U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

# MORPHOLOGY AND POSSIBLE ORIGIN OF GIANT WEATHERING PITS IN THE ENTRADA SANDSTONE, SOUTHEASTERN UTAH: PRELIMINARY FINDINGS

by

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This report is preliminary and has not been reviewed for conformity with the U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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ABSTRACT

Abundant giant weathering pits formed in the lower member of the Entrada Sandstone of Jurassic age are present in two areas within the Glen Canyon region of arid southeastern Utah. The pits are far larger than most of those described in the geologic literature. The pits near Cookie Jar Butte are commonly cylindrical, have low width-to-depth ratios (1.3-3.7), and a depth of closure of as much as 16.5 m. There are few obvious lithologic or structural controls that influence their shapes or locations. In contrast, the pits at Rock Creek Bay are elongate; several of them have long axes in excess of 50 m, and the longest one is 72 m. Many of the pit walls are breached at the top, and the depth of closure is generally less than 6 m. The shapes of these pits are influenced by joint orientation and pit coalescence. Thin-section analyses of near-surface sandstone cores taken from pit walls, floors, and rims at the Cookie Jar Butte site reveal only minor alteration of the fine-grained to very fine grained (mostly 60-250 microns) arkosic sandstone. Quartz grains are generally fresh, and feldspar grains are fresh to slightly weathered. The sandstone is friable and is weakly cemented by calcium carbonate (2.7-9.1 wt. percent); most of the grains are coated by a thin layer of iron oxide. Sandy sediment commonly veneers the bedrock floor of pits at both sites. The sediment at both sites is similar in character to that of the adjacent sandstone and is probably locally derived. Various weathering processes weaken the sandstone on pit walls and floors. Sediment produced by these processes is removed by various combinations of plunge-pool action, wind deflation, and perhaps dissolution and piping. Preliminary field and laboratory data do not clearly identify any single process or group of processes that account for the removal of the sediment from the pits.

## INTRODUCTION

Weathering pits form in a broad spectrum of physical environments. They are typically described in the geological literature as broad and shallow depressions formed on flat to gently-sloping outcrops of bare rock. They are commonly flat-floored basins that are up to several meters wide 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 which removes the decomposed material. Little is known about the age of weathering pits.

Two sites containing abundant and unusually large weathering pits are present on bedrock outcrops in the lower part of the Glen Canyon area, which is partially inundated by Lake Powell. They are formed in outcrops of the lower member of the Entrada Sandstone of Jurassic age near Cookie Jar Butte on the north side of Padre Bay and near the head of Rock Creek Bay in Glen Canyon National Recreation Area, southeastern Utah (fig. 1).

Field and laboratory analyses were carried out in 1992 and 1993. Field measurements indicate that these pits are much deeper than typical weathering pits; they may be among the deepest on earth that have formed in sandstone. They are of considerable interest geomorphologically because of their immense size and because their origin is difficult to explain by conventional theories. These pits are also of interest because they may contain Indian artifacts, fossil plant or animal material, or buried soils.

The major objectives of this report are to: (1) describe the weathering pits in terms of their geologic occurrence, dimensions, and geometry and (2) evaluate several hypotheses that might account for their origin.

## PREVIOUS WORK

Broad, shallow bedrock depressions on level to gently-sloping surfaces have been reported on every continent and in practically every physical environment on earth. They have attracted special attention in arid regions, where they have been the sites of 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 tinajitas. Pits develop on diverse lithologies; intermittent ponds have been reported on quartzite ridges in North Carolina (Reed, Bryant and Hack, 1963), on limestone in Texas (Udden, 1925), on arkose at Ayers Rock in Australia (Twidale, 1982), and unusually deep (8 m) pits occur on granite-gneiss in Brazil (Twidale, 1968). Weathering pits are nearly ubiquitous on gently-sloping outcrops of weathered granite and sandstone. They are so abundant on friable sandstones of the Colorado Plateau that they create a distinctive dome-and-pit

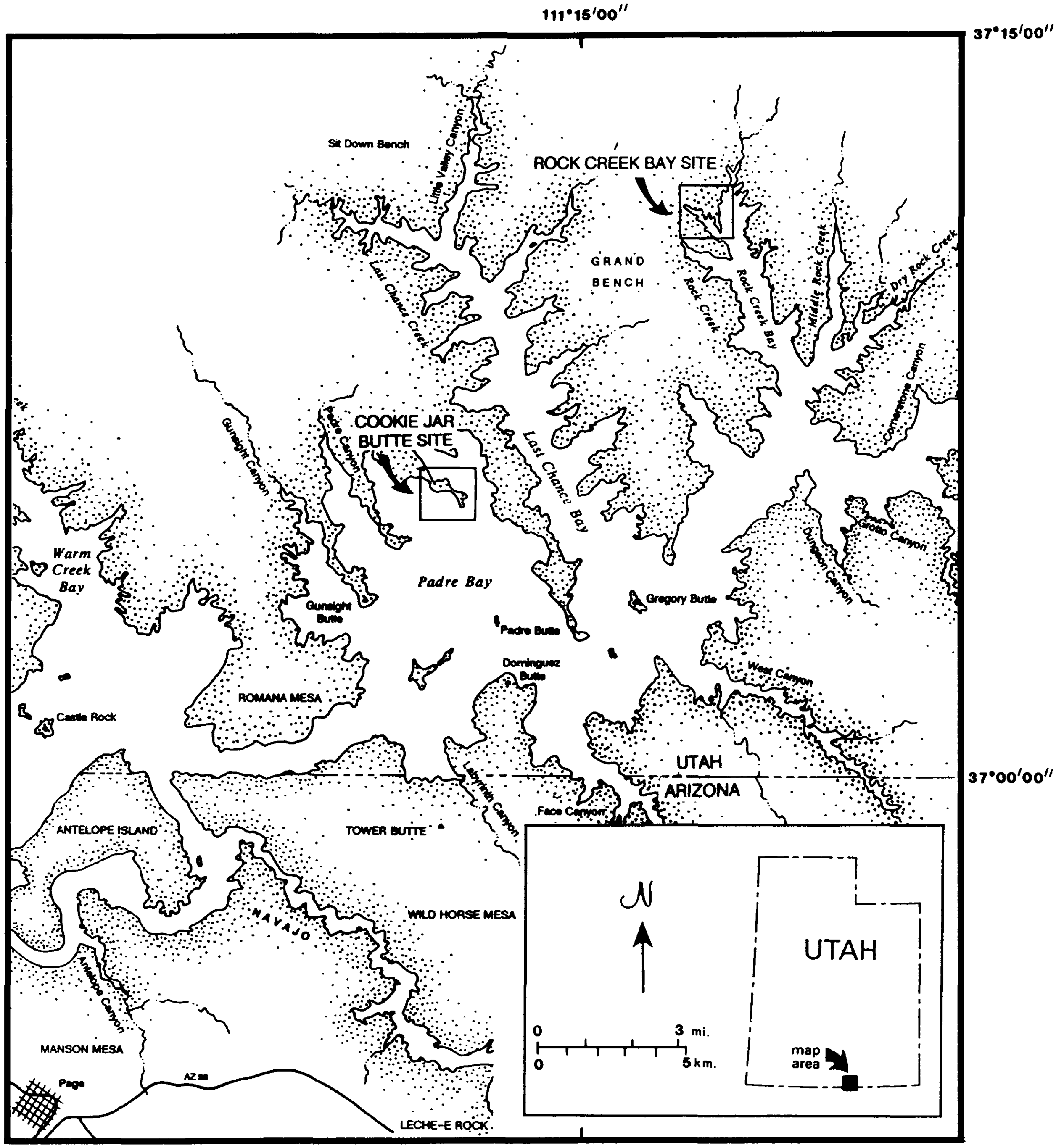


Figure 1. Location map of the Cookie Jar Butte and Rock Creek Bay sites.

landscape.

Bedrock depressions are identified by a wide variety of terms in the geologic literature. These include solution pits and pans (Fairbridge, 1968), etched potholes (Udden, 1925), the gnammas of Australia (Jutson, 1934), cavernous rock surfaces (Blackwelder, 1929), solution depressions (LeGrande, 1952), the oricangas of Brazil (Fairbridge, 1968), and the 'saucer-like depressions' on the Navajo Sandstone in Utah and Arizona (Gregory, 1938). Ollier (1984) uses the term weathering pit to describe various kinds of hollows produced by weathering, and he reserves the term weathering pan for pits that develop on horizontal surfaces. Twidale (1982) refers to all depressions excavated in solid bedrock as rock basins, and recognizes four distinct morphological types, each of which have counterparts at the Cookie Jar Butte and Rock Creek Bay sites.

Previous studies have focused on pits that have high width-to-depth ratios (w/d) and on processes that weather rock rather than those that remove the weathered material. The limited amount of quantitative data on pit morphology indicate that pits are typically circular to elliptical in plan view, flat-floored, have widths of 0.5 m to 3 or 4 m, depths of 5-60 cm, and average w/d ratios of 6:1 to 10:1 (Udden, 1925; Twidale, 1982; Ollier, 1984; Alexandrowicz, 1989). Much deeper holes have been reported by Angeby (1951) and Jennings (1967), but the origin of these depressions appears to be related to plunge-pool action at the base of waterfalls and to collapse into subterranean voids, respectively, and are not due solely to weathering. Weathering processes that have been proposed for pit development emphasize the role of water, which is likely to remain for progressively longer periods of time as the pit deepens, due in part to reduced rates of evaporation. Frequent reference has been 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, Bryan and Hack, 1963; Jennings, 1967; Roberts, 1968; Twidale and Bourne, 1975; Godfrey, 1980; Jennings, 1983; Goudie, 1991; A. Young, 1987; Howard and Kochel, 1988; Alexandrowicz, 1989). There is little agreement among authors, however, on the role and relative importance of specific weathering processes, such as 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 occurrence of salts and calcite has been frequently cited as evidence of crystal wedging (Bradley and others, 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) stated that solution of calcite cement has locally created karstic landforms on slickrock[1] 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 and by localizing salts which promote rock disintegration.

Several mechanisms have been proposed to account for the removal of weathered sediment from pits (Barnes, 1978). Wind deflation is thought to be effective, although Twidale (1982) de-emphasizes the importance of this process. Where pits are in or near intermittent water courses, fluvial action seems to be an obvious process. In deeper pits, especially those that are not integrated into water courses, subsurface removal by dissolution or piping has been proposed, particularly for pits where there are obvious underground conduits to concentrate subsurface flow (Twidale, 1990). Evidence from Venezuela and Australia indicates that there are extensive underground tubes and cavities that have developed in quartz sandstones under climatic conditions that promoted dissolution (Jennings, 1983; R. Young, 1987).

One of the most conspicuous gaps in the literature concerns 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 and others, 1987). The Mistor Pan in Dartmoor, England is a large, well-known pit that was first described in 1291; its depth has not significantly changed between measurements made in 1828 and 1929 (Twidale, 1982). It is likely that the rate of pit growth is highly variable, depending chiefly on factors such as climate and lithology.

## PHYSICAL CHARACTERISTICS OF THE STUDY SITES

The Cookie Jar Butte site 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). At this site there are about 30 hectares of pitted terrain on gently to moderately-sloping surfaces. The Rock Creek Bay site is at the north end of Rock Creek Bay (fig. 1; sec. 12, T. 42 S., R. 6 E. and sec. 7, T. 42 S., R. 7 E. of the Mazuki Point 7.5 minute quadrangle [section numbers are estimates because they are not shown on the quadrangles]). The roughly 10 hectares of pitted terrain at the latter site is on an undulating mesa top. A few giant pits occur in the Entrada Sandstone outside of these sites, either in clusters or as single

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[1]The term slickrock is an informal term referring to barren, smooth outcrops of friable sandstone such as the Navajo and Entrada Sandstones.

pits.

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. The Rock Creek Bay site lies along the northwest-trending Grand Bench Monocline that has southwesterly dips of as much as six degrees (Peterson and Barnum, 1973). Cookie Jar Butte lies along the southeastern margin of the Kaiparowits Downwarp that has regional dips of about one degree toward the northwest (Hackman and Wyant, 1973; Sargent and Hansen, 1982).

The bedrock exposed at the two sites ranges in age from the Middle Jurassic upper member of the Carmel Formation to the Upper Jurassic Salt Wash Member of the Morrison Formation. The latter member forms the caprock of Cookie Jar Butte as well as the unnamed butte near the Rock Creek Bay site. The bedrock at and near the two sites is described in detail by Peterson and Barnum (1973), Sargent and Hansen (1982), and is briefly summarized below. From bottom to top, the rock units include the Navajo Sandstone, Page Sandstone, upper member of the Carmel Formation, lower member of the Entrada Sandstone, middle member of the Entrada, sandstone at Romana Mesa, and the Salt Wash Member of the Morrison Formation. The Navajo Sandstone is a reddish-orange to grayish-pink, fine-grained, crossbedded eolian sandstone. The Page Sandstone is locally present and overlies the Navajo Sandstone. The upper member of the Carmel Formation is a brick-red sequence of interbedded sandstones, silty sandstones, and mudstones. It is generally thin-bedded, but locally may be thickly crossbedded. It is predominately of shallow-water marine and tidal flat origin.

The Carmel is overlain by the lower member of the Entrada Sandstone, in which all of the giant pits have formed. It is an orange reddish-brown to buff, very fine grained sandstone that is thinly to thickly crossbedded. It is described as a quartz-rich sandstone (quartz arenite), composed predominately of subrounded to subangular quartz grains (Harshbarger and others, 1957; Witkind, 1964; Davidson, 1967; Peterson and Pipiringos, 1979). It is approximately 170 m thick at the two sites. Large, irregular masses of structureless sandstone occur locally at the two study sites, 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.

The middle member of the Entrada consists of alternating beds of reddish-brown mudstone and reddish-orange to gray sandstone of variable thickness; it commonly forms a red-and-white banded cliff. It is probably of shallow marine, tidal-flat, lagoonal, and eolian origin. Locally, there are thin beds of the sandstone at Romana Mesa (Peterson and Barnum, 1973) that unconformablly overlie the middle member of the Entrada Sandstone. The sandstone at Romana Mesa is yellowish gray, fine grained, and thin bedded to thickly crossbedded. It is probably a nearshore marine deposit. The sandstone may correlate with the Summerville Formation farther north in central Utah.

The Salt Wash Member of the Morrison Formation overlies the middle member of the Entrada and locally the sandstone at Romana Mesa. The Salt Wash Member consists of about 100 m of resistant, grayish-brown sandstone and conglomerate, and minor beds of reddish-brown mudstone. The member formed as extensive alluvial plain deposits.

The layer-cake structure of the rocks in the Glen Canyon region and 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 the two study sites. Distinctive topographic features that have developed on both the Navajo and Entrada Sandstones include alcoves, varnished cliff 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 Dakota Formation and locally the Wingate Sandstone.

The climate of the lower part of the Glen Canyon region is arid to semiarid and is characterized by considerable variations in both temperature and precipitation due to differences in elevation and aspect. The average July temperature at Wahweap, near Page, Arizona (fig. 1), is $28^{o}$ C, whereas the average January temperature is $0^{o}$ C (National Park Service, unpub. data for 1958-1980). Diurnal temperature variations are marked, especially during the spring and summer, when they often exceed $20^{o}$ C. Mean annual precipitation at Wahweap is a meager 15 cm (National Park Service, unpub. data for 1958-1980), but there are significant year-to-year variations. Prevailing winds are from the southwest and are commonly strongest during the spring. Severe winds are often associated with thunderstorms and squall lines, which also commonly approach from the southwest.

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

Detailed (approx. 1:1,000-scale) maps showing the distribution of weathering pits at the two study sites were prepared with the aid of 1:12,000-scale Bureau of Reclamation color aerial photographs, 1:24,000-scale U.S. Geological Survey topographic maps, and 1:4,000-scale topographic maps (prepared by the Bureau of Reclamation and provided by the National Park Service). Oblique aerial photography taken by Netoff in May 1992 was used to make minor revisions on these maps.

A reconnaissance of the Cookie Jar Butte and Rock Creek Bay sites was conducted by Netoff and Shroba in May 1992, assisted by

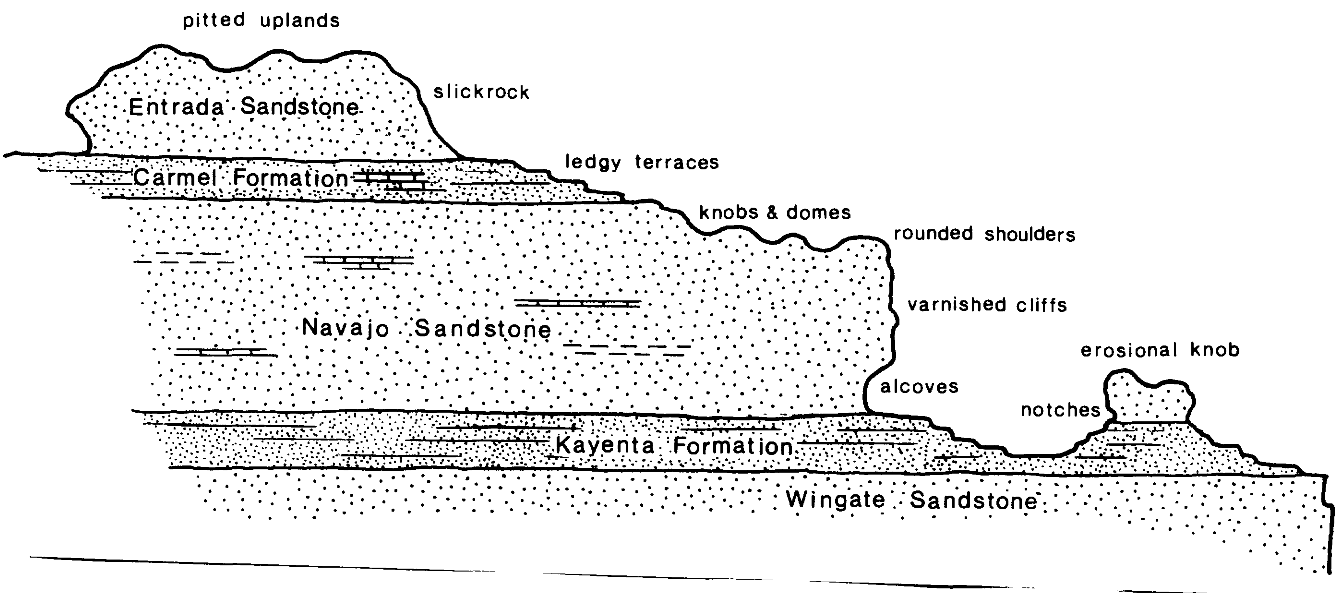


Figure 2. Schematic diagram showing erosional landforms that typically develop on friable sandstone and mudstone in the lower part of the Glen Canyon region. The sandstone at Romana Mesa is only of local extent and is not shown. At high pool (1128 m) the surface of Lake Powell is just above the Carmel-Entrada contact at both the Cookie Jar Butte and Rock Creek Bay sites.

students from Sam Houston State University. Selected pits at both sites were measured and described. Bedrock core samples were extracted from several pits near Cookie Jar Butte and loose sediment on the floors of selected pits near Cookie Jar Butte was described and sampled for laboratory analyses.

More detailed field investigations of the pits at Cookie Jar Butte were conducted during December 1992 and March 1993. All of the large, accessible pits were measured for average width and depth of closure[2], and descriptions were made of 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. Additional visits to Cookie Jar Butte were made in May and July 1993 to collect additional water samples and selected bedrock samples.

The laboratory analyses were conducted to determine the nature of the sandstone in which the pits have formed as well as the nature of the pit-floor sediment and pit water. Thin sections of bedrock cores were examined to determine mineralogy of grains, type and amount of cement, and percent pore space. Selected thin sections were also examined to determine the degree of alteration of the sandstone by diagenesis or near-surface weathering. Pit-floor sediment was analyzed for particle size, and selected samples were examined for the presence of diagnostic tracer grains that were emplaced by Netoff in December 1992. The $CaCO_3$ content of selected sandstone cores was analyzed to determine if there are systematic variations in $CaCO_3$ content that might reflect selective dissolution of the $CaCO_3$ cement. Water samples from selected pits were collected in December 1992 and in March, May, and July 1993 to determine the magnitude of seasonal and diurnal fluctuations in water temperature and pH. Samples of weathered wall rock were examined for salts and other constituents that could promote the weathering of pit walls.

## RESULTS

### Cookie Jar Butte

The giant weathering pits at the Cookie Jar Butte site are usually circular in plan view, cylindrical in shape, have low width-to-depth ratios, and depths of closure of up to 16.5 m (fig. 3). Single pits occur locally, but they commonly occur in clusters; some are so closely spaced that they coalesce. Weathering pits occur on flat outcrops as well as on gentle to moderate slopes (up to 30 degrees) that face north, south, east and west (figs. 4, 5 and 6). A few of them occur on ridge crests and near isolated hilltops (fig. 6). Several of them are aligned along drainage courses (fig. 5), but most are not.

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[2]Width = average of maximum and minimum diameters measured at the inner part of the pit rim; depth of closure = lowest part of pit rim to top of sediment or to bedrock floor in pit.

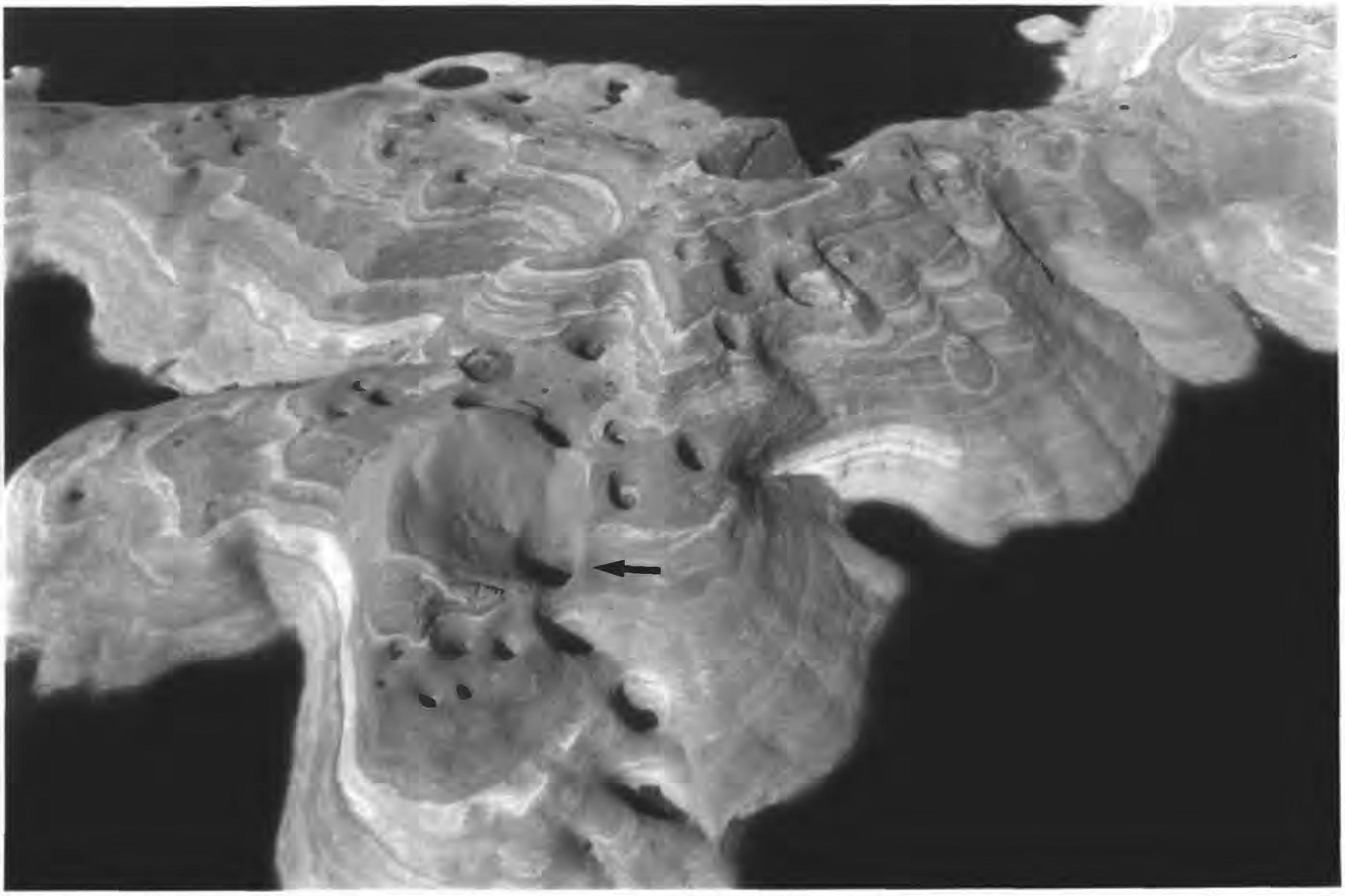

Figure 3. Low oblique aerial photograph of a cluster of pits southeast of Cookie Jar Butte. Note the circular shape of most of the pits and the large mass of structureless sandstone just left (south) of center. The pit at the base of the structureless sandstone (at head of arrow) is CJ-24, which has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

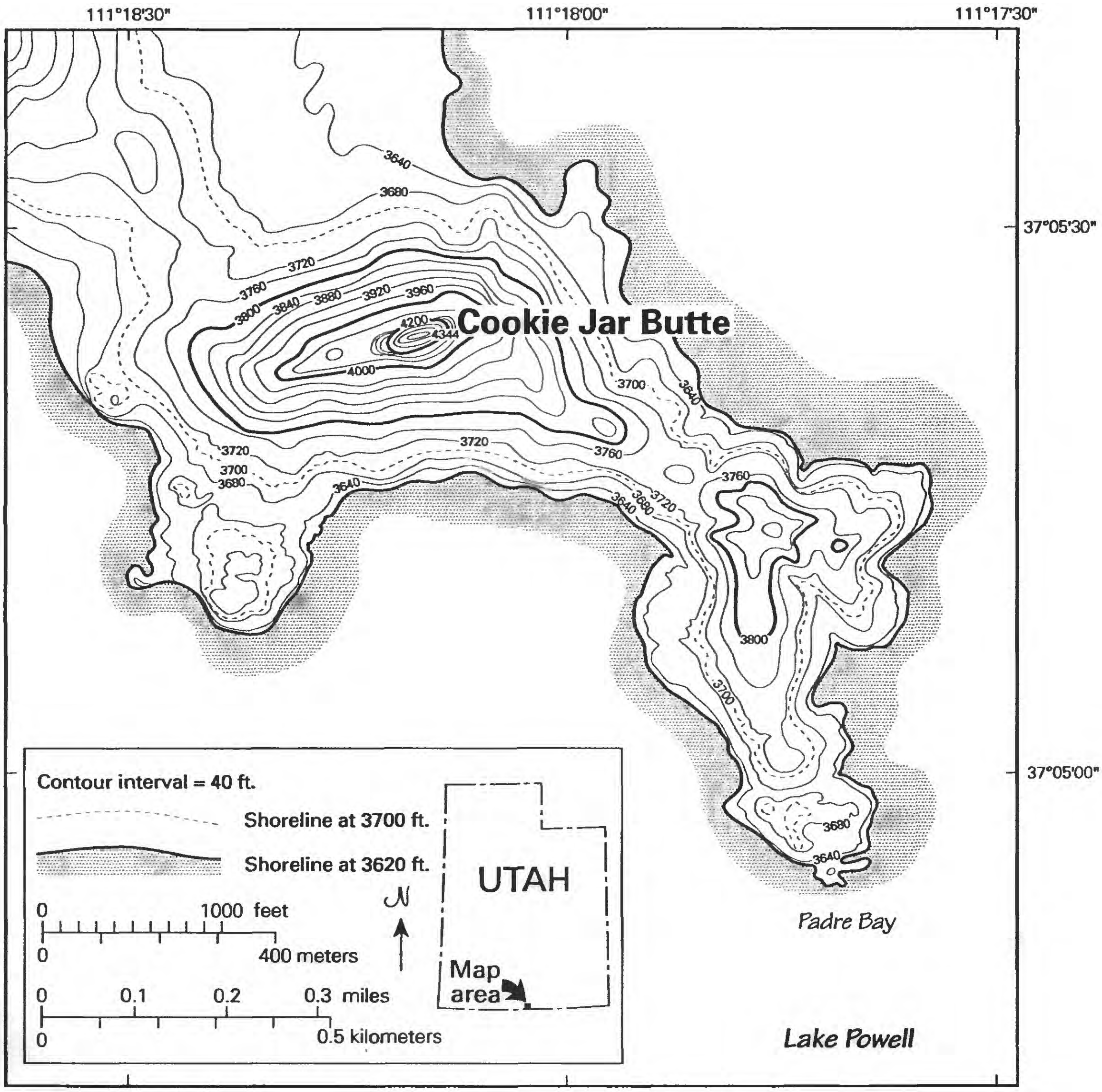


Figure 4. General location map of the Cookie Jar Butte site. Most of the sloping surfaces are outcrops of Entrada Sandstone. Cookie Jar Butte is capped by the Salt Wash Member of the Morrison Formation.

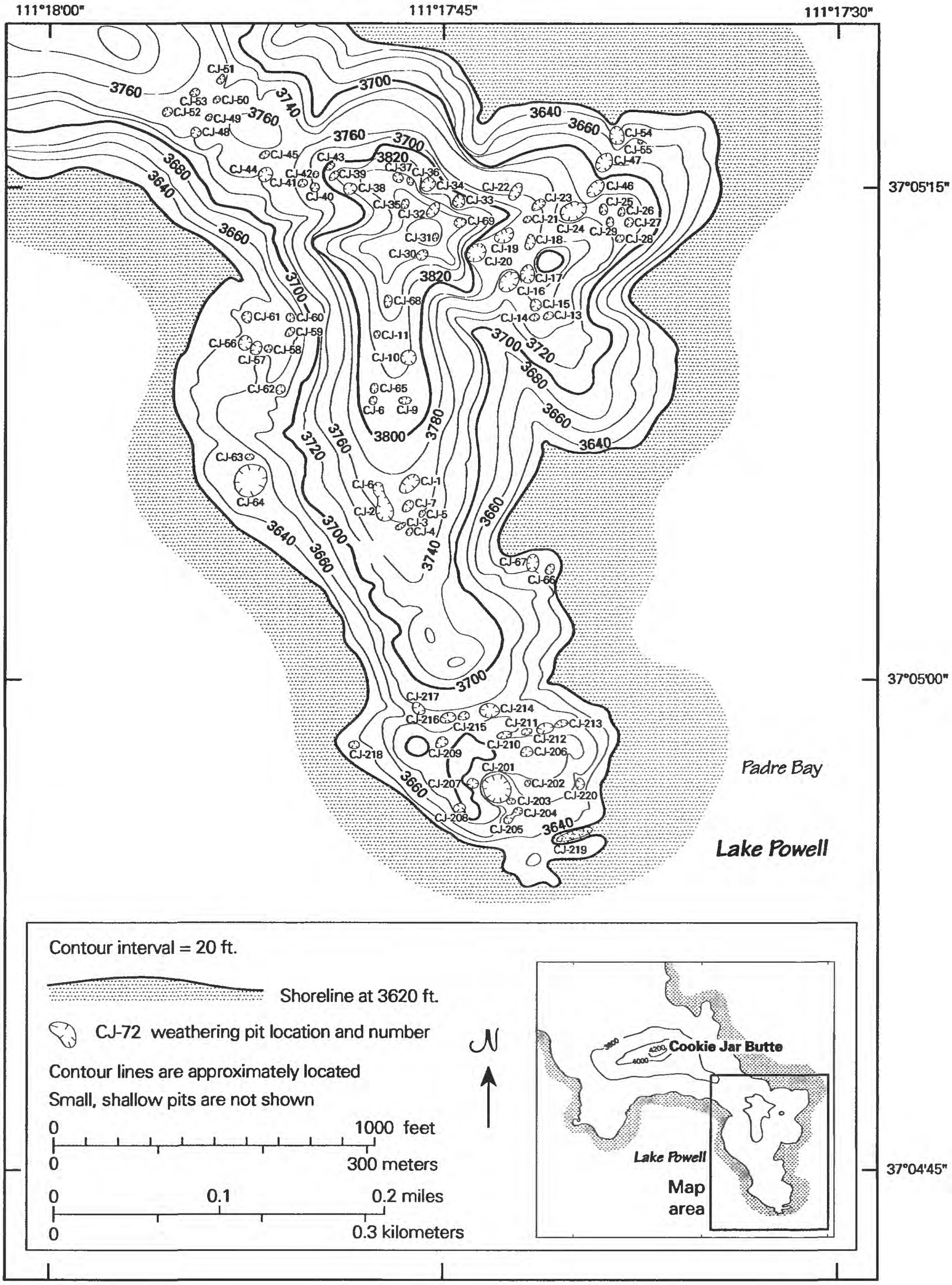


Figure 5. General location map of giant weathering pits southeast of Cookie Jar Butte.

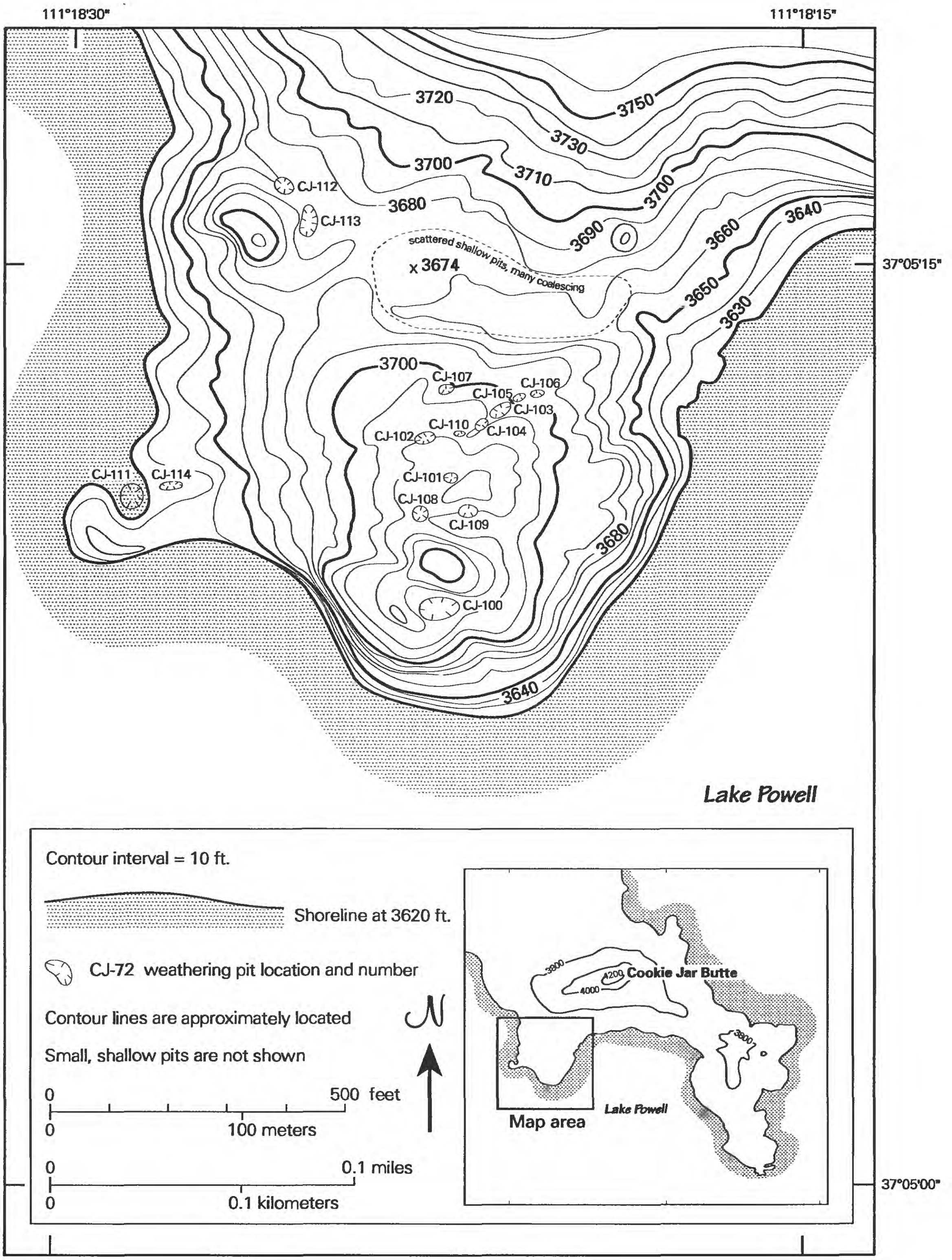


Figure 6. General location map of giant weathering pits southwest of Cookie Jar Butte.

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. 7 and Tables 1 and 2). They are similar in form to the pits commonly described in the literature, but differ significantly from them because of their large dimensions (fig.8). Only three of this type of pit were identified (fig. 7; tables 1 and 2). Two of the pans contained a loose sediment veneer on their floors that was thick enough to support sparse vegetation, and the other one appears to have contained water in it continuously for at least the past three years. It is not known how much of the water in the pit was supplied by rainfall versus how much remained from when lake levels were higher and the pit was inundated.

Bowls have gently-sloping sides and are roughly parabolic in cross-section (fig. 9). Most bowls have flat floors and a very thin layer of sediment that overlies the bedrock. They range in width from about 2 m to nearly 26 m and have relatively low width-to-depth ratios, which average about 7 (tables 1 and 2).

Cylinders have vertical or near vertical walls, flat floors, moderate to great depths (as much 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 in a few, the sediment is nearly one meter thick. The pits resemble giant drill holes, and have an average depth of about 6 m (fig. 10). Many cylinders contain water several meters to several tens of meters deep, which may remain for months or years when moist weather conditions prevail (fig. 11).

Armchairs are similar to cylinders, except part of the pit wall of the armchair has been extensively breached, presumably by some combination of channelized water flow, parallel slope retreat, and perhaps wind abrasion (fig. 12). Breaching reduces the depth of pit closure and results in higher width-to-depth ratios than for similarly-shaped unbreached pits (table 2). Armchairs occur on slopes that vary from a few degrees up to 30 degrees. Considerable antiquity of armchair pits is suggested by their occurrence 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 in order to maintain a closed bedrock depression.

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 (displacement of a few centimeters to a few meters) faults (fig. 13). Salt crystal growth is most obvious following periods of wet weather, such as the winter of 1992-93, and appears to promote

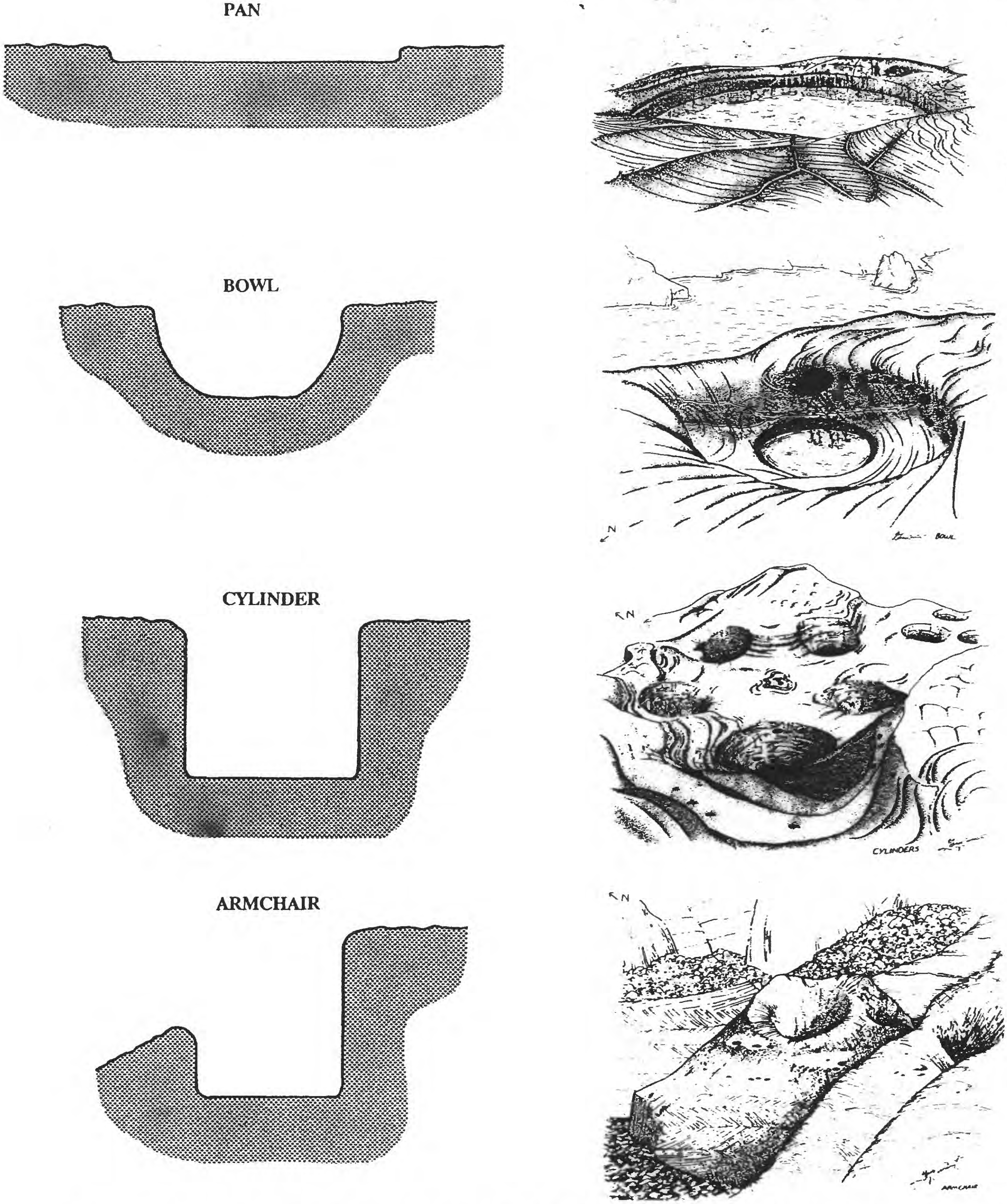


Figure 7. Types of weathering pits at the Cookie Jar Butte and Rock Creek Bay sites. Diagrams on the left are schematic cross sections; sketches on the right are oblique views of actual pits at the Cookie Jar Butte site (sketches by Gary Durant).

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

| Pit no. | W[1] (m) | D[2] (m) | W/D[3] | Pit type |
|---|---|---|---|---|
| CJ-1 | 15.1 | 3.7 | 4.1 | cylinder |
| CJ-2 | 18.1 | 1.9 | 4.6 | bowl |
| CJ-3 | 7.6 | 1.6 | 4.8 | bowl |
| CJ-4 | 5.9 | 2.1 | 2.8 | cylinder |
| CJ-5 | n.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 |
| CJ-102 | 14.3 | n.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 |

[1]W; width = average of maximum and minimum diameters measured at the inner part of the pit rim.

[2]D; depth of closure = vertical distance from the lowest part of the pit rim to the pit floor (bedrock or top of sediment).

[3]W/D; ratio of width to depth of closure (n.d., not determined).

Table 2. Comparison of width-to-depth (W/D) ratios for the four kinds of weathering pits at the Cookie Jar Butte site (T, total number of weathering pits; avg., average value).

| Cylinder | | Bowl | | Armchair | | Pan | |
|---|---|---|---|---|---|---|---|
| Pit no. | W/D | Pit no. | W/D | Pit no. | W/D | Pit no. | W/D |
| CJ-1 | 4.1 | CJ-2 | 4.6 | 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 = 33 | | T = 16 | | T = 10 | | T = 3 | |
| Avg. = | 2.7 | Avg. = | 6.9 | Avg. = | 10.8 | Avg. = | 13.2 |

Figure 8. The large water-filled pan-shaped pit at CJ-64 (foreground) measures 37.5 m wide and 4.6 m deep (photograph by D.I. Netoff).

Figure 9. The flat-floored bowl-shaped pit at CJ-109 (foreground) has a diameter of 6.4 m and a depth of closure of 2.3 m (photograph by D.I. Netoff).

Figure 10. The cylindrical-shaped pit at CJ-100 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 been half full of water recently (photograph by D.I. Netoff).

Figure 11. The partially breached cylindrical-shaped pit at CJ-201 (to the right of the person). When this pit was first observed in May 1990, the water was 16.5 m deep. The water level dropped 7.5 m by December 1992. The pit was flooded by the rapidly-rising waters of Lake Powell during the summer of 1993 (photograph by D.I. Netoff).

Figure 12. An armchair-shaped pit on a bedrock knob about 1.5 km east of Cookie Jar Butte. Note two people standing on the rim of the pit (photograph by D.I. Netoff).

Figure 13. Tafoni aligned along bedding planes at pit CJ-69. The pit walls are moderately well jointed, and although the joints and bedding planes influence the locations of the tafoni, they do not apppear to exert a strong control on the location or shape of pits near Cookie Jar Butte (photograph by D.I. Netoff).

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. The cause of spalling is unknown, but it may be due in part to exfoliation produced by rock expansion, as is suggested by the sets of closely-spaced, face-parallel joints that are locally present (fig. 14). Near-vertical walls on the north-facing sides of many of the pits appear 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 percent versus less than 1 percent lichen cover on non-north-facing pit walls.

A few pits expose a peculiar structureless sandstone in their walls and rims, which contrasts sharply with the ubiquitous cross-bedded sandstone that is characteristic of the Entrada (fig. 15). The contact between the structureless sandstone and the cross-bedded sandstone is irregular, and is commonly at steep angles to the horizontal. Locally, fragments of cross-bedded sandstone are present within the structureless sandstone. These relationships suggest (1) that the structureless sandstone postdates the cross-bedded sandstone and (2) the structureless sandstone may have been subject to liquefaction, perhaps during early diagenesis of the cross-bedded sandstone. Whether or not the locations and/or the form of some of the pits was controlled by these masses of structureless sandstone is unclear.

All pit types commonly have a thin veneer of loose, sandy sediment that covers their bedrock floor. 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. The differences in organic matter content probably resulted from alternating periods of pit desiccation, during which granular disintegration supplied mineral sediment to pit floors, versus periods of increased organic sedimentation that occurred when pits contained biologically-active water. In a few pits, the sediment is greater than one meter thick and is typically unstratified. The upper surface of these sediments is undulatory, and most likely was reworked by the wind (fig. 16). No artifacts or fossils were found in pit-floor sediment, nor have any buried soils been identified. Abrasive fragments larger than sand grains are rare in the pit-floor sediment, except for those pits that contain 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

Figure 14. The entire north wall of pit CJ-19 displays scars produced by spalling. Many of the scars appear to be recent (photograph by D.I. Netoff).

Figure 15. Structureless sandstone forms the rim of pit CJ-24 (middle foreground). The white, undulating line on the far side of the pit (arrow) is a zone of salts concentrated at the contact between the structureless and cross-bedded sandstones. Pit CJ-24 is 27.1 m wide, 14.9 m deep, and is one of the few giant weathering pits that is aligned along a well-defined channel of an ephemeral stream. Plunge-pool action has undercut the far rim of this pit, which will likely become a natural bridge (photograph by D.I. Netoff).

Figure 16. A cluster of giant pits, two of which contain moderately thick pit-floor sediment and a fairly mature vegetation community. Pit CJ-19 (lower left) is 14.3 m wide and pit CJ-16 (far upper right) is 22.9 m wide. Both of these pits are classified as pans (photograph by D.I. Netoff).

composition varies considerably from one pit to another. Grasses such as the foxtail chess (Bromus rubens), sand dropseed (Sporobolus cryptandros), and blue grama (Bouteloua barbata) are common dominants or codominants. 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 above species. Many other annuals are found locally in some pits.

There are no obvious lithologic or structural controls that determine the shape or location of the majority of the pits near Cookie Jar Butte. Joints and small-scale faults are present throughout the Cookie Jar Butte site. Most of them, however, are cemented with varying amounts of $CaCO_3$, which appears to strengthen the sandstone along these zones.

Thin-section analyses of near-surface sandstone cores collected at depths of 0-12 cm from pit rims, walls, and floors indicate that quartz makes up approximately 75 percent of the detrital grains. Most of the remaining grains consist of potassium and plagioclase feldpar, along with minor amounts of mica and rock fragments. The total amount of matrix between sand grains, based on point counts, is about 17 percent. Grains are typically subangular to subrounded, and the dominant grain sizes are medium to very fine sand (60-250 microns). Most quartz grains have distinct grain boundaries and show little or no evidence of dissolution. Feldspars are generally fresh to slightly weathered. Most quartz and feldspar grains are coated with iron oxide of variable thickness. Grains are loosely cemented with $CaCO_3$, which varies from 2.7 to 9.1 weight percent. 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-surface (0-14 cm) sandstone core samples.

Water samples collected from selected weathering pits near Cookie Jar Butte in December 1992, March 1993, and May 1993 indicate significant seasonal variations in pH (table 3). The average pH value of pit water sampled in December was 8.2; the average in March was 7.5; and the average in May was 9.0. Two pits sampled in May gave unusually high pH values of 9.4 and 9.5. The cause of seasonal variations in pit-water pH values is likely due to the combined effects of dilution by rainwater, biological activities, and chemical reactions of pit water with pit floor sediment as well as with the adjacent bedrock. The pH values recorded in March may reflect dilution of pit water resulting from an unusually wet winter in the Glen Canyon region.

## Rock Creek Bay

The mesa-top pits at Rock Creek Bay are generally more elongate than those at Cookie Jar Butte (fig. 17). The elongate

Table 3. Water temperature and pH values measured at selected weathering pits during December 1992, March 1993, and May 1993 (d., pit was dry and values were not determined; n.d., pit contained water, but values were not determined).

| Pit no. | December | | March | | May | |
|---|---|---|---|---|---|---|
| | pH | Temp. (°C) | pH | Temp. (°C) | pH | Temp. (°C) |
| CJ-6 | d. | d. | 7.6 | 19 | d. | d. |
| CJ-10 | d. | d. | 7.0 | n.d. | 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 |

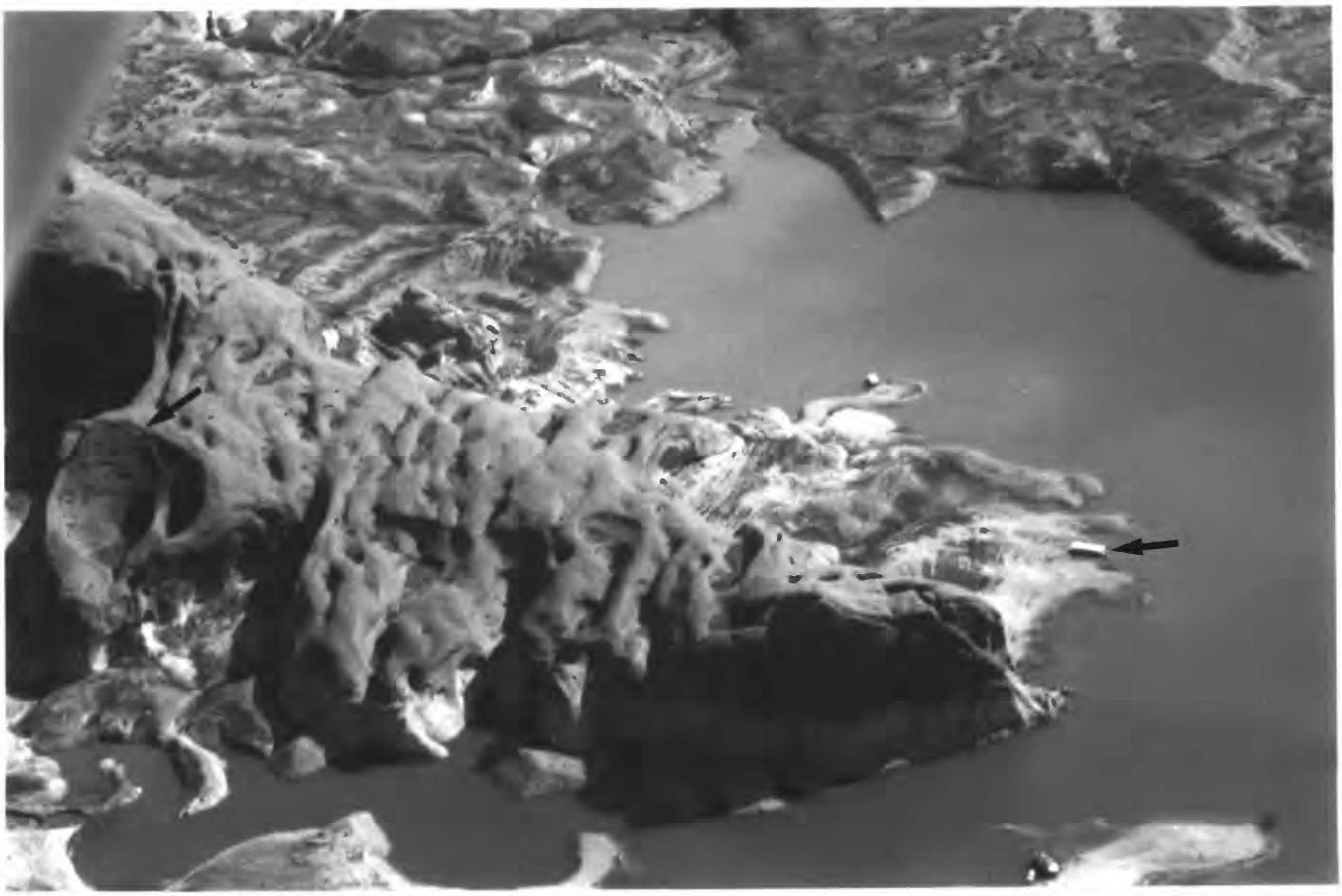

Figure 17. A low oblique aerial photograph of the numerous weathering pits at the Rock Creek Bay site (view toward northeast). Note the elongate shape of the pits. The arrow in the left middle ground points at pit RC-26, which is shown in figure 21. The arrow in the right middle ground points at a 15-m-long houseboat (photograph by D.I. Netoff).

form is likely due to the combined influence of joint control and pit coalescence. The long axes of these pits parallel the northeast strike of a set of linear and curvilinear joints (fig. 18). Pit enlargement along joints results in pit coalescence, giving the pits the appearance of a series of interconnected hourglasses. The long axes of several of these coalesced pits commonly exceed 35 m; the longest one measured 72 m. The breaching and coalescence of pit walls reduces the depth of closure, which is generally less than 6 m and averages 2.6 m. Four of the 10 pits measured are totally breached and have zero depth of closure. Breaching also increases the width-to-depth ratios and often makes it difficult to distinguish individual pits.

Pit elongation and coalescence also make classification of pits difficult. Four basic pit types can be identified where coalescence has not occurred, but with increasing coalescence, pits progressively lose their original form (figs. 19 and 20). Spectacular examples of what we refer to as "hanging pits" occur where the retreat of vertical cliffs has intercepted and completely breached pit rims (fig. 21).

The pits at Rock Creek Bay generally appear to be in a more advanced stage of development than those at Cookie Jar Butte. This is probably the result of accelerated pit development along joints, but may also be due in part to either the physical properties of the sandstone or perhaps the Rock Creek Bay site has been exposed to weathering and erosion for a longer period of time than the Cookie Jar Butte site. Our limited field work at the Rock Creek Bay site has left many intriguing questions unanswered; this area merits further investigation.

## ORIGIN AND AGE OF PITS

Several weathering process are thought to be important in pit initiation and growth; many of them are accentuated by the presence of discontinuities such as bedding planes, joints, and small-scale faults. Pit wall recesses such as tafoni 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 found concentrated within these recesses and it it likely that salt crystal growth plays a role in the weathering of pit walls. Salts may also catalyze quartz dissolution (A. Young, 1987), although we have not detected thin-section evidence of this process.

Other soluble substances may migrate to the rock surface by capillary action, crystallize, and create enough stress to induce granular disintegration. Calcite and gypsum have been suspected of causing granular disintegration in other studies, and we have observed minor calcite wedging in one of the sandstone cores as well as in some of the pit-floor sediment.

Clay mineral hydration and desiccation may also exert

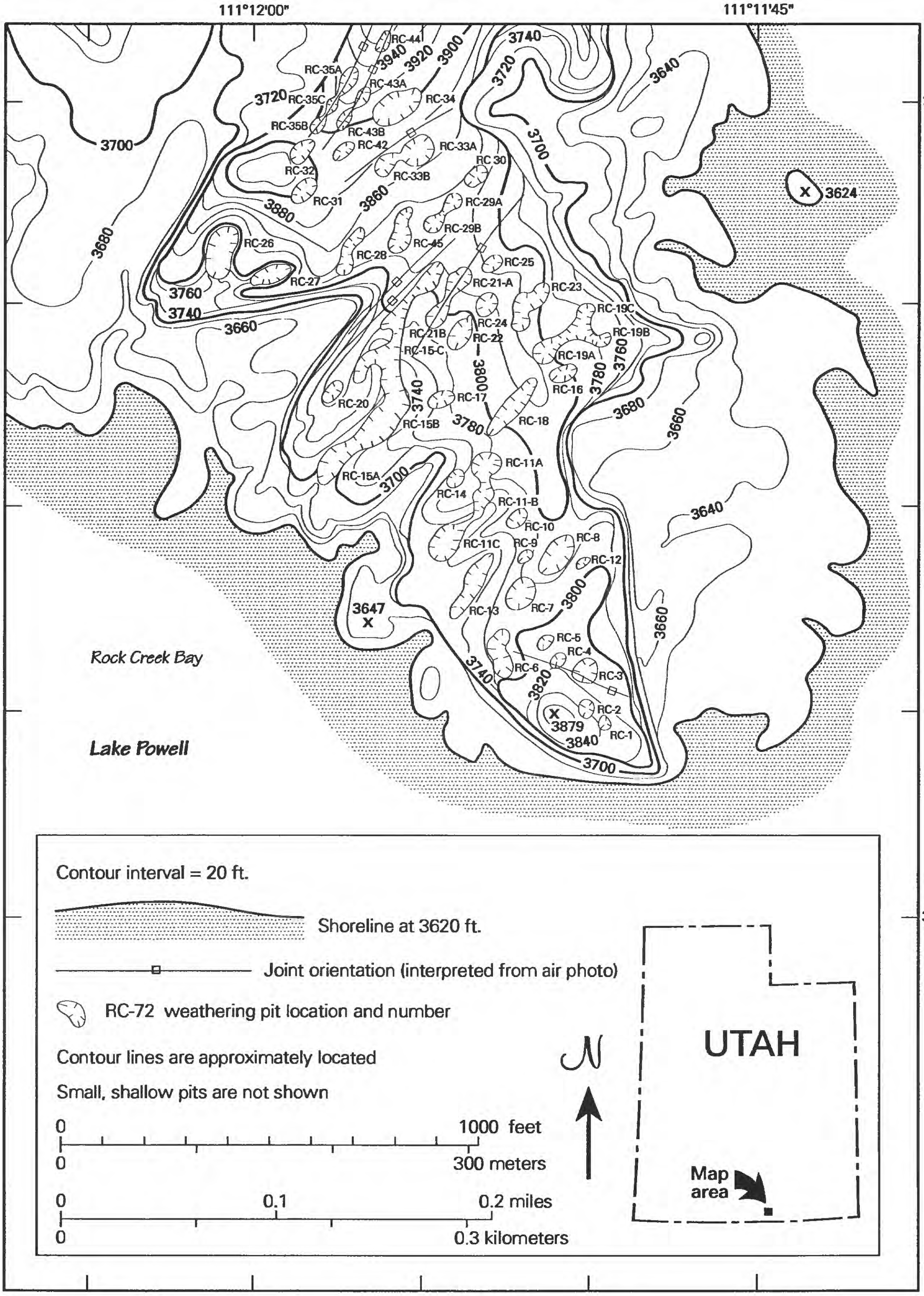


Figure 18. General location map of weathering pits at the Rock Creek Bay site. Note the elongate form and parallel trend of the pits and their alignment along major joints (map based on aerial photograph interpretation).

Figure 19. Early-morning shadows outline coalescing, joint-controlled pits indicated by arrows (RC-35B in the foreground; RC-35C in the middle ground; RC-35A in background). View is toward the northeast (photograph by D.I. Netoff).

Figure 20. An erosional escarpment (middle ground on left side of photograph) that is aligned along a major joint defines the northwestern boundary of pits RC-33A and RC-33B. View is toward the northeast (photograph by D.I. Netoff).

Figure 21. The "hanging" armchair-shaped pit at RC-26 (center of photograph) was not measured, but is estimated to be about 50 m in diameter. View is toward the west (photograph by D.I. Netoff).

disruptive forces in some sandstones (Netoff, 1971). Particle size analysis of a crushed core sample from near Cookie Jar Butte indicates that clay-size material is a significant component (5.7 percent) of the $CaCO_3$-free portion of the sample. Moreover, we have 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 but north-facing pit walls. Spalls parallel the pit walls, and at some sites several closely-spaced, wall-parallel joints penetrate several centimeters into 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, although the effectiveness of solar radiation has been debated for decades (Griggs, 1936, and Ollier, 1969).

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

Chemical weathering process that might be active in pit development include carbonation, dissolution, and hydrolysis. Dissolution of calcite cement may be important not only to initiate pit development, but also to continually free quartz grains which promotes pit enlargement. Thin-section analysis has not provided clear evidence of systematic calcite dissolution in sandstone exposed in pit walls and floors. Dissolution of quartz grains has been advocated for a variety of karst-like sandstone landforms by many geologists, but most of their examples have been from much wetter present or past environments, and the landscapes that they studied are extremely old. The absence of advanced stages of solution of quartz grains observed in thin section discounts solution as a major weathering process in pit development. The slight alteration of both plagioclase and potassium feldspar is likely the result of hydrolysis and perhaps dissolution, but many of these grains appear to be fresh, and consequently feldspar weathering is not believed to play an important role in pit development or the formation of diagenetic clays.

Biological activity has been advocated by several investigators as a causative process in weathering pit development; they site 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 at the Cookie Jar Butte site that we have observed when surface water temperatures exceed about $18^{o}$ C illustrate the intensity of organic activity in these miniature aquatic systems. In addition, the rock varnish on the north-facing walls of many pits may be due in part to organic stains produced by microorganisms. The high pH (9.5) measured in some pit waters should be conducive to silica dissolution (Birkeland, 1984). However, the lack of obvious dissolution features observed in thin-section analysis argues against this mechanism. 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 suggest that either (1) some types of biological activity promote pit wall stability or (2) pit wall stability permits the establishment of some types of biological activity.

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 does not clearly identify any single process or group of processes that account for the removal of weathering products from the pits.

Plunge-pool erosion is the combined effect of the hydraulic forces 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. 22).

Several of the 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, and there is at least one site where plunge-pool erosion is likely to eventually produce a natural bridge (fig. 15). Many pits, however, are not within an organized drainage system, and several of them are on ridge crests or near isolated hills (figs. 12 and 23). Whether or not paleochannels have 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 is not likely to account for pit enlargement.

There is little doubt 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 of a bowl-shaped, 1.6-m-deep pit near Cookie Jar Butte was rapidly removed by a 56 km/hr wind that was 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 floor.

Whether winds at the two study sites can deflate 100 micron-size quartz and feldspar grains out of deep and relatively narrow cylindrical depressions is a critical question. Strong

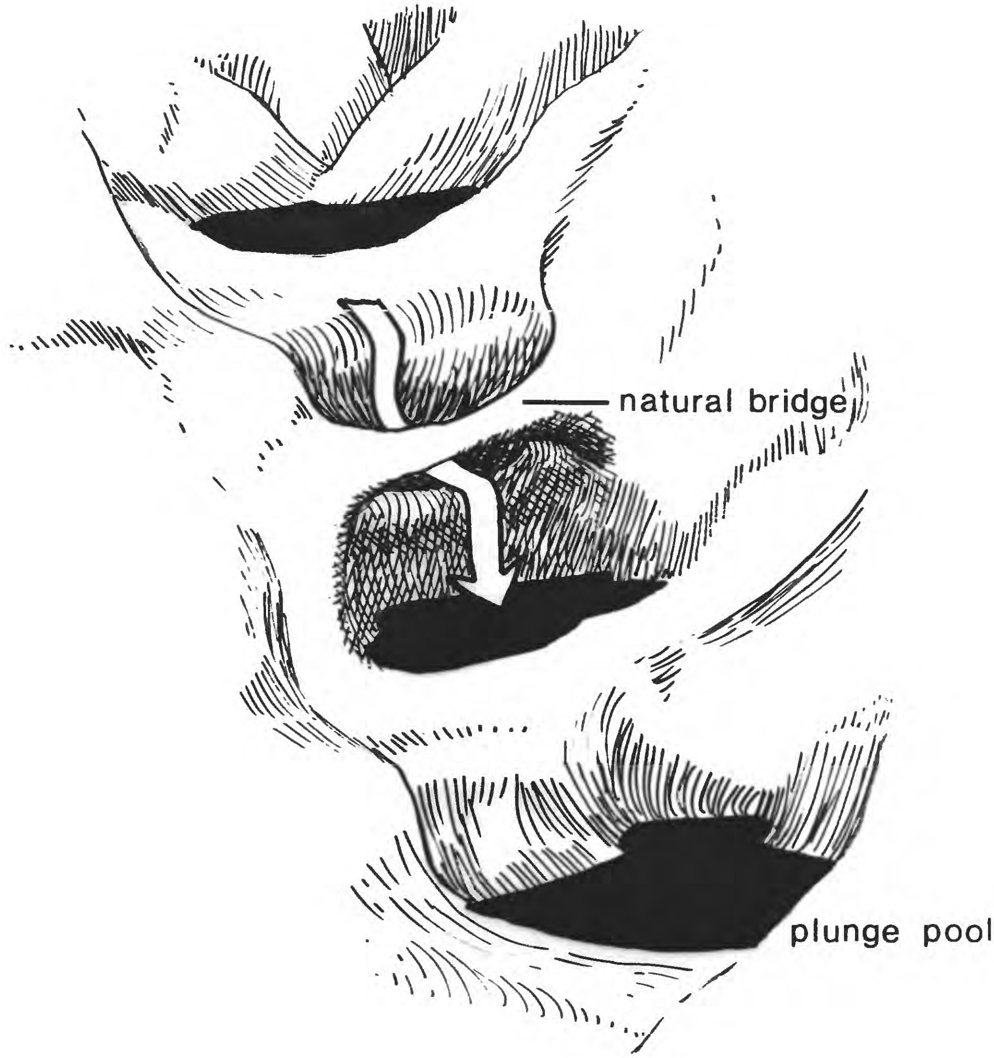


Figure 22. Sketch of plunge-pool basins of the type that commonly form in many of the tributary valleys of the Glen Canyon region (sketch by Nancy Stonington). Also shown is the development of a natural bridge. Compare this with pit CJ-24 in figure 15.

Figure 23. Low oblique aerial photograph of the bedrock knob upon which pit CJ-100 has developed (see arrow in middle foreground). Compare this with the ground-level view of pit CJ-100 in figure 10 (photograph by D.I. Netoff).

wind gusts of as much as 130 km/hr have been recorded on Lake Powell, and episodic winds on favorable topographic sites could be of far greater velocity. Pleistocene winds may have even been stronger than those of the present, when presumably high pressure gradients existed between the warm, low canyon floors and the ice-capped, high plateaus nearby to the north. Moreover, large areas of exposed sandstone in the Canyonlands region of southeastern Utah have been proposed as a possible source of some of the eolian silt in northwestern Colorado (Whitney and Andrews, 1983).

Arguments against wind deflation removing sediment 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 have formed on both the windward and leeward slopes of Cookie Jar Butte. Whether or not paleowinds have removed sediment from the floors of deep and relatively narrow cylindrical pits (e.g., CJ-100) is not known and would be difficult to prove.

Removal of quartz grains by dissolution or piping are attractive hypotheses, but no obvious dissolution features have been detected during thin-section examination of sandstone cores from near Cookie Jar Butte. Joints and small-scale faults at the Rock Creek Bay site may be wide enough to serve as conduits for the removal of sand, but these features have not been carefully examined for evidence of piping. Joints and small-scale faults that intersect pits at the Cookie Jar Butte site are usually cemented with moderately dense $CaCO_3$, and are less likely to transmit water than is the surrounding sandstone. The fact that many of the deeper pits retain water for months or years suggest that the walls and floors of these pits are relatively impermeable. It is possible that conduits wide enough to transport sand may have existed in the past, and have since been sealed by sand and $CaCO_3$, but no convincing evidence has been observed that would support this supposition.

Two other key questions are: (1) how old are the pits and, (2) are they relict features or are they still forming? The maximum limiting age for the pits is the time when the site of the highest pits was exposed to surficial processes, which is controlled by the level of the Colorado River and its tributaries. 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 sites, range from 80 to 250 m/m.y. (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 range in age of the highest (possibly the oldest) weathering pits would be 0.5-1.7 Ma. These values are in general agreement with estimates 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 sites, of at least 190 m/m.y. These rates yield estimated ages for the highest pits of about 0.8 Ma and at least 0.7 Ma, respectively. Based on the above age estimates, we infer that the oldest pits are no older than early Pleistocene.

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. It seems likely that pit wall weathering and pit excavation were active processes in the Pleistocene, and have continued throughout much of the Holocene.

One of the fundamental problems that relates to pit development still remains unanswered: why are giant sandstone weathering pits so restricted in their distribution, 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 the two study sites that would account for their limited distribution. Perhaps there were unique environmental conditions that set the stage and fostered the development of the giant pits and these or other conditions remain conducive to their continued development.

## CONCLUSIONS

The weathering pits at the Cookie Jar Butte and Rock Creek Bay sites are unusually large and deep. Four types that are identified near Cookie Jar Butte include pans, bowls, cylinders, and armchairs. The cylinders have very low width-to-depth ratios (commonly 1.3 - 3.7), and are the deepest of the four types (as much as 16.5 m). Most pits near Cookie Jar Butte are circular in plan view, which seems to result from a lack of structural control in their development. In contrast, pits at the Rock Creek Bay site tend to be elongate in plan view, which appears to result from joint control and pit coalescence. These pits do not readily lend themselves to morphologic classification as do the pits near Cookie Jar Butte, because of pit coalescence, but they are equally impressive in size.

Physical weathering mechanisms appear to dominate over chemical and biological mechanisms in pit development. Sediment removal processes include plunge-pool erosion, wind deflation, and possibly piping and dissolution; but in many pits, there is little tangible support for any specific causative mechanism or group of mechanisms. The ages of the pits are unknown, but they are most likely no older than earliest Pleistocene and show evidence of present-day growth.

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