	1.7	CJ-110	18.3				
CJ-26	1.9	CJ-207	2.3				
CJ-27	2.3	CJ-215	6.9				
CJ-29	3.0	CJ-217	5.6				
CJ-46	2.7						
CJ-56	4.4						
CJ-57	8.3						
CJ-65	2.0						
CJ-100	1.5						
CJ-108	2.2						
CJ-114	3.7						
CJ-201	1.3						
CJ-202	3.0						
CJ-203	2.6						
CJ-206	1.6						
CJ-209	2.0						
CJ-210	1.5						
CJ-211	2.7						
CJ-214	2.4						
CJ-216	2.0						
CJ-218	4.3						
T[a] = 33		T[a] = 16		T[a] = 10		T[a] = 3	
avg.[b] = 2.7		avg.[b] = 7.2		avg.[b] = 10.8		avg.[b] = 13.2	

[a]T = total number of weathering pits.
[b]avg. = average value of width–depth ratios.

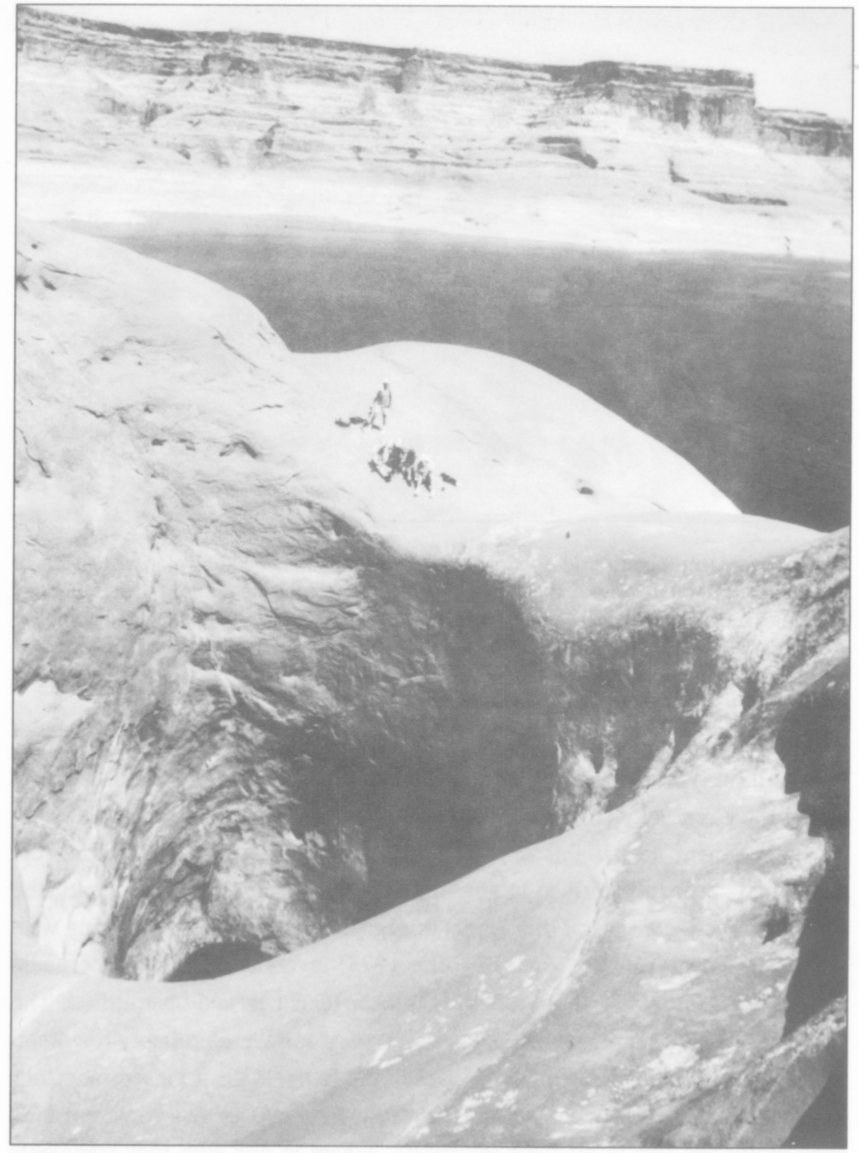

Fig. 6. The cylindrical-shaped pit at CJ-100, located about 550 m southwest of Cookie Jar Butte, has a diameter of 22.6 m and a depth of 15.5 m. Water remained in the pit from at least December 1991 (about 2 m) until July 1993 (almost dry). Calcium carbonate bathtub rings on the pit walls suggest that the pit may have recently been half full of water (photograph by D. I. Netoff 1992).

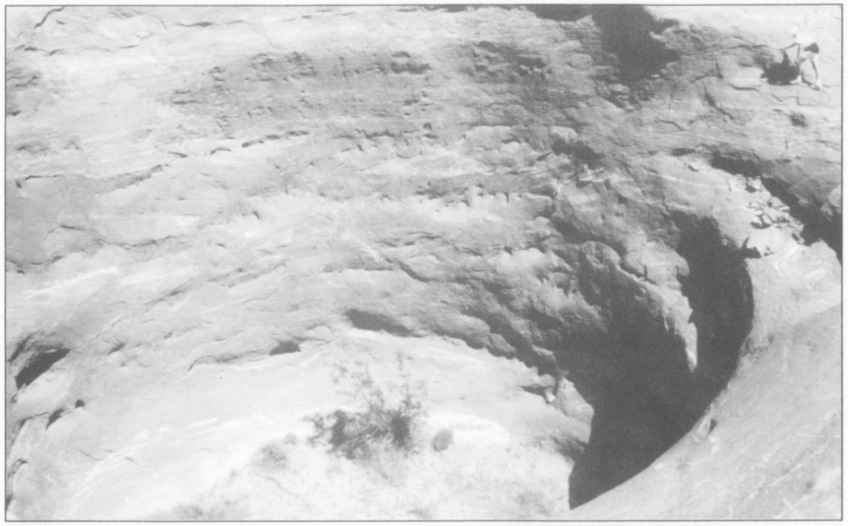

Fig. 7. Tafoni (pitting in vertical bedrock walls) aligned along bedding planes at pit CJ-20 (Fig. 4). Although joints and bedding planes influence the locations of the tafoni, they do not seem to exert a strong control on the location or shape of pits near Cookie Jar Butte. This cylindrical pit is 19.5 m wide and 10.1 m deep. Note person in *upper right* for scale (photograph by D. I. Netoff 1992)

All pit types commonly have a thin veneer of loose, sandy sediment that covers their bedrock floors. The mineralogy, particle size, color, and grain shape of the sediment are similar to that of the sandstone bedrock; therefore, the sediment is probably derived largely from the local bedrock. In some pits, the sandy sediment consists of thin layers of organic-rich material alternating with yellowish-red (5 YR 5/6; Munsell Color 1973) layers that are low in organic material. In some pits, the sediment is thicker than 1 m and unstratified. The upper surfaces of these sediments are undulatory and were probably reworked by the wind (Fig. 8). No artifacts or fossils were found in pit-floor sediment, nor have any buried soils been identified. Abrasive fragments that are larger than sand grains are rare in pit-floor sediments, except in pits with rock fragments from the Morrison Formation, which is exposed in nearby cliffs.

Pits with the thickest pit-floor sediment tend to support the densest plant cover. Plant communities generally consist of grasses, shrubs, herbs, and forbs, although the species composition varies considerably. Grasses such as the foxtail chess (*Bromus rubens*), sand dropseed (*Sporobolus cryptandros*), and blue grama (*Bouteloua barbata*) are common dominants or codominants.

Fig. 8. A cluster of giant pits, two of which contain moderately thick pit-floor sediment and a relatively dense vegetation community. The pit in the *lower left* (CJ-19, Fig. 4) is 14.3 m wide, and the pit in the *far upper right* (CJ-16, Fig. 4) is 22.9 m wide. Both are classified as pans (photograph by D. I. Netoff 1993).

Herbs and shrubs such as the tamarisk (*Tamarix ramosissima*), narrow-leaved yucca (*Yucca angustissima*), Mormon tea (*Ephedra viridis*), and matchbrush (*Gutierrezia microcephala*) vary in abundance and achieve dominance or codominance in some pits. Annuals such as the Russian thistle (*Salsola australis*) are present but are not as common as the other species. Many other annuals are present in some pits.

No obvious lithologic or structural controls determine the shape or location of most pits near Cookie Jar Butte. Joints and small-scale faults are present throughout the lower Entrada Sandstone outcrops. Most, however, are cemented with varying amounts of $CaCO_3$, which seems to strengthen the sandstone along these zones.

Thin-section analyses of near-surface sandstone cores at depths of 0–12 cm from pit rims, walls, and floors indicate that quartz accounts for 65–74% of the detrital grains (Tables 3 and 4). The remaining grains are mostly potassium feldspar with lesser amounts of lithic fragments and plagioclase feldspar. The total amount of pore space between sand grains (excluding calcite cement), based on point counts, is about 19–25%. Grains are typically subangular to subrounded, and the dominant grain sizes are medium to very fine sand (average

Table 3. Point-count summaries of stained thin sections of selected sandstone cores from pit rims, walls, and floors.[a]

Constituent (%)	CJ-17 A2[b]	CJ-17 B2[c]	CJ-101 A2[d]	CJ-101 B2[e]
Quartz	46	50	44	48
Potassium feldspar	12	14	13	11
Plagioclase	3	5	8	4
Calcite	4	3	9	9
Pore space	25	20	24	26
Lithic fragments[f]	10	8	3	2
Q/Q + K + P + L[g]	65	65	65	74
K/Q + K + P + L	16	18	18	16
P/Q + K + P + L	4	7	11	7
L/Q + K + P + L	14	11	5	3
Grain size (μ)				
Maximum	158	210	225	162
Minimum	30	32	35	37
Average	90	95	97	92
1s[h]	26	35	30	23
Total counts	208	208	208	208

[a]Pit CJ-101 is located 500 m southwest of Cookie Jar Butte, and pit CJ-17 is located 800 m southeast of Cookie Jar Butte (Fig. 4).
[b]Pit CJ-17 A2 is sample from pit wall at a depth of 3.8–5.1 cm.
[c]Pit CJ-17 B2 is sample from pit floor at a depth of 1.9–4.4 cm.
[d]Pit CJ-101 A2 is sample from pit rim at a depth of 1.9–3.2 cm.
[e]Pit CJ-101 B2 is sample from pit wall at a depth of 2.5–5.1 cm.
[f]Lithic fragments: fine-grained rock fragments + biotite and amphibole.
[g]Q = monocrystalline + polycrystalline quartz; K = potassium feldspar; P = plagioclase; L = lithic fragments.
[h]1s = one sample standard deviation.

90–100 μ, based on point counts and sieve analyses). Most quartz grains have distinct grain boundaries and show little or no evidence of dissolution (pitting or embayments). The feldspar grains are either slightly weathered or unweathered in roughly equal proportions. A reddish-orange to yellowish-orange coating as thick as 5μ covers most grains. These coatings are probably a combination of iron oxides and clay minerals (Fig. 9). Grains are loosely cemented with $CaCO_3$ (2.7–9.1 wt.% based on Chittick gasomatic determinations) and clays (1–6 wt.% based on particle-size analysis). No consistent trends in $CaCO_3$ content were detected among samples from pit floors, walls, and rims, nor were significant differences in $CaCO_3$ content observed between surface and near-

Table 4. Point-count summaries of unstained thin sections of selected sandstone cores from pit rims, walls, and floors.[a]

Constituent (%)	CJ-101 A3[b]	CJ-101 B1[c]	CJ-101 B5[d]	CJ-101 C2[e]	CJ-103 C1[f]
Quartz and feldspars	67	73	68	69	70
Calcite	13	9	10	5	7
Pore space	15	12	17	19	19
Lithic fragments[g]	5	5	4	7	5
Total counts	276	240	268	212	204

[a]Pits CJ-101 and CJ-103 are located about 500 m southwest of Cookie Jar Butte.
[b]Pit CJ-101 A3 is sample from pit rim at a depth of 3.2–4.4 cm.
[c]Pit CJ-101 B1 is sample from pit wall at a depth of 0–2.5 cm.
[d]Pit CJ-101 B5 is sample from pit wall at a depth of 10.2–12.1 cm.
[e]Pit CJ-101 C2 is sample from pit floor at a depth of 1.9–4.4 cm.
[f]Pit CJ-103 C1 is sample from pit floor at a depth of 0–3.2 cm.
[g]Lithic fragments: fine-grained rock fragments + biotite and amphibole.

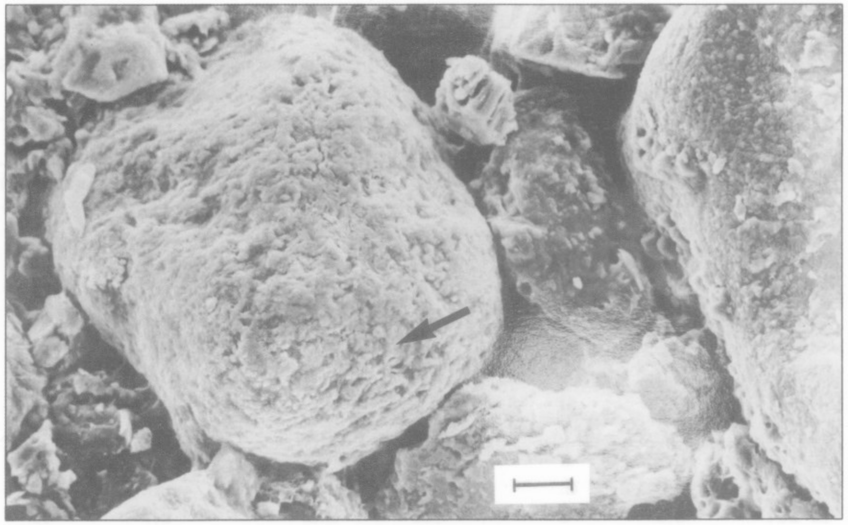

Fig. 9. Scanning electron microscope photomicrograph of a sandstone core (CJ-101 C3, located about 500 m southwest of Cookie Jar Butte) showing clay coatings on a quartz grain (*arrow*). Bar scale is 10μ.

surface (0–12 cm) sandstone core samples. The borders of the calcite cement may be convex, possibly the result of dissolution, or may show sharp crystal faces (T. R. Walker, 1993, personal communication), indicating a lack of etching or dissolution. Small (<1%) amounts of gypsum cement were also observed.

Water sampled from selected weathering pits near Cookie Jar Butte in December 1992, March 1993, and May 1993 indicate significant seasonal variations in pH (Table 5). The average pH value of pit water samples in December was 8.2; the average in March was 7.5; and the average in May was 9.0. Two water samples in May gave unusually high pH values of 9.4 and 9.5.

Discussion

Weathering Processes

Several weathering processes are thought to be important in pit initiation and growth; many are accentuated by the presence of discontinuities such as bedding planes, joints, and small-scale faults. Pit wall recesses such as tafoni

Table 5. Water temperature and pH values measured at selected weathering pits during December 1992, March 1993, and May 1993.[a]

Pit number	December		March		May	
	pH	Temp.(° C)	pH	Temp.(° C)	pH	Temp.(° C)
CJ-6	d.[b]	d.	7.6	19	d.	d.
CJ-10	d.	d.	7.0	n.d.[c]	d.	d.
CJ-15	n.d.	n.d.	7.4	11	n.d.	n.d.
CJ-30	d.	d.	7.6	n.d.	d.	d.
CJ-32	n.d.	n.d.	n.d.	n.d.	9.5	21
CJ-57	8.5	0	7.7	18	8.9	23
CJ-64	8.0	0	7.8	15	8.7	23
CJ-100	n.d.	n.d.	7.5	9	9.1	18
CJ-108	8.4	0	7.4	9	9.4	20
CJ-109	d.	d.	8.4	12	d.	d.
CJ-201	8.0	6	7.4	n.d.	8.7	19
CJ-214	n.d.	n.d.	7.6	n.d.	8.7	20

[a]Pits CJ-100, CJ-108, and CJ-109 are located 500–600 m southwest of Cookie Jar Butte; the remaining pits listed are located southeast of Cookie Jar Butte (Fig. 4).
[b]Pit was dry, and values were not determined.
[c]Pit contained water, but values were not determined.

and small alcoves are commonly aligned along bedding planes and to a lesser extent along joints and small-scale faults. These are sites where moisture is localized, which in turn accelerates moisture-dependent weathering processes. Salts are commonly concentrated in these recesses, and salt crystal growth may cause granular disintegration of pit walls. Salts may also catalyze quartz dissolution (Young 1987a), although we did not detect thin-section evidence of this process.

Other soluble substances may migrate by capillary action to the rock surface, crystallize, and create enough stress to induce granular disintegration. Calcite and gypsum have been suspected of causing granular disintegration in friable sandstone (Laity and Malin 1985), and we observed minor calcite wedging in one of the sandstone cores. Scanning electron microscope examination of a salt-encrusted, weathered bedrock sample at pit CJ-3 revealed nearly pure gypsum crystals.

Clay mineral hydration and desiccation may also exert disruptive forces in some sandstones (Netoff 1971). Particle size analysis of a crushed core sample from pit CJ-13 indicated that clay-size material is a significant component (5.7%) of the $CaCO_3$-free portion of the sample. Moreover, we observed well-developed cracks in dry pit-floor sediment in many pits, suggesting the presence of expandable material in these sediments. Contraction of pit-floor sediment suggests that sandstone bedrock in contact with the sediment may be subject to colloidal plucking.

Spalling of pit walls is common on all except north-facing exposures. Spalls parallel the pit walls; at some sites, sets of closely spaced, face-parallel joints exist in the wall rock. The cause of spalling is not known, but the joint pattern resembles expansion-induced exfoliation. Thermal expansion caused by solar radiation may initiate spalling, especially after the rock has been weakened by other weathering processes. The effectiveness of solar radiation, however, has been debated for decades (Griggs 1936; Ollier 1969).

Freezing and thawing may be effective weathering agents where water is abundant, such as at seeps, alcoves, and tafoni. Pit waters may freeze and form surface ice as thick as several centimeters during cold winters, and expansion and contraction of ice in contact with pit walls may promote disintegration.

Chemical weathering processes that may contribute to pit development include carbonation, dissolution, and hydrolysis. Dissolution of calcite cement should free quartz and feldspar grains and promote pit enlargement. Thin-section analysis revealed at least some calcite dissolution in sandstone exposed in pit walls and floors, although some samples showed no signs of dissolution (T. R. Walker, 1993, personal communication). Karst landforms on quartzose sandstones formed by dissolution of quartz grains have been reported by many geologists (e.g., Jenning 1983; Young 1987b; Young and Young 1992), but most of their examples were from much wetter present or past environments, and the landscapes that they studied are extremely old. We found no evidence of extensive dissolution of quartz grains, and we therefore discounted solution as a major weathering process in pit development. The slight alteration of plagioclase and potassium feldspar is probably the result of hydrolysis and perhaps dissolution, but many of these grains seem to be fresh, and consequently feldspar weathering is not believed to play an important role in pit development or in the formation of diagenetic clays.

Biological activity has been advocated by several investigators as a causative process in the development of weathering pits; they cite evidence such as the dark organic stains that often coat bare bedrock pit floors and the presence of lichens on pit walls and rims. The pea-soup color of the water in several of the pits that we observed when surface water temperatures exceeded about 18° C illustrates the intensity of organic activity in these miniature aquatic systems. Biological activity is probably partly responsible for seasonal variations in pit-water pH values. The high pH (9.5) in some pit waters should be conducive to silica dissolution (Birkeland 1984). The lack of obvious dissolution features in thin-section analysis, however, argues against this mechanism.

Rock varnish on the north-facing walls of many pits may be due in part to organic stains from microorganisms (Fig. 10). The presence of lichens and rock varnish on north-facing pit walls and the relative lack of spalling, salt crystal growth, and granular disintegration on those walls suggests that either some types of biological activity promote pit-wall stability or pit-wall stability permits the establishment of some types of biological activity.

Removal of Weathering Products

The removal of sandstone weathering products from weathering pits is probably accomplished by some combination of plunge-pool action, wind deflation, and perhaps dissolution or piping. Although evidence at selected pits supports one or more of these mechanisms, preliminary field and laboratory data do not clearly identify any single process or group of processes that accounts for the removal of weathering products from the pits.

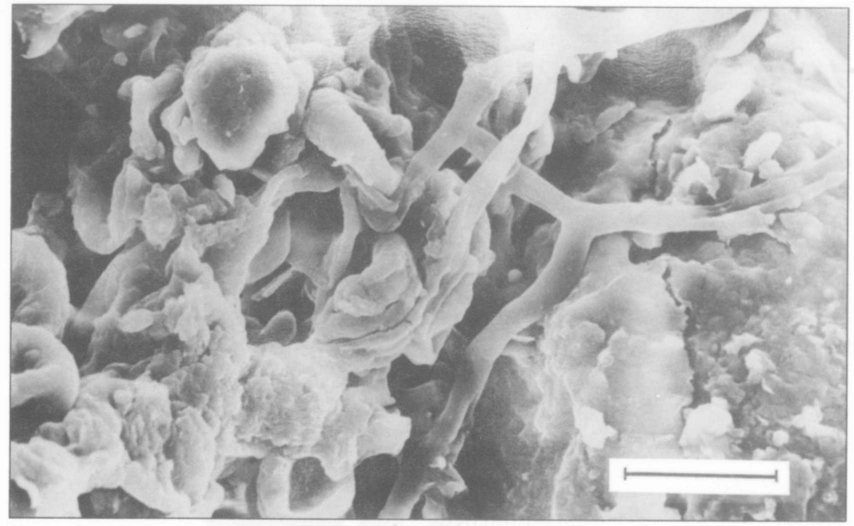

Fig. 10. Scanning electron microscope photomicrograph of rock varnish on the north-facing pit wall at CJ-13 (Fig. 4). The filaments and spherical structures are largely organic, most likely a combination of bacteria and fungi. Bar scale is 10μ.

Plunge-pool erosion is the combined effect of the hydraulic force of water and the abrasive action of sand and gravel in swirling pools; perhaps erosion is enhanced by solution of the calcite cement. Plunge-pool erosion requires channelized flow and stream gradients sufficient to generate at least moderate flow velocities; it is most effective where resistant, abrasive tools are present. Countless examples of large, multiple plunge pools along many of the tributaries of the Colorado River in the Glen Canyon region illustrate the intensity of plunge-pool action, even along intermittent streams (Fig. 11).

Several giant weathering pits near Cookie Jar Butte are roughly aligned along bedrock channels that have sufficient drainage areas and gradients to induce plunge-pool erosion, which at least at one site may eventually produce a natural bridge (Fig. 3). Many pits, however, are not in an organized drainage system, and several pits are on ridge crests or near isolated hills. Whether paleochannels contributed to pit enlargement at these sites is difficult to determine. The absence of abrasive fragments on the floors of these pits also suggests that plunge-pool erosion does not account for pit enlargement.

Little doubt exists that wind deflation is capable of removing loose, dry sand from shallow pits. In May 1993, a thin veneer of loose sand on the floor

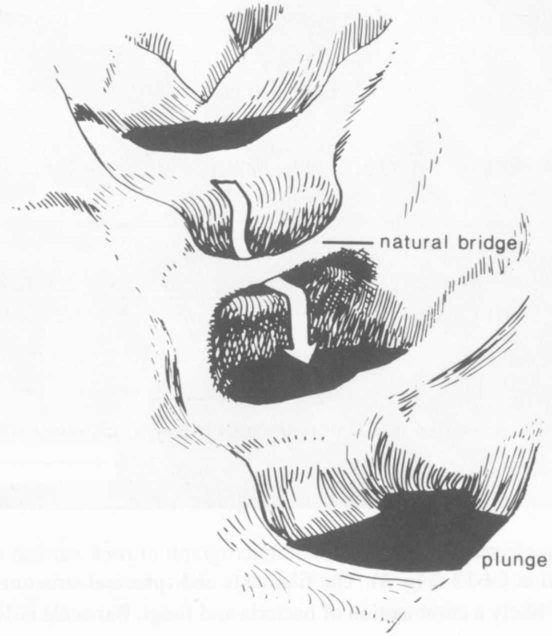

Fig. 11. Sketch of plunge-pool basins of the type that commonly form in many of the tributary valleys of the Glen Canyon region (sketch by Nancy Stonington). A natural bridge similar to the one depicted here will soon develop at pit CJ-24 (Fig. 3).

of a bowl-shaped, 1.6-m-deep pit near Cookie Jar Butte was rapidly removed by wind with a velocity of 56 km/h measured at the pit rim. Eolian sediment removal is halted when weathering pit depth exceeds the capacity of the strongest winds to remove the sediment from the pit floor.

Whether winds can deflate 100-μ-size quartz and feldspar grains from deep and narrow cylindrical depressions is a critical question. Wind gusts as strong as 130 km/h have been recorded on Lake Powell (John Ritenour, 1992, personal communication), and episodic winds on favorable topographic sites could be of far greater velocity. Winds may have been even stronger in the Pleistocene when presumably high-pressure gradients existed between the warm, low canyon floors and the nearby ice-capped, high plateaus to the north of Glen Canyon. Moreover, large areas of exposed sandstone in the Canyonlands region of southeastern Utah have been proposed as a possible source of eolian silt in the Piceance Creek basin of northwestern Colorado (Whitney and Andrews 1983).

Arguments against the removal of sediment by wind from the floors of deep pits include the lack of wind scour features on pit walls, pit floors, and other bedrock surfaces, as well as the fact that the giant pits formed on both the windward and leeward slopes of Cookie Jar Butte. Whether paleowinds removed sediment from the floors of deep and narrow cylindrical pits is not known and would be difficult to prove.

Two plausible hypotheses for the removal of quartz grains include removal by dissolution and removal by piping, but we did not detect obvious dissolution features in thin-section analysis. Joints and small-scale faults that intersect pits near Cookie Jar Butte may have been large and open enough at one time to serve as conduits for the removal of sand, but they are now completely cemented with $CaCO_3$ and are less likely to transmit water than the surrounding sandstone. Retention of water for months or years in many of the deeper pits suggests that the walls and floors of these pits are relatively impermeable. The conduits may have been wide enough to transport sand in the past and have since been sealed by sand and $CaCO_3$, but no convincing evidence has been observed that supports this supposition.

Antiquity of Weathering Pits

Two other key questions are, How old are the pits? and Are they relict features or are they still forming? The maximum limiting age of the pits is the time when the pit-bearing sandstone was exposed to surficial processes, which is controlled by the time when the Colorado River and its tributaries cut down to the level of the existing pits. Estimated downcutting rates based on terrace heights above Bullfrog Creek (a tributary of the Colorado River in Glen Canyon about 117 km [channel distance] northeast of our study site) range from 80 to 250 m/m.y. (meters per million years; Biggar and Patton 1991). If this range is used to estimate when the Colorado River was at the elevation of the highest of the giant weathering pits near Cookie Jar Butte (134 m above the modern channel of the Colorado River), the estimated age range of the highest (possibly the oldest) weathering pits would be 0.5–1.7 Ma (million years ago). These values are in general agreement with estimates of downcutting rates by Hunt (1969) and Machette and Rosholt (1991). Hunt (1969) determined an average rate of downcutting of the Colorado River of 165 m/m.y. based on the river's present sediment load. Machette and Rosholt (1991) used uranium-trend dating to determine an average rate of downcutting in the upper part of the Grand

Canyon—about 140 km southwest of our study site—of at least 190 m/m.y. These rates yield estimated ages of the highest pits of about 0.8 to 0.7 Ma. We infer, therefore, that the oldest pits are no older than early Pleistocene.

Considerable antiquity of armchair pits is suggested by their presence on moderate slopes; nearly level bedrock outcrops promote pit development because ponded water localizes weathering processes and accelerates pit deepening. The formation of armchairs predates the breaching of the pit rims by slope retreat. The rate of pit deepening must have at least kept pace with slope retreat to maintain closed bedrock depressions.

Evidence of present-day pit-wall weathering includes abundant spalls, salt-crystal growth, and loose debris along the base of pit walls and on pit floors. Indirect evidence of the recency of pit excavation includes the lack of thick sediment on pit floors. Alternatively, the presence of local rock varnish and lichen cover on pit walls implies temporary pit wall stability. Pit development may have begun as far back as early Pleistocene and may have continued through the Holocene.

One of the fundamental questions about pit development remains unanswered: Why is the distribution of giant sandstone weathering pits so restricted, especially considering the vast expanse of exposed friable sandstones throughout the Colorado Plateau? We see nothing unique in the bedrock structure, topography, or climate at Cookie Jar Butte that would account for the limited distribution. Perhaps unique environmental conditions set the stage for and fostered the development of the giant pits, and these or other conditions remain conducive to their continued development.

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