SEDIMENT ACCUMULATION WITHIN WEATHERING PITS ON DANCE HALL ROCK, GRAND STAIRCASE-ESCALANTE NATIONAL MONUMENT, UTAH

by

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TABLE OF CONTENTS

CHAPTER **PAGE**

FIGURES

LIST OF FIGURES **PAGE**

TABLES

LIST OF TABLES PAGE

SEDIMENT ACCUMULATION WITHIN WEATHERING PITS ON DANCE HALL ROCK, GRAND STAIRCASE-ESCALANTE NATIONAL MONUMENT, UTAH

ABSTRACT: The purpose of this paper was to examine if the depth and degree of circularity of weathering pits affects the accumulation of sediment. Thirty pits were surveyed over two one-week periods on Dance Hall Rock. Weathering pits were measured to determine their maximum width, minimum width, vertical depth, and depth of pit-floor sediment. Additional descriptions of sediment texture, topographic position, orientation, weathering debris, evidence of particle movement by wind, and vegetation were also completed *in situ*. Stepwise multiple regression was performed using SPSS version 10. Vertical pit depth and an index of circularity were selected as the independent variables with sediment depth functioning as the dependent variable. Initial evaluation of the variables indicated that they were not normally distributed, therefore two regression models were developed to assess how the raw data and transformed data affected the model's explanatory ability. Although both models indicated that the depth and degree of circularity of a pit made significant contributions in explaining the variation in sediment depth, the residuals displayed sufficient non-normality to suggest that neither model was a "good fit". Field observations and statistical analysis indicate that these two measures of pit shape, alone, cannot account for all the variation in sediment depth. Rather that the accumulation and deflation of sediment is a complex process involving the interaction of numerous physical and biological factors.

Key Words: weathering pits, potholes, Dance Hall Rock, sediment accumulation, deflation, Colorado Plateau.

1. INTRODUCTION

> *"What is it about these formations that make them so fascinating to the viewer? It must be that they represent the rare and unusual in nature. Bare rock is less common than covered rock, smooth rocks rarer than rough rocks and light-colored rocks rarer than dark-colored ones."* (Stokes 1986: 126)

The Colorado Plateau, which is drained by the Colorado River and its tributaries, is an expansive mass of land that stretches across 400,000 km^2 and covers parts of Utah, Colorado, Arizona, and New Mexico (Baars 1993; Betancourt 1990). Elevations on the plateau range from 900 meters (3000 feet) in the desert lowlands to well over 3600 meters (12,000 feet) on the high plateaus (Baars 1993). "Physiographically, the major landforms are high plateaus on the upfolds, hogbacks on their flanks, lower plateaus between the upfolds, laccolithic complexes, and an intricate set of canyons" (Betancourt 1990: 261).

The plateau region has been sculpted by differential erosion over millions of years, producing varied landscapes and erosional features. Weathering pits, the focus of this paper, are one of erosional features commonly found on the Colorado Plateau. These phenomena are of special interest because of their distinctive and unique characteristics.

The term "pothole" is commonly used in the southwest region of the United States to describe confined bedrock depressions (Graham 1997). These depressions are also referred to as weathering pits, hollows, deflation basins, pans, rock basins, enclosed basins, cisterns, caldrons, huecos, dew holes, and tinajas (Goudie 1991; Howard and Kochel 1988; Netoff et al. 1995; Twidale 1990; Fairbridge 1968). This paper utilizes two terms, "potholes" and "weathering pits" (pits), depending on the size of the depression. The term potholes refers to comparatively small depressions ubiquitous on the Colorado Plateau sandstones, that range in size from extremely small hollows, no bigger than a fist, to larger pan shaped depressions (Graham 1997; Netoff et al. 1995). In contrast, the term "weathering pit" refers to deeper and wider depressions that have definable walls.

1.a. Research Question

Weathering pits are most notably found on the lower Entrada Sandstone of the Colorado Plateau, where vegetation is limited, surfaces are physically susceptible, and bare rock is exposed. Smaller potholes and pits are found throughout the plateau, yet *giant* weathering pits are found in only a few areas in southern Utah. These large pits occur in varying densities and topographic positions, as well as in various sizes, degrees of circularity, and vertical depths. Furthermore, the pits contain different types and depths of accumulated sediment and vegetation growth.

Wind deflation appears to be the primary mechanism of sediment removal on Dance Hall Rock. While other sediment removal processes have been proposed, such as "plunge-pool" erosion or dissolution and piping, the topographic position and retention of water within pits, argues against these two mechanisms. Current signs of weathering - including spalls, granular disintegration, and tafoni on the pit walls, as well as sediment excavation and recent bedrock debris on pit floors - have led researchers to believe that these pits are still actively enlarging (Netoff et al. 1995; Netoff and Shroba 2001). Additionally, the removal of sediment appears important to the ongoing growth of the pit, yet the accumulation of coarse fragments, vegetation, and physical or biological crusts can retard downward erosion by armoring the surface and preventing further wind excavation. It is clear that the deflation of sediment from pits is dependent upon the many variables that also affect the accumulation of sediment.

This paper describes the gross physical features present in the weathering pits on Dance Hall Rock, and examines whether deep weathering pits accumulate more sediment than shallower pits. Given that weathering pits are highly variable two general research questions will be explored:

1. Does the vertical depth and degree of circularity of a pit affect the amount of sediment it retains?
2. What do the variations in sediment depth and weathering pit characteristics suggest about sediment accumulation and deflation within pits?

2. SITE DESCRIPTION

2.a. Local Geology

Giant weathering pits have only been found in a few localities on the Colorado Plateau. A number of weathering pits are found on sandstone monoliths in the southeast portion of the Grand Staircase-Escalante National Monument, Utah. The Grand Staircase-Escalante National Monument lies on the western edge of the Colorado Plateau physiographic province. In this part of the Colorado Plateau, the "rocks dip gently northward, and are deformed by mostly north-south trending faults, anticlines, synclines, and monoclines" (Doelling et al. 2000: 189).

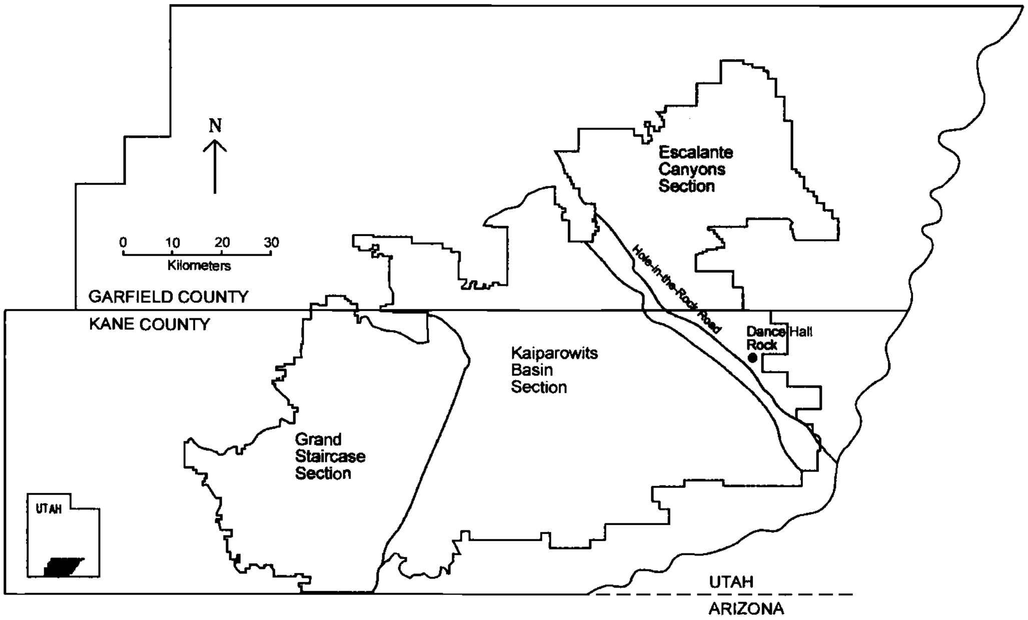

Figure 1. Map of the three sections comprising the Grand Staircase-Escalante National Monument, Utah.

Dance Hall Rock, a prominent sandstone outcrop, is located in the northeast Escalante Canyons Section of the monument toward the southern end of the gently dipping southwest limb of the Circle Cliffs Uplift (Doelling et al. 2000; Fillmore 2000). It is located approximately 40 miles down Hole-in-the-Rock Road. Figure 1 shows the location of Dance Hall Rock in relationship to the three geographical sections comprising the Grand Staircase-Escalante National Monument, Utah. Dance Hall Rock is approximately a 54 ha area and has an average elevation of 1440 meters (4725 feet). It lies on the sandstone benches between the Straight Cliffs on the southwest and the narrow canyons of the lower Escalante River drainage basin on the east (Doelling et al. 2000).

The rock units within the monument extend in age from the Permian to the Cretaceous (Doelling et al. 2000). The bedrock stratigraphy surrounding Dance Hall Rock, however, ranges in age from the upper Triassic to upper Jurassic (Doelling et al. 2000; Fillmore 2000). The rock units (from oldest to youngest) include the Navajo Sandstone (upper Triassic/lower Jurassic), Page Sandstone (middle Jurassic), Paria River and Winsor Member of the Carmel Formation (middle Jurassic), the Gunsight Butte Member of the Entrada Sandstone (middle Jurassic), Romana Mesa Sandstone (middle Jurassic), and Salt Wash Member of the Morrison Formation (upper Jurassic) (Doelling et al. 2000; Fillmore 2000).

Changing environmental conditions on the Colorado Plateau are reflected in the stratigraphy of the rock units. The Navajo Sandstone was deposited during the late Triassic/early Jurassic Period when the region was covered by large sand dunes that extended from southern to northern Utah

(Stokes 1988; Baars 1983). Near Dance Hall Rock, the Navajo Sandstone is overlain by the Page Sandstone, Carmel Formation, and Entrada Sandstone, which were deposited during the middle Jurassic as shallow seas from Canada transgressed and regressed across parts of Arizona, Utah, Wyoming, and Montana (Stokes 1986; Hintze 1988; Fillmore 2000). The Page Sandstone was deposited on the landward side of the Carmel Sea as dune and beach deposits (Doelling et al. 2000). The Carmel Formation was deposited under shallow marine conditions, and near Dance Hall Rock is composed primarily of sandstone and siltstone containing thin to medium beds of gypsum (Hintze 1988; Stokes 1986; Baars 1983; Doelling et al. 2000). As the seas retreated, the shallow marine environment was replaced by a more arid wind-blown dune environment, which formed the Entrada Sandstone (Doelling et al. 2000; Fillmore 2000; Baars 1983). During the upper Jurassic, as the climate became somewhat wetter, the Morrison Formation was deposited by north-east flowing rivers interspersed with floodplain and shallow lake deposits (Baars 1983; Hintze 1988; Doelling et al. 2000).

Dance Hall Rock lies within the lower member (Gunsight Butte) of the Entrada Sandstone, which overlies the upper member (Winsor) of the Carmel Formation (Doelling et al. 2000). The Gunsight Butte Sandstone is orange-brown to red orange and is characterized as being very fine to fine-grained sandstone (Doelling et al. 2000). This is a silty arkosic sandstone containing subrounded to rounded quartz grains (Doelling et al. 2000; Netoff et al. 1995). The beds display large-scale cross bedding with thin lenses of brown mudstone

(Doelling et al. 2000). Netoff et al. (1995; 2001) found that the lower Entrada Sandstone near Cookie Jar Butte (19 miles to the southwest) was porous and weakly cemented with calcite and clay. Locally, the contact between the underlying Winsor Member (Carmel Formation) and the Gunsight Butte Member (Entrada Formation) is very irregular. It appears as if the large Entrada outcrops have "sunk" into the Upper Carmel Formation due to post-depositional disturbance (Doelling et al. 2000; Fillmore 2000).

The smooth, rounded Entrada outcrops are prominent features along Hole-in-the-Rock Road. Figure 2 is a picture of the southwest front of Dance Hall Rock as visible from Hole-in-the-Rock Road. These monolithic "slickrim" domes include Dance Hall Rock, Sooner Rocks, Cave Point and Lone Rock.

Figure 2. The southwest face of Dance Hall Rock.

Although all of these outcrops contain pits of various sizes on their surfaces, giant weathering pits are primarily exposed at Dance Hall Rock, Sooner Rocks, and Cave Point.

2.b. Climatic History: Late Pleistocene to the Present.

The climatic history of the Colorado Plateau has been primarily reconstructed using ^{14}C dating on plant macrofossils contained within numerous ancient packrat middens (Betancourt 1990; Fillmore 2000). These fossil records have been used to create a general climatic history of the Colorado Plateau based on changes in the geographic distribution of vegetation since the Late Pleistocene (Betancourt 1990; Thompson et al. 1993). The arid conditions of the Colorado Plateau are ideal for the preservation of ancient middens, which provide the most abundant and detailed record concerning the Late Pleistocene/Holocene environment (Fillmore 2000).

During the Late Pleistocene (approximately 18,000 yr B.P.), climate conditions on the Colorado Plateau were generally cool and dry during the summer, and cool and wet during the winter (Betancourt 1990; Thompson et al. 1993; Patton et al. 1991). The depression of vegetation zones suggest that summer temperatures were cooler than present day (Betancourt 1990; Thompson et al. 1993). For example, plant fossils indicate that the elevation of vegetation on the plateau, including Blue Spruce, Rocky Mountain Juniper, sagebrush, limber pine, Engelmann spruce, and subalpine fir were depressed approximately 600 to 1200 meters below modern levels (Thompson et al. 1993; Betancourt 1990; Fillmore 2000). Furthermore, the absence of ponderosa pine and low abundance of summer-flowering herbs and grasses imply that summers were also drier than present day (Betancourt 1990). Yet many of the lakes in and around the Colorado Plateau either contained fresh water or were moderately deeper than they are today, suggesting that winters were wetter than at present (Thomson et al. 1993; Betancourt 1990). Based on these vegetation and hydrologic records, the plateau was dominated by a cool-dry summer/cool-wet winter regime during the Late Pleistocene (Betancourt 1990; Thompson et al. 1993; Patton et al. 1991; Peterson 1994).

Changes in the plateau's vegetation zones and composition occurred during the transition into the early Holocene, between 12,000 – 9,000 yr B.P. (Betancourt 1990; Patton et al. 1991). In the early part of this period, the region was still covered by a woodland environment dominated by montane and subalpine conifers, indicating that the climate was still cooler and wetter than modern levels (Thompson et al. 1993). Vegetation fossils indicate that changes in temperature and precipitation patterns began to occur at about 10,000 yr B.P., allowing many plants to increase their range northward as well as to higher elevations on the Colorado Plateau (Betancourt 1990; Thompson et al. 1993; Fillmore 2000). Although the northward migration of various species (including Utah juniper, spruce, little-leaf mountain mahogany, single-leaf ash, and hackberry) indicates a gradual change from a cool winter-wet/summer-dry regime to a slightly warmer, more arid climate, vegetation fossils also indicate that cool-moist summer conditions still predominated, allowing some species (sagebrush, Utah juniper and other montane conifers) to persist at unexpectedly low elevations where they are no longer found (Betancourt 1990; Thompson et al. 1993). Hence, plant assemblage migration patterns indicate that by 9,000 yr B.P. the climate was slightly warmer than at present, but with greater summer rainfall, i.e., the plateau still had greater moisture than today (Thompson et al. 1993; Betancourt 1990; Patton et al. 1991).

The early to middle Holocene (9,000 – 6,000 yr B.P.) was marked by increasing aridity and temperatures on the Colorado Plateau. However, "even during the latter part of this period, commonly associated with hot-dry conditions…, it appears to have been wetter than today on the Colorado Plateau" (Betancourt 1990: 286). Betancourt (1990) and Thompson et al. (1993) both agree that the increase of ponderosa pine and Gambell oak on the Colorado Plateau appear to indicate that there was an increase in summer precipitation, even above the present level. The increase in summer precipitation was due to greater subtropical moisture likely caused by either changes in air-flow patterns generated by an enhanced Bermuda High, or simply the occurrence of more tropical storms (Betancourt et al. 1990; Patton et al. 1991; Peterson 1994).

The climate of the Colorado Plateau has continued to increase in aridity throughout the Holocene (Fillmore 2000). Plant fossils from plateau middens 2,000 yr B.P. are similar to the modern vegetation, suggesting that the modern climate was largely established by then (Patton et al. 1991). The present climate of the Colorado Plateau ranges from arid to semi-arid and is often harsh and varied, caused, in part, by elevation and aspect differences in the local topography (Netoff et al. 1995; Thompson et al. 1993; Patton et al. 1991). Extreme variations in precipitation, temperature, and wind conditions occur both seasonally and daily and have a high degree of spatial variability (Graham 1997).

Yearly precipitation throughout the Colorado Plateau displays a strong bimodal pattern with maximum rainfall in the summer and secondary peaks in the spring and fall (Graham 1999; Thompson et al. 1993; Peterson 1994). Summer rainfall is associated with the "monsoonal" flow from the Pacific or Gulf of Mexico, as well as thermal convective showers (Thompson 1993; Peterson 1994). Autumn, winter, and spring precipitation is caused by the migratory flow of low-pressure cells from the Pacific (Thompson 1993; Peterson 1994). The mean annual precipitation at Bullfrog Basin, Utah (20 miles to the northeast of Dance Hall Rock) is 15 cm (6 inches) (National Climatic Data Center 1971-2000 Monthly Normals).

Temperatures on the Colorado Plateau display extreme seasonal and daily fluctuations. The mean annual temperature at Bullfrog Basin, Utah is generally 15° C (59.2° F), however peak summer temperatures can exceed 35° C (95° F), and in the winter, temperatures can drop below 0° C (32° F) (National Climatic Data Center 1971-2000 Monthly Normals). In addition, daily temperature variations can often surpass 10° C (50° F), especially in the spring and fall (Netoff et al. 1995).

The wind regime on the Colorado Plateau is highly variable and localized, with the strongest winds occurring in the early spring, fall, and early winter (Peterson 1994; Netoff et al. 1995). Generally, winds prevail from the southwest and can be quite strong; for example wind gusts as high as 137 kmh

(85 mph) have been recorded on Lake Powell (Netoff et al. 1995; Peterson 1994). Strong wind gusts are associated with the leading edge of storm fronts, which also typically approach from the southwest.

3. MECHANISMS ASSOCIATED WITH WEATHERING PIT DEVELOPMENT AND ENLARGEMENT

Limited studies of weathering pits on the Colorado Plateau indicate that the presence of moisture, wind, and salt in arid lands create an environment in which many chemical and physical weathering agents promote the formation and enlargement of weathering pits (Birkeland 1999). The literature explains that sandstone may be weakened and disintegrate due to a number of mechanical and chemical processes. Although there is no consensus among researchers as to the *principal* cause of pit development and enlargement, it is generally accepted that some combination of chemical and physical weathering - including freeze/thaw cycles, thermal stress, salt weathering, clay hydration, biochemical weathering, and calcite and quartz dissolution - is responsible. (Birkeland 1999; Boggs 2001; Fairbridge 1968; Goudie 1991; Howard and Kochel 1988; Netoff et al. 1995; Netoff and Shroba 2001; Young and Young 1992). These weathering processes are explored in further detail below.

3.a. Mechanical Weathering Agents

The freeze-thaw cycle of water can generate sufficient internal pressure changes to rupture rock, as well as weaken and disintegrate sandstone over time (Birkeland 1999; Boggs 2001). Water is often found at the bottom of pits, as well as in pit wall features such as fractures, alcoves, and tafoni (Netoff et al. 1995). Repeated freezing and thawing of water contained within pits may generate enough force to fracture the rock, generally along preexisting microfractures within the sandstone, promoting granular disintegration, as well as spalling of large, angular blocks from the pit walls (Boggs 2001; Birkeland 1999; Netoff et al. 1995). It is not clear to what extent freezing and thawing promotes this process; however, it has been hypothesized that shales and sandstones may disintegrate more readily since they are not as strongly cemented as other rock types (Boggs 2001).

On the Colorado Plateau, the surface temperature of sandstone fluctuates both daily and seasonally. These temperature differences can create internal stresses which can weaken granular bonds over time, in turn causing particle disintegration or spalling on the surface of the bedrock (Birkeland 1999; Young and Young 1992). Many weathering pits on the Colorado Plateau occur on smooth, unvegitated sandstone outcrops where *surface* temperatures can exceed 50° C (122° F) in the summer and drop well below -20° C (-4° F) in the winter (Findley 1975; Graham 1997). Findley (1975) also noted that in shallow potholes, diurnal temperature changes could be as high as –1° C (30° F). Although many studies debate whether thermal stress is an effective weathering agent, at the very least, it seems likely that these fluctuations in surface temperature may weaken sandstone, making it susceptible to other forms of physical and chemical weathering (Young and Young 1992; Birkeland 1999).

The hydration of clay minerals and lichen growth, in conjunction with moisture content, is another physical weathering agent that may contribute to further pit enlargement. The expansion and contraction of clay minerals, contained within the pit floor sediments, is capable of plucking or dislodging granules from the surrounding sandstone bedrock (Netoff et al. 1995; Birkeland 1999). Lichen has also been observed within some pits and may contribute to both physical and chemical weathering. When the lichen contracts during a dry spell, loose sandstone fragments that have become attached to the underside of lichen may be pulled away from rock surface (Birkeland 1999). Furthermore, lichen presence may enhance biochemical weathering of the sandstone surface.

Several processes are principal to the physical weathering of sandstone by salts including crystal growth, thermal expansion of crystals, and hydration of crystals (Birkeland 1999). Furthermore, the evaporation of water within weathering pits helps to localize salts, which are often visible within pit wall recesses (Goudie 1991). Capillary migration and the subsequent surface crystallization of saline solutions, such as gypsum, calcite, and salt, "generate internal pressures that can force cracks apart or cause granular disintegration of weakly cemented rocks" (Boggs 2001: 4). Increases in surface temperature can also cause existing crystals to expand, dislodging both individual grains and blocks of sandstone (Birkeland 1999; Netoff et al. 1995; Boggs 2001). Finally, the hydration of salt crystals localized in pore spaces, tafoni, fractures, joints, and other discontinuities within the pit can produce sufficient stress to cause extensive spalling and rock disintegration (Birkeland 1999; Netoff et al.

1995). Hence, it is generally accepted that the presence of salt and moisture play a significant role in pit enlargement (Netoff and Shroba 2001).

3.b. Chemical Weathering Agents

Dissolution of both calcite and silica has been proposed as the *primary* mechanism behind pothole formation and enlargement by various authors who argue that ponded water on surface depressions promotes pit development by enhancing and localizing various chemical and physical weathering processes (Fairbridge 1968; Howard and Kochel 1988; Ritter et al. 1995). Although Howard and Kochel (1988) maintain that potholes and pits on Navajo and Entrada Sandstones result from calcite dissolution, they offer scant evidence to support their claim. Other authors have noted that biological activity from algae, lichen, and dark organic stains can alter the pH of pit water, creating an alkaline environment that is conducive to silica dissolution (Birkeland 1999; Boggs 2001; Netoff et al. 1995). Yet analysis of multiple weathering pit samples by Netoff et al. (1995) found some evidence of calcite dissolution, but "no evidence of *extensive* dissolution of quartz grains" (46), even at high pH levels.

The role of dissolution in weathering pit formation and enlargement continues to be the subject of debate. Although it is apparent that dissolution contributes to the formation of pits in many different localities and lithologies, many of these pits are either underlain by thick evaporite beds (e.g., salt, gypsum, and limestone) or originate from much older and wetter environments (Netoff et al. 1995; Goudie 1991). While most researchers agree that dissolution does have an effect on the formation and enlargement of pits on the lower Entrada sandstone, what remains at issue is the *extent* to which it contributes to pit development and its continued impact on the growth of giant weathering pits.

3.c. Sediment Removal Mechanisms

The continued enlargement of weathering pits appears to depend on the ongoing deflation of pit-floor sediment that is derived from the multiple chemical and physical weathering mechanisms (Goudie 1991; Netoff and Shroba 2001). The deflation of pit sediment is necessary to prevent complete infilling of the pit and to remove weathered material from the sandstone surface of the pit which could armor the surface and potentially prevent downward erosion (Goudie 1991). "Pit-infilling sediments comprise: residual mineral material produced due to rock weathering in-situ, material washed-out from the surface…and transported by wind, as well as allochthonous and autochthonous organic substance" (Alexandrowicz 1989: 280).

As with pothole formation, there is no consensus among researchers as to the *primary* mechanism of sediment removal. Many believe that wind is largely responsible for removing sediment, whereas other authors maintain that "plunge-pool" action or subsurface dissolution and piping are the principal mechanisms. While further research is needed to determine the specific mechanisms behind giant weathering pit formation, the ongoing excavation of sediment seems crucial to weathering pit growth.

It is no surprise that pits organized along drainage paths are susceptible to the corrosive action of channalized water, where the gradient and drainage areas are sufficient to support "plunge-pool" erosion (Netoff et al. 1995). "Plunge-pool" erosion occurs when water attains a flow velocity that is capable of not only removing and depositing sediment, but also of eroding and enlarging pits (Howard and Kochel 1988; Netoff et al. 1995). However, many of the giant weathering pits that have significant sediment removal at Dance Hall Rock, Sooner Rocks, and Cookie Jar Butte are not located along drainage paths, but rather, they occur in isolation along divides or fairly level surfaces where water cannot be sufficiently channalized (Fairbridge 1968; Howard and Kochel 1988; Netoff et al. 1995; Netoff and Shroba 1997). Therefore, the removal of sediment from these giant weathering pits must result from other sediment removal mechanisms, such as dissolution and subsurface piping, or wind.

Dissolution of silica and calcite has been presented as a mechanism of removing sediment, in addition to being a means of enlarging weathering pits. Yet, many pits retain water for months to years, indicating that most of the joints, fractures, walls, and floors of pits are either relatively impermeable or sealed with calcite cement (Netoff et al. 1995; Netoff and Shroba 1997; Goudie 1991). Furthermore, as Netoff et al. (1995) noted, many pit samples show limited evidence of calcite cement or quartz dissolution. Although a small amount of sediment may be removed through the process of dissolution and subsurface piping, the work by Dr. Netoff (Netoff et al. 1995; Netoff and

Shroba 1997; Netoff and Shroba 2001) suggests that the dissolution of silicate grains and removal by ground water is negligible (less than 2 percent). Consequently, wind appears to be the primary agent of sediment removal from pits located on the Colorado Plateau (Netoff and Shroba 1997; Netoff and Shroba 2001)

Wind is an especially effective agent of erosion and deflation, particularly when it exists in conjunction with physically-susceptible materials, an arid or semi-arid climate, and where the surface is not armored by lag material (Graf et al. 1987; Goudie 1991). Furthermore, it appears that strong winds are capable of excavating sediment from pits, particularly when the sediment has limited vegetation or surface crust cover, minimal sediment moisture, and the particle size is neither too coarse nor too fine (Goudie 1991; Netoff and Shroba 2001; Netoff et al. 1995). Preliminary experiments by Netoff and Shroba (1997) found that various distinct wind patterns are, at times, present within very deep pits (> 12 meters). These wind vortices and rotors are capable of flattening pit-floor vegetation and producing sediment structures on the floors of weathering pits, such as ramps, ridges, and active sand dunes (Netoff and Shroba 1997; Netoff and Shroba 2001). Although many researchers agree that strong winds can remove sediment from shallow to moderately deep pits, the question remains, what factors affect the deflation of sediment from within pits.

4. FIELD WORK

Of the many weathering pits located on Dance Hall Rock, thirty pits were selected for analysis. Observations and field data were collected over two one-week periods during the summer (August 17 –23, 2001) and early spring (March 10-16, 2002). Sixteen pits were documented during the first visit and an additional fourteen pits during the second visit. Small-scale field maps were created at a scale of approximately 1:7,700 using 1:24,000 U.S. Geological Survey topographic maps and digital orthophoto quadrangles (DOQ).

Several parameters determined the selection of pits for sampling. Depressions that appeared to be simply a low point in the topography and did not clearly have a measurable depth, failed to meet the definition of a "pit". In addition, small, shallow depressions typically found on various sandstones within southern Utah were also excluded. Finally, areas where the Entrada Formation appeared to be "sunken" into the upper part of the Carmel Formation were avoided. After eliminating those considered unsuitable, selection of sampled pits was influenced primarily by elevation, orientation, accessibility, and position to ensure representative selections.

4.a. Methods

Weathering pits were measured to determine their maximum width, minimum width, vertical depth, and depth of pit-floor sediment. The maximum and minimum widths were measured on the rim, across the pit, from top-edge to top-edge of the enclosure. The vertical distance was determined from the top of the lowest rim to the surface of the pit floor. Sediment depth was measured only in weathering pits that had sediment which were safely accessible. Depths of sediment were determined by using a marked metal rod at ten systematic, non-aligned sampling points and averaging the results.

Weathering pits were also described and photographed in detail. Descriptions included sediment texture, topographic position, orientation, presence of weathering debris, evidence of particle movement by wind, and estimates of vegetation density and type. Furthermore, in compliance with Monument restrictions, no samples were removed and precautions were taken to limit disturbance to pit-floor communities. Instead, pit-floor sediment and vegetation were studied *in-situ* and photographs were used to document pit-floor sediment structures, vegetation, and weathering debris.

4.b. Observations and Descriptions

4.b.i. Location

The weathering pits found on Dance Hall Rock are generally found on level to moderately sloping sandstone surfaces (10 to 20 degrees), occur in isolation, clusters, or along low gradient drainages, and appear to be preferentially oriented. Although other studies have found that weathering pits display no preferential orientation (Netoff et al. 1995; Howard and Kochel 1988), a majority of the pits on Dance Hall Rock have a general orientation of northeast to southwest. Figure 3 is an aerial photo of Dance Hall Rock (approximately 1:6,500 using a 1:24,000 DOQ) that shows the general orientation and shape of the larger weathering pits, as well as the three areas where the pits were described.

Weathering pits were selected to represent three different topographical areas (figure 1) on Dance Hall Rock: Area 1 (approximately 1440 meters (4725 feet)); Area 2 (approximately 1433 meters (4700 feet)); and Area 3 (approximately 1453 meters (4768 feet)). Vertical pit depth, sediment depth, and degree of circularity, as well as the amount of vegetation, coarse fragments, and water varied for pits within each area. Some common features, beyond elevation, did, however, characterize the three areas.

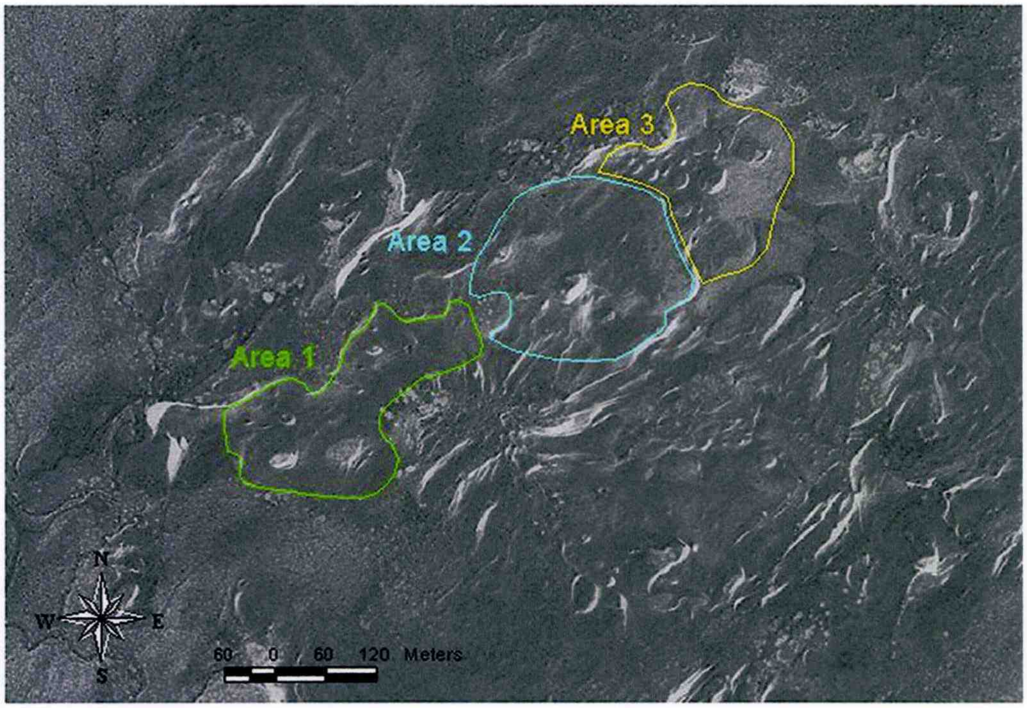

Figure 3. Aerial photo of Dance Hall Rock with sampling areas outlined

The pits in Area 1 varied between those that contained sediment with dense vegetation, those with sediment and little to no vegetation, and those with no sediment or vegetation. The sediment within pits was predominantly very fine to fine-grained with little to no evidence of coarse fragments and, in general, the pits that had the greatest sediment depth and most abundant vegetation were found in this area.

Many of the pits in Area 2, which have a lower elevation than the pits in the other two areas, contained fine-grained sediment intermixed with varying amounts of coarse fragments. Pits in this area were also often shallower than in the other areas. Although vegetation was present, it tended to concentrate where sediments were deepest with sparse coverage elsewhere. Area 2 pits all occurred below the contact between the lighter and darker sandstones seen in figure 4.

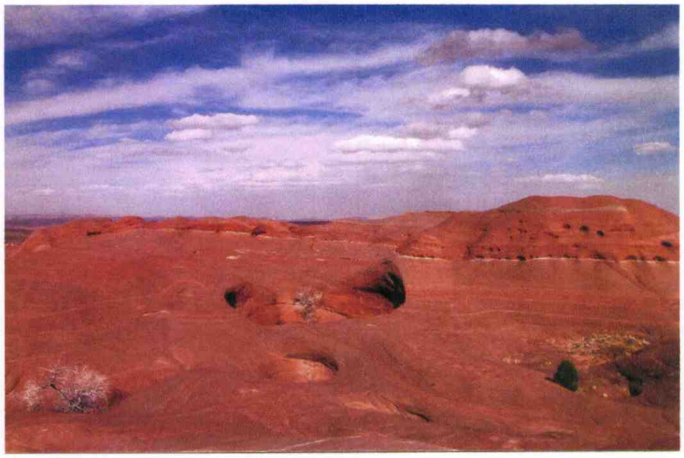

Figure 4. Distinct light color and pitted appearance of contact between the lighter and darker sandstones

Area 3 had two distinct zones. The pits on the central and western portion of Area 3 tended to be very deep and contained only very small patches of coarse fragments with little to no fine-grained sediment, and little to no vegetation. These pits have a higher elevation that the pits in Area 1, 2, and the northern part of Area 3. The contact between the lighter and darker sandstones (figure 5) was visible within all of the deep pits located in this part of Area 3. The pits in the northern part of Area 3 were not quite as deep, contained moderate amounts of loose sandy sediment, occurred below the sandstone contact, and also had little to no vegetation.

Figure 5. Contact between lighter and darker sandstone visible within pit.

4.b.ii. Size

Regardless of location, all the weathering pits on Dance Hall Rock are circular to oval in shape, with the majority tending to be more elliptical in plan view as seen in figure 1. The floors of the pits are generally flat or slightly bowled, and the walls range from being concave, vertical, to slightly outwardly sloped. Generally the weathering pits are wider than they are deep and have average width-to-depth ratios ranging from 1.52 to 24.25 (see Appendix A for individual pit data).

4.b.iii. Weathering and Sediment

The presence of sediment was noted in approximately 70% of the weathering pits, generally within the pits in Areas 1, 2, and the northern part of Area 3, and appeared to be locally derived. Most of the sediment contained within the pits was composed of medium to very-fine-grained sand particles with little organic matter. Although the occurrence of coarse fragments was rare, many of the pits located in Area 2 contained coarse fragments, on top of the fine-grained sediment, that mostly likely originated from the nearby Morrison Formation (Netoff 2001, personal communication). Figure 6 shows the fine sediment topped with a layer of coarse gravel in pit 17, the white debris are pieces of bone.

Figure 6. Fine red sediment topped by coarse dark gravel.

Signs of weathering were visible along the walls and floors of pits, but varied considerably among the pits. Evidence of weathering included small alcoves (figure 7) in a few of the largest pits, small scale pitting on the vertical

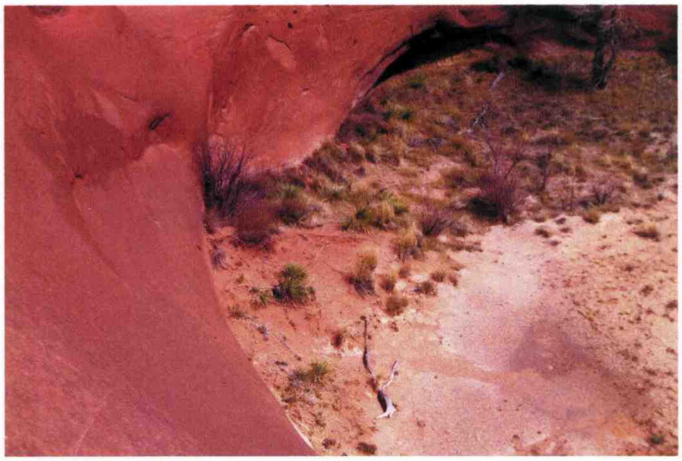

Figure 7. Small alcove in pit 14.

walls, tafoni along bedding planes (figure 8), spalling, sandstone debris on the pit floors (figure 9), and weathering along lithologic discontinuities within the pits. Many of the deep pits in Area 3 displayed considerably weathering along the contact between the lighter and darker sandstones (figure 8).

Figure 8. Weathering along contact between lighter and darker sandstones.

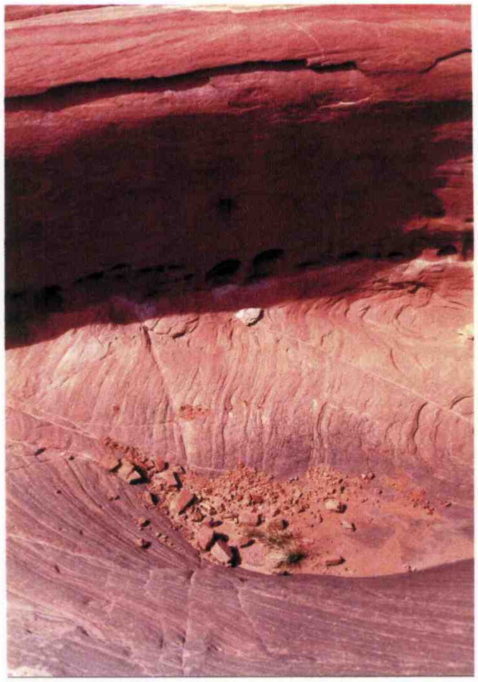

Figure 9. Debris on pit floor.

Indications of strong wind presence within pits were noted through pit floor vegetation, dunes, and ramps within various pits. The vegetation (grasses and shrubs) in many pits was flattened toward the pit floor, indicating strong wind activity on the surface of the pit floor. Furthermore, small dunes and ramps were visible within many pits with and without vegetation. Some dunes had been stabilized or partly stabilized by vegetation; where as other dunes and ramps were still active. Figure 10 shows a ramp being formed along the southwest wall of pit 18, although it is not evident in the photo, sand is being actively deflated by strong wind gusts. Figure 11 shows a small dune of the west wall of pit 13 that is partly stabilized by vegetation.

Figure 10. Ramp along the southwest wall.

Figure 11. Partly stabilized sand dune.

Indications that water is periodically present within pits include "bathtub ring" mineral deposits and dark organic stains (rock varnish). Pits which lacked visible sediment or which contained sediment with sparse or no vegetation, possessed noticeable mineral deposits and/or dark organic stains on the inner and bottom walls. Although rock varnish was visible on the walls of nearly all pits, especially where water flows down into the pit, dark organic stains and bathtub rings on the bottom portion of pits were not visible in pits that contained sediment with moderate to extensive vegetation. Figure 12 shows a "bathtub ring" on the inner perimeter of pit 3 and the dark organic stains near the water's edge. Figure 13 clearly shows dark organic stains lining the bottom portion of pit 16

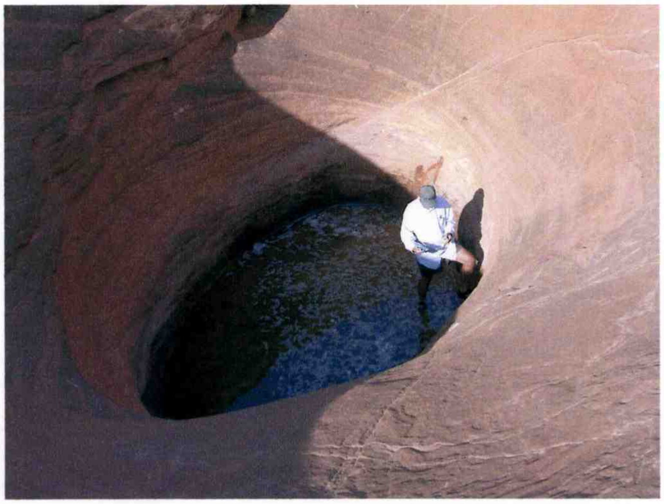

Figure 12. Mineral deposits forming a "bathtub ring".

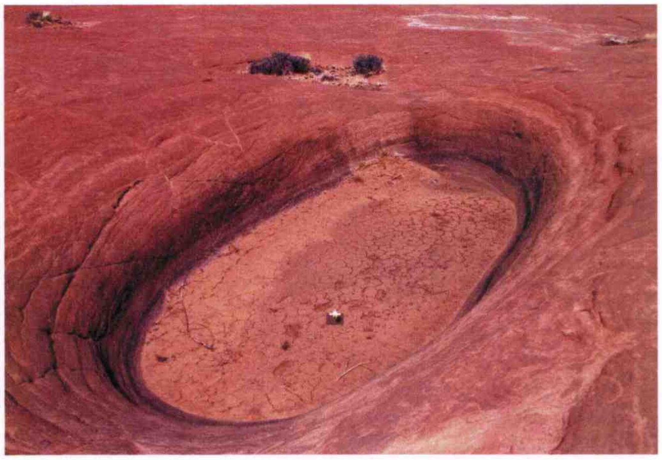

Figure 13. Dark organic stains.

4.b.iv. Vegetation and Soil Communities

Modern vegetation surrounding Dance Hall Rock is largely composed of desert scrub and grassland communities including sagebrush, shadscale, salt brush, black brush, mormon-tea (ephedra), Utah juniper, broom snakeweed, and various grasses such as Indian rice grass, dropseed, and needle and thread grass (Betancourt 1990; Thompson et al. 1993). In addition, weathering pits provide moist areas that support cottonwood trees, narrowleaf yucca, prairie grasses, and other shrubs and herbs. Although, biological soil crusts (cryptobiotic crusts) are abundant on the benches around Dance Hall Rock, mature crusts are not often visible within weathering pits, occurring primarily in pits that had limited plant growth. Figure 14 is an example of a vegetation community within pit 8.

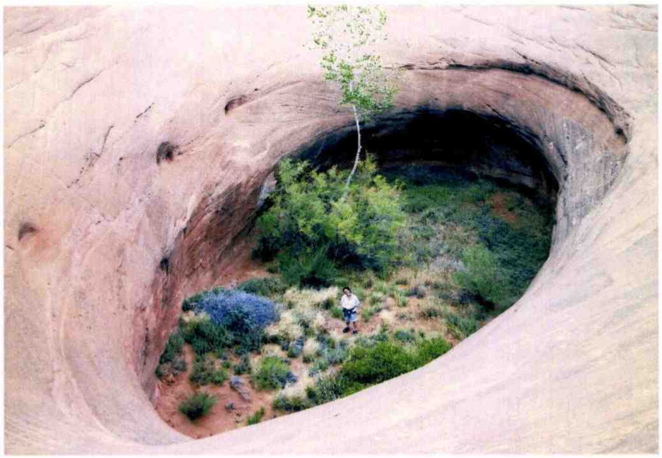

Figure 14. Plant community containing grasses, shrubs, and several cottonwood trees.

5. RESULTS

Stepwise multiple regression was performed using SPSS version 10. Vertical pit depth and an index of circularity were selected as the independent variables with sediment depth functioning as the dependent variable. Vertical pit depth was determined from the top of the lowest rim to the surface of the pit floor and ranged from .40 to 12.8 meters. An index of circularity (degree of circularity) was calculated using the ratio of the maximum and minimum diameters:

$$\mathit{Cirularity\ Index} = \frac{\mathit{MaxDiameter}}{\mathit{MinDiameter}}$$

Index values ranged from 1.02 to 3.38, with a circular shape having an index of approximately 1 and more oblong, or elliptical, pits having a higher index value. The sediment depth within the pits was averaged from ten sample points and varied from 0.001 to .90 of a meter. Table 1 summarizes the data for each weathering pit.

The initial evaluation of the variables (found in Appendix B) indicated that although there appeared to be a roughly linear relationship between the dependent and independent variables, all three were not normally distributed. Therefore, two regression models were developed to assess how the raw data and transformed data affected the model's explanatory ability. The first model utilized the original, i.e., untransformed, variable data and the second model used variables that were transformed to approximate a normal distribution.

Table 1.
Summary of weathering pit data (n=30)

Pits	Max Diameter, meters	Min Diameter, meters	Index of Circularity	Vertical Pit Depth, meters	Sediment Depth, meters
1	45.72	36.57	1.25	12.80	0.90
2	27.50	18.70	1.47	10.80	0.43
3	14.50	8.10	1.79	3.20	0.23
4	4.20	3.00	1.40	0.50	0.05
5	5.60	4.10	1.37	2.70	0.03
6	6.20	4.60	1.35	2.80	0.03
7	7.70	3.60	2.14	1.00	0.05
8	26.80	9.70	2.76	6.00	0.76
9	6.30	5.90	1.07	3.30	0.00
10	17.20	7.40	2.32	0.95	0.24
11	9.30	6.10	1.52	0.61	0.11
12	10.00	7.30	1.37	0.50	0.10
13	14.50	10.30	1.41	4.10	0.42
14	39.30	29.00	1.36	7.90	0.62
15	10.70	5.00	2.14	1.05	0.12
16	14.60	5.90	2.47	1.28	0.10
17	17.40	11.70	1.49	0.60	0.04
18	10.70	9.70	1.10	2.90	0.10
19	8.80	8.60	1.02	1.90	0.02
20	22.50	19.00	1.18	3.70	0.00
21	15.80	13.70	1.15	2.70	0.00
22	10.00	6.70	1.49	3.00	0.00
23	5.40	3.70	1.46	2.30	0.00
24	12.20	9.40	1.30	5.50	0.00
25	16.50	11.10	1.49	2.00	0.00
26	7.20	6.80	1.06	4.60	0.00
27	7.30	3.90	1.87	2.70	0.15
28	8.20	7.00	1.17	1.50	0.03
29	16.20	4.80	3.38	0.70	0.63
30	6.70	5.50	1.22	0.40	0.31
Mean	**14.17**	**9.56**	**1.58**	**3.13**	**0.18**
Std. Deviation	**9.80**	**7.51**	**0.56**	**2.97**	**0.25**

5.a. Regression Model One

In the first regression model, vertical pit depth (p=0.000) and index of circularity (p=0.012) made significant contributions in explaining the variation in sediment depth within weathering pits. Table 2 shows the correlation matrix for the variables in the first model.

Table 2.
Correlations among variables for sediment depth within weathering pits, using Pearson's r (n=30)

	Sediment Depth	Vertical Pit Depth	Circularity Index
Sediment Depth	1.00		
Vertical Pit Depth	0.607**	1.00	
Circularity Index	0.412*	-0.198	1.00

Note: ** Correlation is significant at the 0.000 level (1-tailed)
* Correlation is significant at <0.05 level (1-tailed)

The correlations suggested that as the pit deepened and became more elliptical, sediment accumulation also increased. In this model, the independent variables explained approximately 64% of the variation in sediment depth, which was statistically significant, F=26.527, p=0.000. Table 3 summarizes regression Model One.

Table 3.
Model^c summary of first regression model.

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	0.594^a	0.353	0.331	0.201876	0.353	15.847	1	29	0.000
2	0.814^b	0.663	0.639	0.148394	0.309	25.671	1	28	0.000

a. Predictors: (Constant), vertical pit depth
b. Predictors: (Constant), vertical pit depth, degree of circularity
c. Dependent Variable: sediment depth

It is tempting to infer that the combined effect of the predictor variables (degree of circularity and depth of the pit) explain a moderate amount of the variability of sediment depth. However, an examination of standardized residual plots (found in Appendix B) indicated that the residual error was not normally distributed. Although the histogram of the residuals is not skewed, the actual distribution is rough in shape with sharp peaks. The residuals in the probability plot approximate a straight line for part of the data, but deviate moderately in the middle third of the plot. Finally, the scatterplot of the standardized residuals vs. the predicted values of the dependent variable suggest heteroscedasticity, as the cloud of dots seem to be clustered on the left side of the graph. In short, the residuals do not meet the assumption of normality and threaten the model's validity.

5.b. Regression Model Two

The second regression model was developed to correct for the heteroscedasticity detected in the first model. To approximate a normal distribution, the dependent variable (sediment depth) was transformed using a square root function before being entered into the regression model. The explanatory variables (vertical pit depth and degree of circularity) remained untransformed. Again both vertical pit depth (p= 0.006) and degree of circularity (p=0.004) made significant contributions to explaining the variation in sediment depth. Table 4 shows the correlation matrix for the variables in the second model. As observed in Model One, the correlations imply that both the depth and circularity of the pit are important determinants for sediment depth. However in Model Two only approximately 50% of the variation in sediment depth was explained by the independent variables. Table 5 summarizes the second regression model, which was also statistically significant F=15.463, p=0.000.

Table 4.
Correlations among variables for normalized sediment depth within weathering pits, using Pearson's r (n=30)

	SQRT of Sediment Depth	Vertical Pit Depth	Circularity Index
SQRT of Sediment Depth	1.00		
Vertical Pit Depth	0.453**	1.00	
Circularity Index	0.472**	-0.198	1.00

Note: ** Correlation is significant at <0.01 level (1-tailed)

Table 5.
Model[c] summary of second regression model.

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	0.476[a]	0.227	0.200	0.253017	0.227	8.496	1	29	0.007
2	0.731[b]	0.535	0.502	0.199678	0.308	18.562	1	28	0.000

a. Predictors: (Constant), degree of circularity
b. Predictors: (Constant), degree of circularity, vertical pit depth
c. Dependent Variable: SQRT of Sediment Depth

By normalizing the dependent variable, the R^2 value dropped from 64% to 50%. Examination of standardized residual plots (found in Appendix B) indicated that the distribution of the residuals was generally more normal than the first regression model. However, it is important to note that although the scatterplot of the standardized residuals vs. predicted values of the dependent variable was more dispersed, it still showed some evidence of heteroscedasticity. By transforming the dependent variable, the overall "fit" of the model improved, but still displayed sufficient non-normality to suggest that the variation in sediment depth is dependent on multiple variables not entered into the model.

In short, neither model appears to be a “good fit”. The small sample size makes it difficult to determine if the depth of the pit and degree of circularity are reliable predictors. Furthermore, the R^2 value is sufficiently small to indicate that numerous factors affect sediment accumulation, and prediction based solely on pit depth and degree of circularity would be unreliable. Moreover, the problems detected with the normality of the residuals implies that, in addition to other variables being needed to explain how sediment accumulates within deep pits, there is a complex relationship between the variables that may not be linear and would be best examined through non-parametric statistics or computer simulation models.

6. DISCUSSION

This paper set out to test whether deep, narrow weathering pits accumulate more sediment than shallower pits. It became obvious during the field survey that while depth may influence sediment accumulation, it is not the only, or even the most important variable. Examination of the pits supported Netoff’s contentions that sediment accumulation is affected by multiple factors, including vertical pit depth, width-to-depth ratio, and cross-sectional shape. The amount of sediment also varied with the degree of surface protection, either by plants, surface crusts, or coarse fragments. Other factors which potentially affect sediment accumulation include wind velocity, the presence of water, topographic position, and variations in physical and chemical composition, including cementation, porosity, texture, and structure. In short, it seems likely that a variety of factors within each pit affect how sediment accumulates and is ultimately removed.

The statistical analysis was conducted to determine the relationship between the sediment depth and the vertical depth of the pits. Although the two variables (sediment depth and vertical depth) were correlated (see table 2), pit depth alone was only able to explain approximately 35% (see table 3) of the variation in sediment depth for the first regression model. By normalizing the distribution of sediment depth, the predictive ability of vertical pit depth dropped to about 30% (see table 5) suggesting that other variables also impacted sediment depth. Previous studies have suggested that sediment depth is related to the average width-to-depth ratio of the pit (Netoff et al. 1995; Netoff and Shroba 1997; Netoff and Shroba 2001). The results of this study, however, suggest that the average width-to-depth ratio was not significant (see correlation matrix in Appendix B). Therefore, this study also calculated an index of circularity for comparison, to determine if the degree of circularity of a pit affected sediment accumulation. The results of the statistical analysis suggest that the degree of circularity, combined with pit depth, better predict *some* of the sediment depth variation as opposed to simply pit depth or the average width-to-depth ratio. Examination of the residuals in both regression models, however, implies that circularity and depth cannot, alone, account for all the variation in sediment depth (see Appendix B). The remaining discussion focuses on the various factors which may augment sediment accumulation and/or deflation, and explores areas for future research.

6.a. Surface Stabilizing Mechanisms

Weathering pit sediment results from the physical and chemical processes that erode the pit, as well as from the effects of wind and water. Sediment in weathering pits at Dance Hall Rock can be found with and without vegetation, surface crusts (biological and physical), and coarse fragments. Evaluation of these pits suggests that the presence of these elements enhance sediment stability within pits, increasing the sediment's resistance to deflation and promoting the retention of accumulated sediment.

The presence of vegetation, crusts, and coarse fragments varied from pit to pit. Generally, vegetation was limited to pits where there was enough sediment and moisture to support plant growth. The vegetation tended to concentrate in areas where the sediment was deep, such as on dunes and ramps (Netoff et al. 1995). In many other pits, vegetation was sparse, leaving large areas of sediment unprotected. Coarse fragments and physical or biological crusts sometimes covered these unprotected areas, which also promoted sediment stability. Biological crusts, however, were visible only in pits with sparse vegetation cover *and* limited physical crusts. It is important to note that although biological crusts can stabilize pockets of shallow soil (Belnap 2001), their presence within weathering pits is not widespread and where present, they do not appear as mature crusts.

The conclusions of this study suggest that the absence of vegetation, coarse fragments, or crusts makes sediment more susceptible to wind and/or water erosion. This is because vegetation, crusts, and coarse fragments help retain existing sediment within pits by stabilizing the deposits and hindering removal. However, numerous pits had sediment without visible surface stabilizers. Thus this study further concludes that the presence of these stabilizers do not entirely account for sediment presence in pits. This suggests that additional factors, such as water and textural, structural, or lithologic variations within the sandstone, affect sediment accumulation.

6.b. Water

Previous studies have shown that the presence of water within pits is affected by the pits' position, the degree of microfractures within the pit, and the porosity and cementation of the surrounding sandstone (Netoff et al. 1995; Netoff and Shroba 2001; Howard and Kochel 1991). Prior research demonstrated that many deep weathering pits retain water from months to years (Netoff et al. 1995; Netoff and Shroba 2001; Graham 1999), however varying levels of cementation, porosity, and microfractures affect the pit's ability to retain water.

The majority of pits located on Dance Hall Rock are found on flat or moderate sloped surfaces, with only a handful of pits being found along shallow drainages. Due to their location away from drainages, most of the pits on Dance Hall Rock have a limited to nonexistent watershed. Hence, water in these pits results from direct precipitation and runoff from the surrounding sandstone.

This study is in an agreement with previous studies, which found that water leaves the pit primarily through evaporation, percolation into the surrounding sandstone, and runoff into the fracture pathways (Howard and Kochel 1991; Netoff et al. 1995). Since many pits retain water for long periods, it seems that the removal of water through these mechanisms is highly variable, and may depend of factors such as aspect, pit shape, and position, as well as the degree to which joints, fractures, and intergranular spaces are sealed with cementing agents.

During the first field session in August 2001, many pits, including some that were not surveyed, contained significant levels of water. Water in pits ranged from saturated sediment to well over half a meter above the sediment surface. In addition, some pits, both dry and with water, had a "bathtub ring" of mineral deposits and dark organic stains, which suggests that these pits contain water intermittently throughout the year. What remains unclear is the affect of water on sediment accumulation, sediment deflation, development of surface stabilizing mechanisms (vegetation and crusts), and the potential dissolution of weathered sediment. It seems probable that water in pits would help retain sediment by capturing sand particles that were either blown into the pit or enter through runoff. Additionally, the presence of water would likely hinder removal of sediment by wind.

With regards to Dance Hall Rock, the presence of water within the pit would seem to promote both sediment accumulation and deflation. Many of the pits are not located along drainages, thus they are not susceptible to "plunge pool" erosion, which would help remove accumulated sediment. Also, many pits have significant amount of water, which would conceivably help accumulate sediment while temporarily preventing excavation by the wind. Yet pits that frequently fill up with water or retain deep water for considerable lengths of time would also inhibit *extensive* vegetation and protective physical and biological crusts, which would help stabilize the sediment in the event the water evaporated. It seems to follow that by limiting sediment-stabilizing agents, such as crusts and vegetation, accumulation of sediment is augmented only while the water is present, because once the water has evaporated, the sediment could easily be removed from the weathering pit by strong winds.

However, the research also suggests that water does not necessarily preclude vegetation or biological crusts from growing, but may simply affect the type of vegetation or location of plants and crusts that will persist. For instance some plants and crusts develop on high points within the pit that are above the zone of saturation, such as dunes. Other plants can root underwater or in saturated sediment conditions. In sum, it appears that water plays a complicated role in sediment accumulation and deflation within weathering pits. While it initially attracts particles and prevents wind removal; it may hinder the formation of protective vegetation and crusts, thereby promoting subsequent wind removal once the water evaporates; or by serving as a means for sediment accumulation, create a bed for subsequent seed germination or crust development, thereby promoting sediment stability.

Finally, researchers have proposed that sand may be removed through dissolution and/or piping when water is present (Howard and Kochel 1988; Fairbridge 1968), although little research has been done to address this process in weathering pits. The observations in this study are in agreement with Dr. Netoff's conclusions (Netoff et al. 1995; Netoff and Shroba 1997; Netoff and Shroba 2001), that dissolution and subsurface piping is probably not an important mechanism. For instance weathering pits often retain large amounts of water, suggesting that the surrounding sandstone and passageways through which dissolution would take place have been sealed by cement. Yet it is also conceivable that some pits have not been fully sealed, allowing very fine sediment particulates to be removed through dissolution and/or piping. In short, although it seems likely that the widespread removal of pit sediment through dissolution is minimal, due to sparse research, it is difficult to assess the importance of dissolution as a mechanism of sediment removal in weathering pits.

6.c. Textural, Structural, and Lithologic Impacts

Weathering pits on Dance Hall Rock are found at a variety of elevations and aspects. Previous geologic research indicated that Dance Hall Rock is predominantly a porous, fine-grained sandstone with thin lenses of brown mudstone, and is weakly cemented by small amounts of calcite and clay (Doelling et al. 2000; Netoff and Shroba 2001). Textural, structural, and lithologic variations within the sandstone, such as porosity, particle size, cementation, joints, or fractures, likely affect weathering, which in turn would affect sediment accumulation.

Literature indicates that Dance Hall Rock is principally part of the lower Entrada Sandstone (Gunsight Butte Member), however a clear contact between an upper Entrada unit (possibly the Cannonville Member) is visible in the eastern part of the site (refer to figure 4). The majority of pits on Dance Hall Rock have formed within the smooth weathering Gunsight Butte Member, with only a small number of pits forming above the contact. Surveyed pits that formed above the contact consisted of those from the central and western part of Area 3 (figure 3). Although many of the pits above the contact contained fresh talus along the walls and small patches of coarse fragments, interestingly, none of the pits contained *significant* accumulations of fine-grained sediment and appeared to be scoured clean. These pits are generally very deep, being found on the same topographic high, and contained no measurable sediment; however they varied in cross-sectional shape, depth-to-width ratio, and degree of circularity. Furthermore, although pits without sediment were found in other areas, none were as deep or displayed the same characteristic appearance of being scoured clean. The differences between pits formed above and below the contact implies that minor textural or lithologic variations in the sandstone units may impact pit depth and sediment accumulation.

Previous studies indicated that joints and faults are present throughout the Entrada Sandstone, yet whether their presence determines the location of *all* pits appears to be uncertain (Netoff et al. 1995; Howard and Kochel 1988; Goudie 1991). In addition, although Netoff et al. (1995) indicated that the lower Entrada outcrops contain "joints and small-scale faults...Most, however, are cemented with varying amounts of $CaCO_3$, which seems to strengthen the sandstone along these zones" (41). While it is clear that some weathering pits at Dance Hall Rock are related to obvious regional joints within the Entrada Sandstone, others are not readily apparent and may be enlargements of chance surface depressions. Further research is needed to determine if the location of *all* weathering pits in the lower Entrada Sandstone is determined by the underlying structural controls of the sandstone.

Particle size affects the ability of wind to deflate particles from pits. Particles that are very small, such as clays and silt, are more stable and are difficult to deflate; additionally particles that are too large, such as the coarse fragments found in various pits in Area 2 and 3, are also hard to excavate. Sediments contained within weathering pits at Dance Hall Rock are composed largely of fine to very-fine-grained sand (250 µm – 100 µm), yet pits with visible mud cracks and coarse fragments are common throughout the site. While finer grains are capable of being deflated by strong winds (Netoff 2001, personal communication), pits with high silt and clay content, coarse gravel, and extensive vegetation or crusts hinder wind excavation. Further research exploring how changes in textural, structural, or lithologic characteristics affect weathering and sediment accumulation within pits may yield interesting results.

6.d. Sediment Removal by Wind

Many researchers agree that strong winds can remove sediment from shallow to moderately deep pits, citing sediment structures on pit floors as evidence of wind movement and deflation. Other mechanisms including "plunge pool" sediment removal and dissolution have been suggested. Yet the vast majority of pits on Dance Hall Rock do not form along drainages capable of supporting "plunge pool" erosion, and wide-scale sediment removal by dissolution and piping seems improbable since most pits retain water for long periods of time (Netoff and Shroba 1997; Netoff and Shroba 2001). Therefore this paper contends that the removal of sediment from weathering pits on Dance Hall Rock is primarily accomplished through wind.

The degree of wind excavation appears to be dependent on the interaction between numerous variables, including pit morphology, surface protection, water presence, topographic position, wind velocity, and variations in texture, structure, or lithology. Furthermore, the semi-arid climate of the plateau also contributes to the deflation of pit sediment by restricting the amount of moisture present for vegetation growth and augmenting evaporation, which reduces sediment cohesion and localizes salt within pits (Goudie 1991; Netoff and Shroba 2001). It follows that the interaction of these variables affects sediment accumulation and ultimately sediment deflation.

The wind regime on the Colorado Plateau is highly variable and localized. Although many researchers agree that wind is an effective agent of deflation, little research has been done to assess the removal of sediment from large weathering pits. Several studies by Netoff and Shroba (1997; 2001) have identified two basic types of wind rotors and vortices that occur within pits; however, the experiments have been limited to only a few giant weathering pits (Netoff 2001, personal communication). It is evident that strong winds are present in giant pits, however the lack of wind-speed records for the Dance Hall Rock area makes it difficult to assess how changes in wind velocity affect sediment deflation in weathering pits. Furthermore, while researchers have speculated that wind speeds on the Colorado Plateau may have been stronger in the past (Netoff and Shroba 2001; Patton et al. 1991), the area would have also been more moist (Betancourt 1990; Thompson et al. 1993). A wetter climate would enhance sediment cohesion and also support more vegetation, potentially hindering the deflation of sediment from pits. Current records of wind velocities near Dance Hall Rock are limited, but high winds are common in the early spring and fall, and in association with storm fronts. In addition, the Straight Cliffs to the southwest may enhance wind velocities around Dance Hall Rock. Interesting areas for further research would be determining the velocity of wind within pits (Netoff and Shroba 2001; Netoff 2001, personal communication), if the topographic position of the pit influences wind velocity, and how wind rotors and vortices change based on pit morphology.

7. CONCLUSIONS

This paper set out to explore whether pit depth was a significant factor in explaining the variations in sediment depth. As the research progressed, it became clear that while vertical pit depth is an important element, it certainly was not the determining factor for sediment accumulation. The statistical results and observations indicate that the accumulation and deflation of sediment in pits is a complex system involving the interaction of various physical and biological factors. Where features such as vegetation, soil crusts, and coarse fragments clearly promote sediment stability; other elements including water coverage, pit morphology, lithologic variations, and topographic position may at times augment sediment accumulation, while at other times they may promote deflation.

Wind deflation appears to be the primary mechanism of sediment removal for many pits, since most pits are not found along drainages capable of supporting “plunge-pool” removal of sediment, and the retention of water within pits argues against the removal of sediment by dissolution and piping. Given that the removal of sediment from weathering pits appears essential for continued downward growth, sediment that becomes stabilized by vegetation, surface crusts, or coarse fragments becomes difficult to excavate and could prevent further downward erosion. It is clear that the deflation of sediment from pits is dependent upon the many variables that also affect the accumulation of sediment.

An avenue for potentially promising research includes additional sampling and research to more clearly identify how variations in wind velocity interact with giant weathering pits, and ultimately affect sediment accumulation and deflation. Alternatively, the personal journals of local residents, explorers, and pioneers may contain entries documenting the shape and size of specific pits having distinct, identifiable characteristics. Such records might contribute to documenting the changes over time. By utilizing both physical and cultural records, researchers may be able to more clearly identify the mechanisms that affect sediment accumulation and deflation.

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APPENDIX A
Raw Data

Appendix A. Weathering pit data*

Pits	Topographic Areas	Maximum Diameter[a]	Minimum Diameter[a]	Vertical Pit Depth[a]	Sediment Depth[a]	Degree of Circularity[b]	Width to depth ratio[c]	Top surface area[d]
1	1	45.72	36.57	12.80	0.900	1.25	2.86	1313.17
2	1	27.50	18.70	10.80	0.434	1.47	2.14	403.89
3	1	14.50	8.10	3.20	0.234	1.79	3.53	92.25
4	1	4.20	3.00	0.50	0.049	1.40	7.20	9.90
5	1	5.60	4.10	2.70	0.030	1.37	1.80	18.03
6	1	6.20	4.60	2.80	0.030	1.35	1.93	22.40
7	1	7.70	3.60	1.00	0.053	2.14	5.65	21.77
8	1	26.80	9.70	6.00	0.759	2.76	3.04	204.17
9	1	6.30	5.90	3.30	0.000	1.07	1.85	29.19
10	2	17.20	7.40	0.95	0.244	2.32	12.95	99.97
11	2	9.30	6.10	0.61	0.112	1.52	12.62	44.56
12	2	10.00	7.30	0.50	0.097	1.37	17.30	57.33
13	2	14.50	10.30	4.10	0.425	1.41	3.02	117.30
14	2	39.30	29.00	7.90	0.620	1.36	4.32	895.12
15	2	10.70	5.00	1.05	0.124	2.14	7.48	42.02
16	2	14.60	5.90	1.28	0.105	2.47	8.01	67.65
17	2	17.40	11.70	0.60	0.039	1.49	24.25	159.89
18	2	10.70	9.70	2.90	0.100	1.10	3.52	81.52
19	3	8.80	8.60	1.90	0.016	1.02	4.58	59.44
20	3	22.50	19.00	3.70	0.000	1.18	5.61	335.76
21	3	15.80	13.70	2.70	0.000	1.15	5.46	170.01
22	3	10.00	6.70	3.00	0.000	1.49	2.78	52.62
23	3	5.40	3.70	2.30	0.000	1.46	1.98	15.69
24	3	12.20	9.40	5.50	0.000	1.30	1.96	90.07
25	3	16.50	11.10	2.00	0.000	1.49	6.90	143.85
26	3	7.20	6.80	4.60	0.000	1.06	1.52	38.45
27	3	7.30	3.90	2.70	0.150	1.87	2.07	22.36
28	3	8.20	7.00	1.50	0.030	1.17	5.07	45.08
29	1	16.20	4.80	0.70	0.625	3.38	17.50	61.07
30	1	6.70	5.50	0.40	0.308	1.22	15.25	28.94

[a] All measurements taken in meters.

[b] Determined by the ratio between the maximum and minimum diameters.

[c] Determined by the ratio between the average diameter and the vertical pit depth.

[d] Determined by Area of Ellipse = Br_1r_2

APPENDIX B
Statistical Data

DESCRIPTIVE STATISTICS FOR EACH VARIABLE USED IN THE REGRESSION MODELS

Statistics

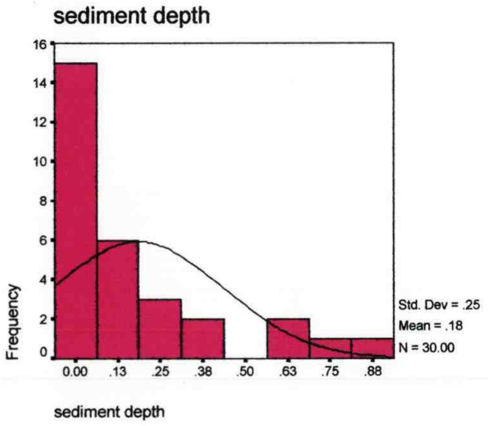
		sediment depth	square root_sediment depth	vertical pit depth	degree of circularity
N	Valid	30	30	30	30
	Missing	31	31	31	31
Mean		.182783	.3213	3.1297	1.5858
Median		7.515E-02	.2712	2.7000	1.4039
Std. Deviation		.251034	.2868	2.9755	.5551
Skewness		1.609	.709	1.902	1.699
Std. Error of Skewness		.427	.427	.427	.427
Kurtosis		1.685	-.517	3.800	2.796
Std. Error of Kurtosis		.833	.833	.833	.833
Minimum		.0001	.01	.40	1.02
Maximum		.9000	.95	12.80	3.38

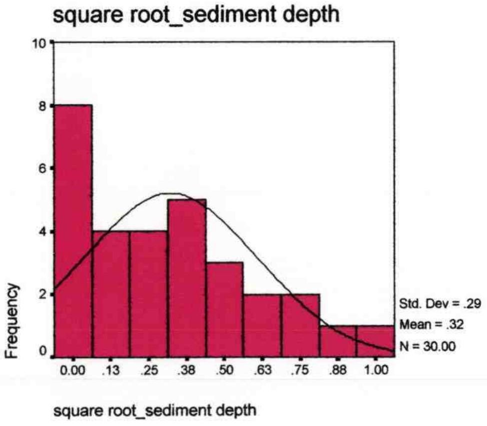
Correlations

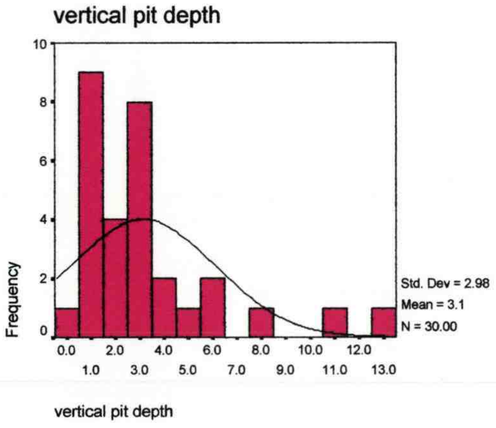
		sediment depth	vertical pit depth	degree of circularity	square root_sediment depth	width to depth ratio
sediment depth	Pearson Correlation	1.000	.607**	.412*	.951**	.032
	Sig. (2-tailed)	.	.000	.024	.000	.865
	N	30	30	30	30	30
vertical pit depth	Pearson Correlation	.607**	1.000	-.198	.453*	-.515**
	Sig. (2-tailed)	.000	.	.294	.012	.004
	N	30	30	30	30	30
degree of circularity	Pearson Correlation	.412*	-.198	1.000	.472**	.304
	Sig. (2-tailed)	.024	.294	.	.008	.102
	N	30	30	30	30	30
square root_sediment depth	Pearson Correlation	.951**	.453*	.472**	1.000	.145
	Sig. (2-tailed)	.000	.012	.008	.	.443
	N	30	30	30	30	30
width to depth ratio	Pearson Correlation	.032	-.515**	.304	.145	1.000
	Sig. (2-tailed)	.865	.004	.102	.443	.
	N	30	30	30	30	30

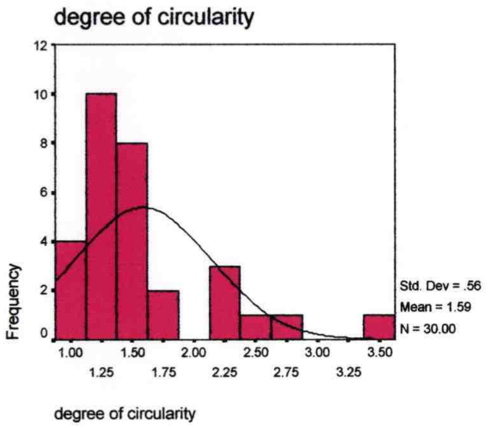
**. Correlation is significant at the 0.01 level (2-tailed).

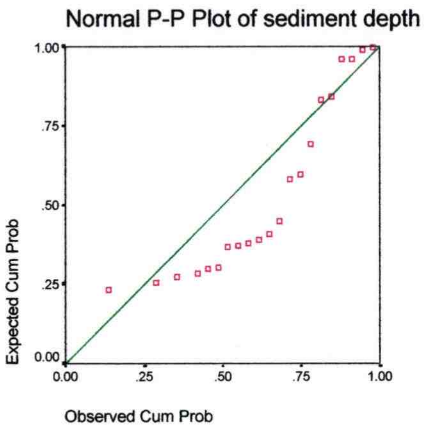
*. Correlation is significant at the 0.05 level (2-tailed).

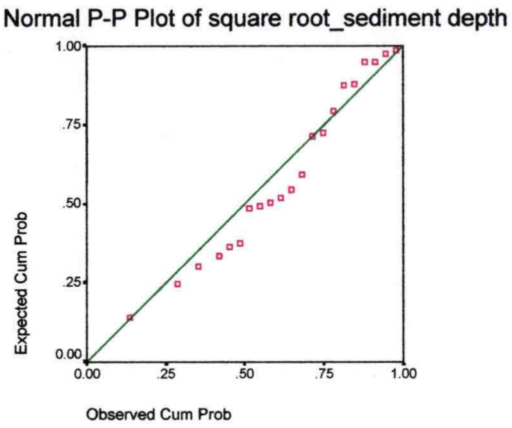







degree of circularity


Normal P-P Plot of sediment depth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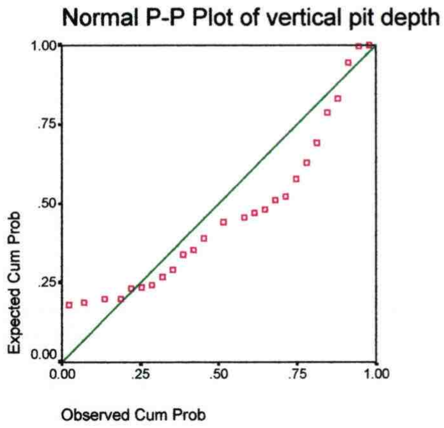
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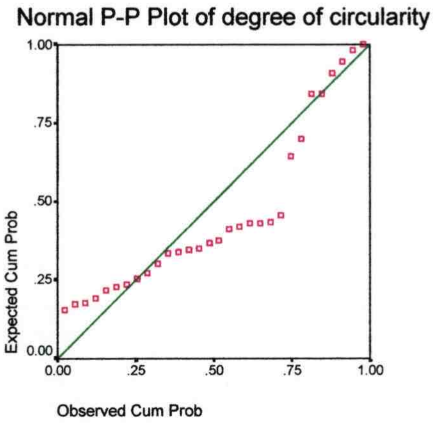
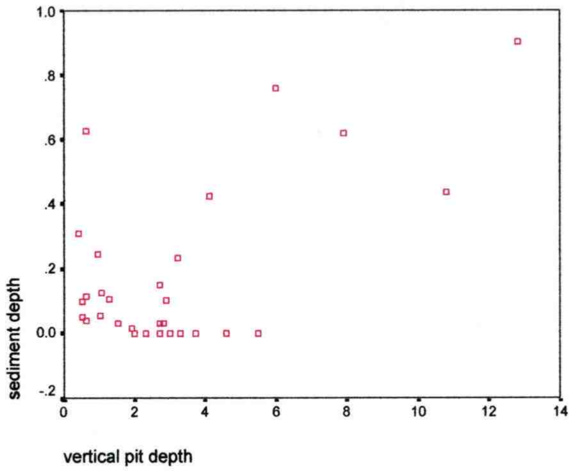
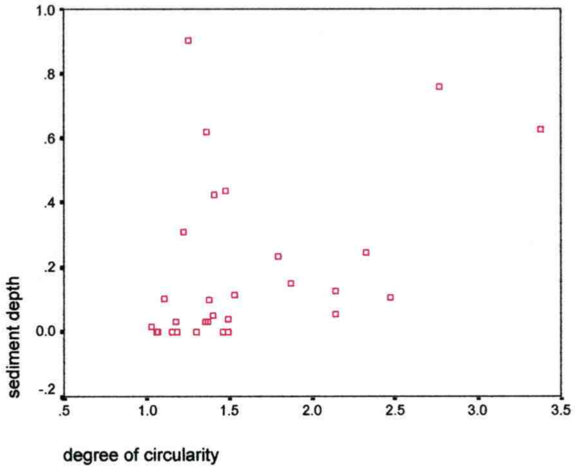
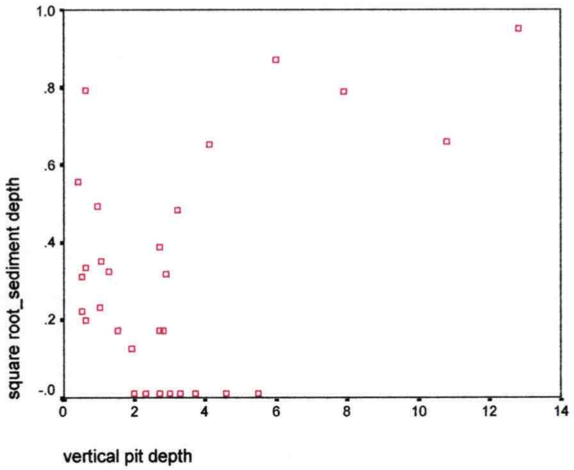
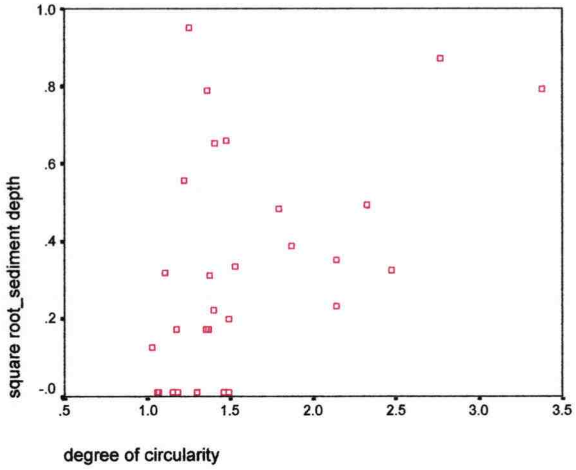

Normal P-P Plot of degree of circularity


1.0
.8
.6
.4
.2
0.0
-.2
sediment depth
0
2
4
6
8
10
12
14
vertical pit depth


1.0
.8
.6
.4
.2
0.0
-.2
sediment depth
.5
1.0
1.5
2.0
2.5
3.0
3.5
degree of circularity


1.0
.8
.6
.4
.2
-.0
square root_sediment depth
0
2
4
6
8
10
12
14
vertical pit depth


1.0
.8
.6
.4
.2
-.0
square root_sediment depth
.5
1.0
1.5
2.0
2.5
3.0
3.5
degree of circularity

REGRESSION MODEL 1

Descriptive Statistics

	Mean	Std. Deviation	N
sediment depth	.182783	.251034	30
vertical pit depth	3.1297	2.9755	30
degree of circularity	1.5858	.5551	30

Correlations

		sediment depth	vertical pit depth	degree of circularity
Pearson Correlation	sediment depth	1.000	.607	.412
	vertical pit depth	.607	1.000	-.198
	degree of circularity	.412	-.198	1.000
Sig. (1-tailed)	sediment depth	.	.000	.012
	vertical pit depth	.000	.	.147
	degree of circularity	.012	.147	.
N	sediment depth	30	30	30
	vertical pit depth	30	30	30
	degree of circularity	30	30	30

Model Summary[c]

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.607[a]	.368	.345	.203121	.368	16.295	1	28	.000
2	.814[b]	.663	.638	.151092	.295	23.604	1	27	.000

a. Predictors: (Constant), vertical pit depth

b. Predictors: (Constant), vertical pit depth, degree of circularity

c. Dependent Variable: sediment depth

ANOVA[c]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.672	1	.672	16.295	.000[a]
	Residual	1.155	28	4.126E-02		
	Total	1.828	29			
2	Regression	1.211	2	.606	26.527	.000[b]
	Residual	.616	27	2.283E-02		
	Total	1.828	29			

a. Predictors: (Constant), vertical pit depth

b. Predictors: (Constant), vertical pit depth, degree of circularity

c. Dependent Variable: sediment depth

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	2.264E-02	.054		.417	.680	-.089	.134					
	vertical pit depth	5.117E-02	.013	.607	4.037	.000	.025	.077	.607	.607	.607	1.000	1.000
2	(Constant)	-.404	.097		-4.179	.000	-.602	-.205					
	vertical pit depth	6.043E-02	.010	.716	6.281	.000	.041	.080	.607	.771	.702	.961	1.041
	degree of circularity	.251	.052	.554	4.858	.000	.145	.356	.412	.683	.543	.961	1.041

a. Dependent Variable: sediment depth

Excluded Variables[b]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics		
						Tolerance	VIF	Minimum Tolerance
1	degree of circularity	.554[a]	4.858	.000	.683	.961	1.041	.961

a. Predictors in the Model: (Constant), vertical pit depth

b. Dependent Variable: sediment depth

Coefficient Correlations[a]

Model			vertical pit depth	degree of circularity
1	Correlations	vertical pit depth	1.000	
	Covariances	vertical pit depth	1.607E-04	
2	Correlations	vertical pit depth	1.000	.198
		degree of circularity	.198	1.000
	Covariances	vertical pit depth	9.254E-05	9.824E-05
		degree of circularity	9.824E-05	2.659E-03

a. Dependent Variable: sediment depth

Collinearity Diagnostics[a]

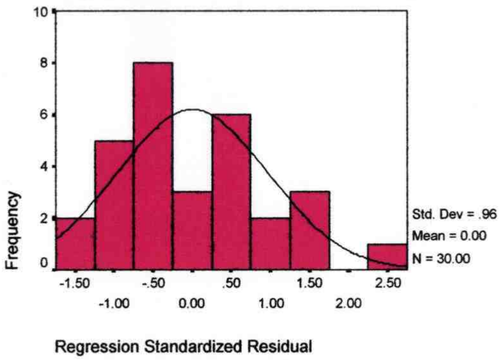
Model	Dimension	Eigenvalue	Condition Index	Variance Proportions		
				(Constant)	vertical pit depth	degree of circularity
1	1	1.731	1.000	.13	.13	
	2	.269	2.534	.87	.87	
2	1	2.556	1.000	.01	.05	.01
	2	.398	2.536	.01	.79	.06
	3	4.671E-02	7.397	.97	.16	.93

a. Dependent Variable: sediment depth

Residuals Statistics[a]

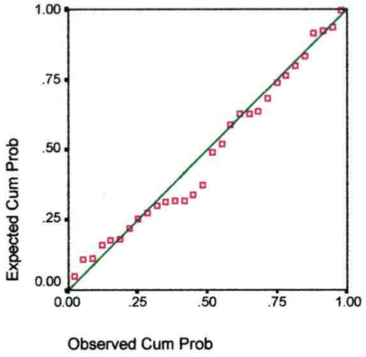
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	-7.4E-02	.683072	.182783	.204361	30
Residual	-.253795	.382547	4.26E-17	.145789	30
Std. Predicted Value	-1.258	2.448	.000	1.000	30
Std. Residual	-1.680	2.532	.000	.965	30

a. Dependent Variable: sediment depth



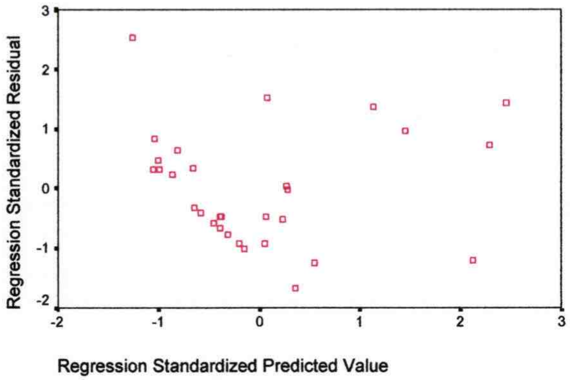
Histogram

Dependent Variable: sediment depth



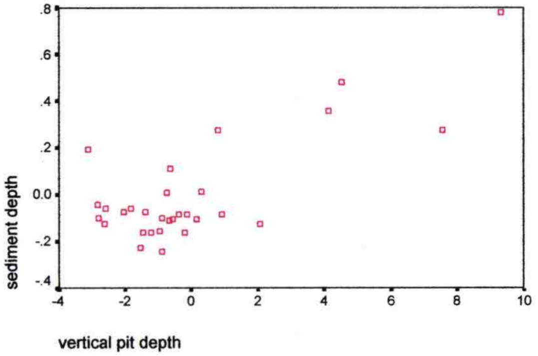
Normal P-P Plot of Regression Standardized Residual

Dependent Variable: sediment depth



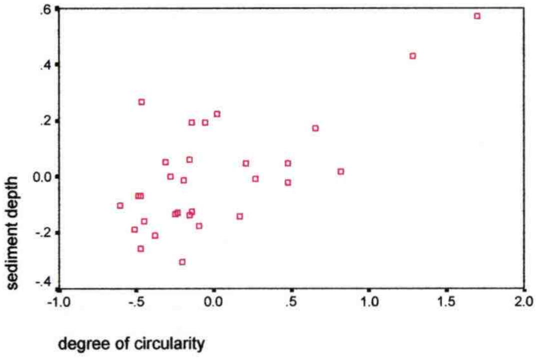
Scatterplot

Dependent Variable: sediment depth



Partial Regression Plot

Dependent Variable: sediment depth



Partial Regression Plot

Dependent Variable: sediment depth

REGRESSION MODEL 2

Descriptive Statistics

	Mean	Std. Deviation	N
square root_sediment depth	.3213	.2868	30
vertical pit depth	3.1297	2.9755	30
degree of circularity	1.5858	.5551	30

Correlations

		square root_sediment depth	vertical pit depth	degree of circularity
Pearson Correlation	square root_sediment depth	1.000	.453	.472
	vertical pit depth	.453	1.000	-.198
	degree of circularity	.472	-.198	1.000
Sig. (1-tailed)	square root_sediment depth	.	.006	.004
	vertical pit depth	.006	.	.147
	degree of circularity	.004	.147	.
N	square root_sediment depth	30	30	30
	vertical pit depth	30	30	30
	degree of circularity	30	30	30

Model Summary[c]

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.472[a]	.223	.195	.2573	.223	8.040	1	28	.008
2	.731[b]	.534	.499	.2030	.311	18.003	1	27	.000

a. Predictors: (Constant), degree of circularity

b. Predictors: (Constant), degree of circularity, vertical pit depth

c. Dependent Variable: square root_sediment depth

ANOVA[c]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.532	1	.532	8.040	.008[a]
	Residual	1.854	28	6.620E-02		
	Total	2.386	29			
2	Regression	1.274	2	.637	15.463	.000[b]
	Residual	1.112	27	4.119E-02		
	Total	2.386	29			

a. Predictors: (Constant), degree of circularity

b. Predictors: (Constant), degree of circularity, vertical pit depth

c. Dependent Variable: square root_sediment depth

Coefficients[a]

		Unstandardized Coefficients		Standardized Coefficients			95% Confidence Interval for B		Correlations			Collinearity Statistics	
Model		B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	-6.57E-02	.144		-.455	.653	-.361	.230					
	degree of circularity	.244	.086	.472	2.836	.008	.068	.420	.472	.472	.472	1.000	1.000
2	(Constant)	-.330	.130		-2.540	.017	-.596	-.063					
	degree of circularity	.302	.069	.585	4.364	.000	.160	.444	.472	.643	.573	.961	1.041
	vertical pit depth	5.483E-02	.013	.569	4.243	.000	.028	.081	.453	.632	.557	.961	1.041

a. Dependent Variable: square root_sediment depth

Excluded Variables[b]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics		
						Tolerance	VIF	Minimum Tolerance
1	vertical pit depth	.569[a]	4.243	.000	.632	.961	1.041	.961

a. Predictors in the Model: (Constant), degree of circularity

b. Dependent Variable: square root_sediment depth

Coefficient Correlations[a]

Model			degree of circularity	vertical pit depth
1	Correlations	degree of circularity	1.000	
	Covariances	degree of circularity	7.408E-03	
2	Correlations	degree of circularity	1.000	.198
		vertical pit depth	.198	1.000
	Covariances	degree of circularity	4.797E-03	1.773E-04
		vertical pit depth	1.773E-04	1.670E-04

a. Dependent Variable: square root_sediment depth

Collinearity Diagnostics[a]

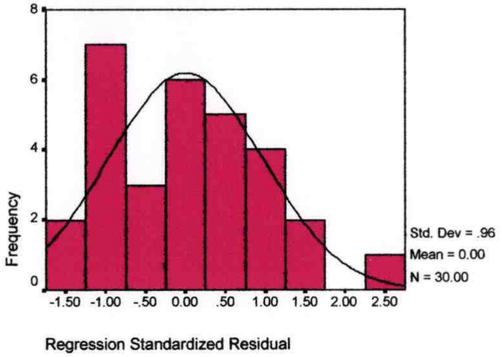
Model	Dimension	Eigenvalue	Condition Index	Variance Proportions		
				(Constant)	degree of circularity	vertical pit depth
1	1	1.946	1.000	.03	.03	
	2	5.444E-02	5.978	.97	.97	
2	1	2.556	1.000	.01	.01	.05
	2	.398	2.536	.01	.06	.79
	3	4.671E-02	7.397	.97	.93	.16

a. Dependent Variable: square root_sediment depth

Residuals Statistics[a]

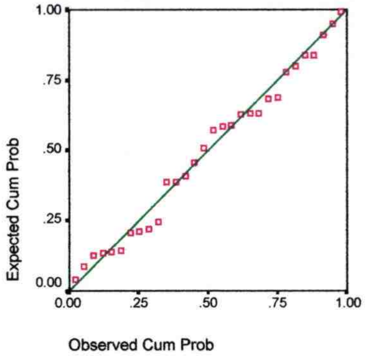
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	6.056E-02	.8345	.3213	.2096	30
Residual	-.3543	.4947	-6.48E-17	.1958	30
Std. Predicted Value	-1.244	2.448	.000	1.000	30
Std. Residual	-1.746	2.437	.000	.965	30

a. Dependent Variable: square root_sediment depth



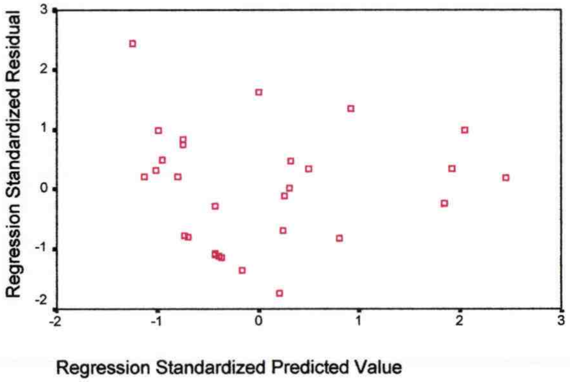
Histogram

Dependent Variable: square root_sediment depth



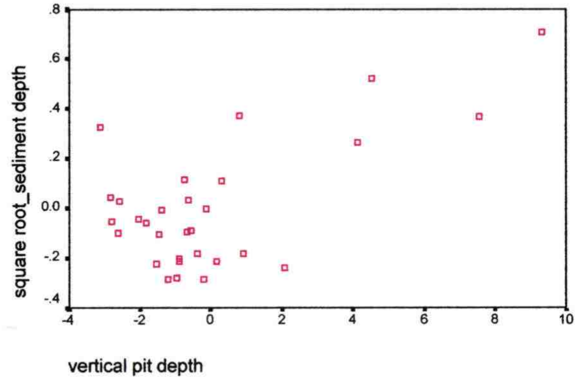
Normal P-P Plot of Regression Standardized Residual

Dependent Variable: square root_sediment depth



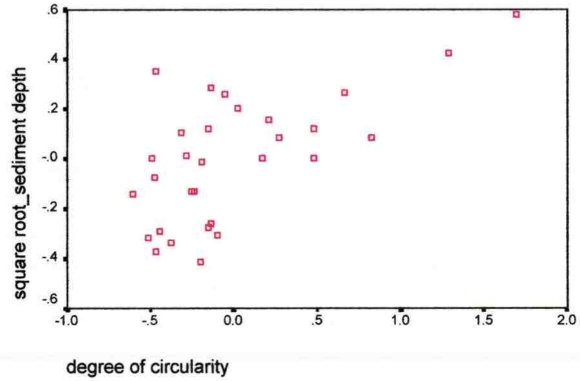
Scatterplot

Dependent Variable: square root_sediment depth



Partial Regression Plot

Dependent Variable: square root_sediment depth



Partial Regression Plot

Dependent Variable: square root_sediment depth