Presented to the Lincoln Gem + Mineral Club on Nov. 18th, 1989 in appreciation for the scholarship money and the moral support given me by the club members during my Master's thesis research. I cannot thank all of you enough.

thanks again

Bevin J. Schwartman, M.S.

A GEOLOGIC STUDY OF THE BIOTURBATED LOWER WHITNEY ASH BED (OLIGOCENE), NEAR CHIMNEY ROCK NATIONAL HISTORIC SITE,

WESTERN NEBRASKA

by

Kevin J. Schwartman

A Thesis

Presented to the Faculty of
The Graduate College in the University of Nebraska
In Partial Fulfillment of Requirements
for the Degree of Masters of Science

Major: Geology

Under the Supervision of Professor David B. Loope

Lincoln, Nebraska

June, 1989

A Geologic Study of the Bioturbated Lower Whitey Ash Bed (Oligocene), Near Chimney Rock National Historic Site Western Nebraska

Kevin J. Schwartman, M.S.
University of Nebraska, 1989
Advisor: David B. Loope

ABSTRACT: The Lower Whitney Ash is a thick, regionally correlative vitric tuff located within the Whitney Member of the Brule Formation. The ash bed is an airfall deposit covering about 7000 square miles (18,130 square kilometers) of western Nebraska. The Ash is over 20 feet (6.1 meters) thick in southwestern exposures and thins toward the east and northeast to about 5 feet (1.5 meters).

A petrographic analysis of the ash shows it to be made up of 85 to 95 percent rhyolitic glass, 10 to 15 percent mineral crystals, and generally less than 5% allogenic material. The ash is heavily bioturbated, so any original bedding has been destroyed. On fresh surfaces, the ash appears chalky-white with brown burrow mottling due to the presence of numerous trace fossils.

An excellent area to observe the trace fossils is on outcrops of the Lower Whitney Ash south of State Highway 92 on and surrounding Chimney Rock National Historic Site near Bayard, Nebraska. These consist of root casts (rhizoliths) and invertebrate gallery systems (burrows with chambers)

Dedicated with love to my family;
Especially my mother, Shirley Mae Rockel.
Without who's support, this thesis would
never have been completed.

The eyes believe themselves; the ears believe other people.
(Chinese Fortune)

The procession was composed of three gentlemen on foot and a mule laden with stones. These gentlemen were geologists. Geologists are charming company- particularly for other geologists.
(R. Topffer, 1841)

The fewer the facts, the stronger the opinion.
(Arnold H. Glasow)

TABLE OF CONTENTS

LIST OF ILLUSTRATINS

LIST OF TABLES

ACKNOWLEDGEMENTS

This study was completed with the help I recieved from the following people to whom I am greatly indebted: my advisor, Dr. David Loope, and co-advisor Dr. Robert Goodwin whose helpful suggestions proved invaluable, especially while editing this paper, and to James Swinehart II for serving on my defense committee and for suggesting the Lower Whitney Ash for my thesis project. I also appreciate the help I recieved from Dr. William Wayne on the subject of diastems and Janet Wright for her help on rhizoliths.

A special thanks goes to Julie Gilbert, Chris Rudnick, and Edward Southwick for their instruction in the use of the computer which made writing this paper much easier. Also, I appreciate the help of Mike Moran, not only for his assistance on the computer, but for his help in the darkroom and with the scanning electron microscope. I thank Ruth Ford for her assistance in the geology library and for knowing the exact location of the sources I needed for this project, and also Norman Brown for allowing me to work and collect samples on his land southeast of Chimney Rock.

Thanks also go out to my friends in the Lincoln Gem & Mineral Club for the two scholarships and all the moral support I recieved from them these past few years. And finally, I give a very special thanks and all my love to my family for all their support, especially during my work on this Master's project.

INTRODUCTION

The Lower Whitney Ash is located in western Nebraska and is exposed in outcrops of the Whitney Member of the Brule Formation which is of Middle Oligocene age (Swinehart, Sounders, DeGraw, and Diffendal, 1985). The ash attains a maximum thicknes of about 20 feet (6.1 m) along the Platte River Valley and thins to about 5 feet (1.5 m) toward the east and northeast.

The San Juan Volcanic Field in southern Colorado is the most likely source area (Swinehart, Sounders, DeGraw, and Diffendal, 1985). Volcanoes in this area began producing siliceous material during the Oligocene about 30 million years ago (Lipman, 1975). The eruptions originated from quartz latite and low-silica rhyolite volcanoes. The eruptions would have been very explosive and could have ejected a large volume of pyroclastic material high into the atmosphere. The mineralogy of the silicious volcanoes within the San Juan Field appears to be similar to phenocrysts found within the Lower Whitney Ash. Unfortunately, mineral composition of volcanic ash cannot be used to determine the area of origin for a distal source. This is because denser minerals will fall out of suspension first, leaving less-dense silicic minerals and glass to be carried farther away. This process is known as "eolian fractionation" (Fisher and Schmincke, 1984).

The Lower Whitney Ash is of interest to sedimentologists because of its areal extent of over 7000 $mi.^2$ (18,130 km^2) its thickness, and the extensive bioturbation of the ash relatively soon after it was deposited. Excellent exposures of the bioturbated ash can be found within outcrops of the Lower Ash on and surrounding Chimney Rock (Secs. 17 and 20, T. 20 N., R. 52 W. of the South Bayard 7 1/2 min. Quadrangle). Chimney Rock has a complete section of the Lower Whitney Ash which is up to 11.1 feet (3.4 m) thick.

The Lower Ash is widely used as a stratigraphic marker for the Whitney Member of the Brule Formation. The Upper Whitney Ash is also used as a marker bed, but it is thinner and less distinct than the Lower Ash. Neither ash bed has been recognized in the Brule Formation of Badlands National Park in South Dakota (Schultz and Stout, 1955). The Lower Ash thins to 5 feet (1.5 m) to the northeast, so the Lower Whitney Ash probably pinches out before it reaches the "Big Badlands" of South Dakota. According to Stout, DeGraw, and Tanner (1971), both the Upper and Lower Whitney Ash Beds are located in the Whitney Siltstones of northeastern Colorado in a section southwest of Peetz in Logan County. These sediments are nearly identical to those found in the Whitney Member of the Brule Formation in Western Nebraska.

Regional Stratigraphy

The Whitney Member (Mid-Oligocene) consists of a massive, pinkish-brown volcaniclastic siltstone containing two widespread vitric tuff beds (the Upper and Lower Ash Beds). The Whitney also contains localized mudstones and fine- to medium-grained sandstones (Swinehart, Sounders, DeGraw, and Diffendal, 1985; Swinehart and Loope, 1987). Underlying the Whitney Siltstones is the Orella Member of the Brule Formation. The Orella is made up of brown to greenish-gray volcaniclastic mudstones and siltstones. In the upper section, these sediments are interbedded with lenticular beds of fine to medium-grained sandstones (Swinehart, Sounders, DeGraw, and Diffendal 1985; Swinehart and Loope, 1987).

Within the study area (fig. 1), the Gering Formation unconformably overlies the Whitney Member. The Gering consists of gray to brown, volcaniclastic fine- to medium-grained sandstones which are both horizontally and cross-stratified (Swinehart, et al, 1985; Swinehart and Loope, 1987). All of the above sediments also contain localized ash beds.

Sedimentology

Volcanic ash is deposited in a geologically short time as compared to many other sediments. It may take thousands to millions of years to accumulate the sediment necessary to produce one meter of limestone; whereas, one meter of

FIELD AREA

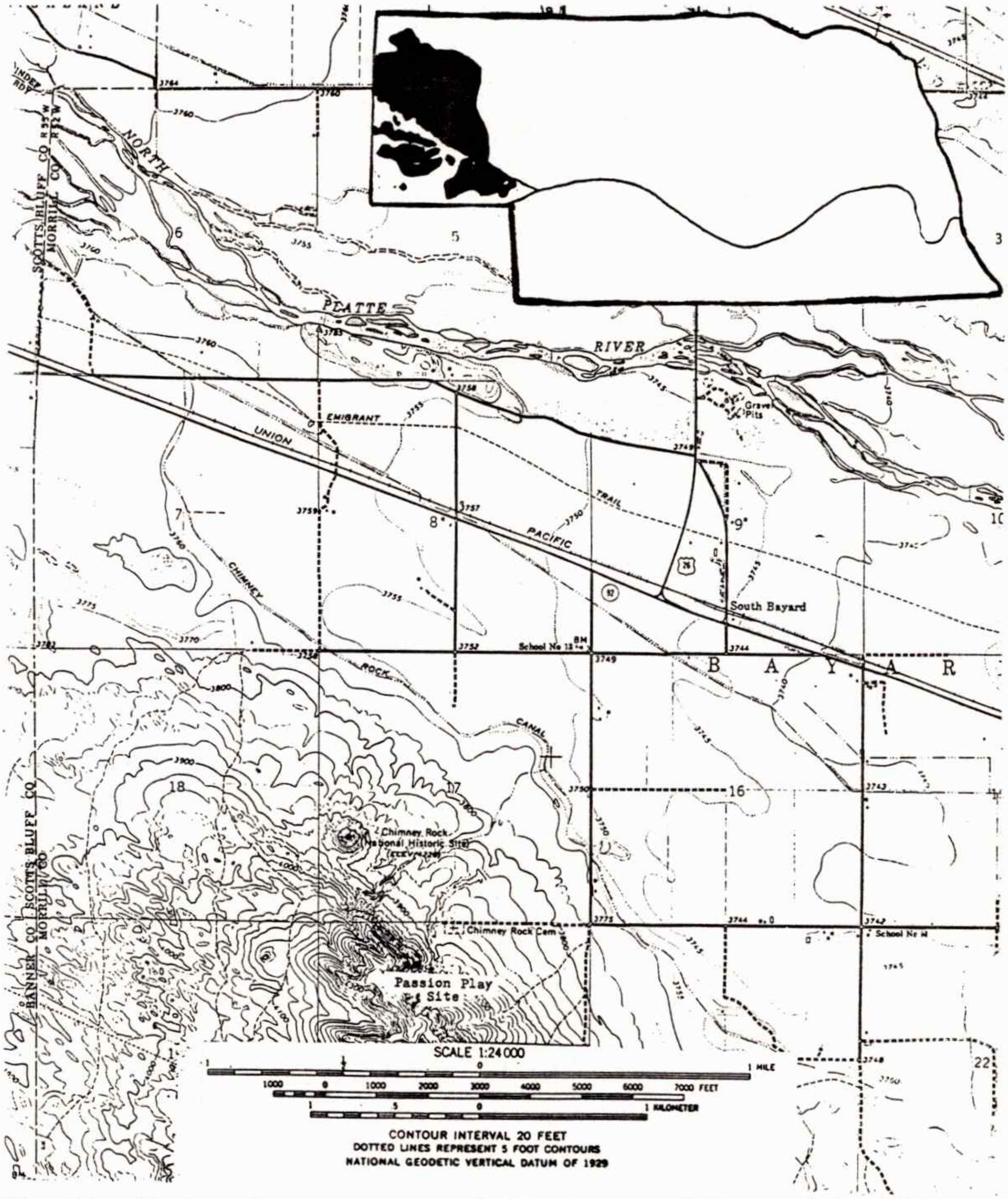


Fig 1) Regional occurance of the Lower Whitney Ash (Swinehart et al, 1985). The ash bed was studied on outcrops surrounding Chimney Rock National Historic site. Large samples were collected at the Passion Play Site about 0.5 mile (0.8 km) SE of Chimney Rock in the stream-cut valley just south-southwest of the cemetary.

STRATIGRAPHY OF CHIMNEY ROCK

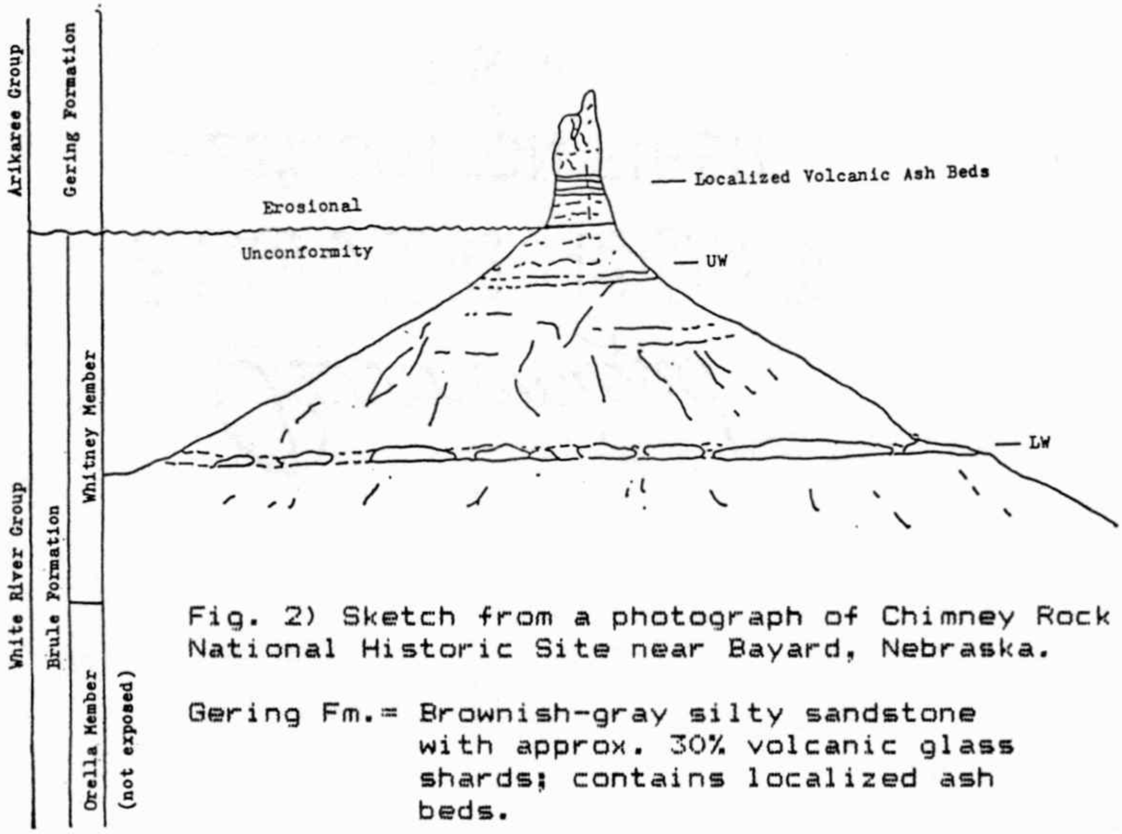


Fig. 2) Sketch from a photograph of Chimney Rock National Historic Site near Bayard, Nebraska.

Gering Fm.= Brownish-gray silty sandstone with approx. 30% volcanic glass shards; contains localized ash beds.

Brule Fm.= Pinkish-brown siltstone with approx. 50% volcanic glass shards; Whitney Member contains two regionally correlative ash beds.

UW= Upper Ash Bed
LW= Lower Ash Bed

volcanic ash may accumulate in a few hours or days (Fisher and Schminke, 1984).

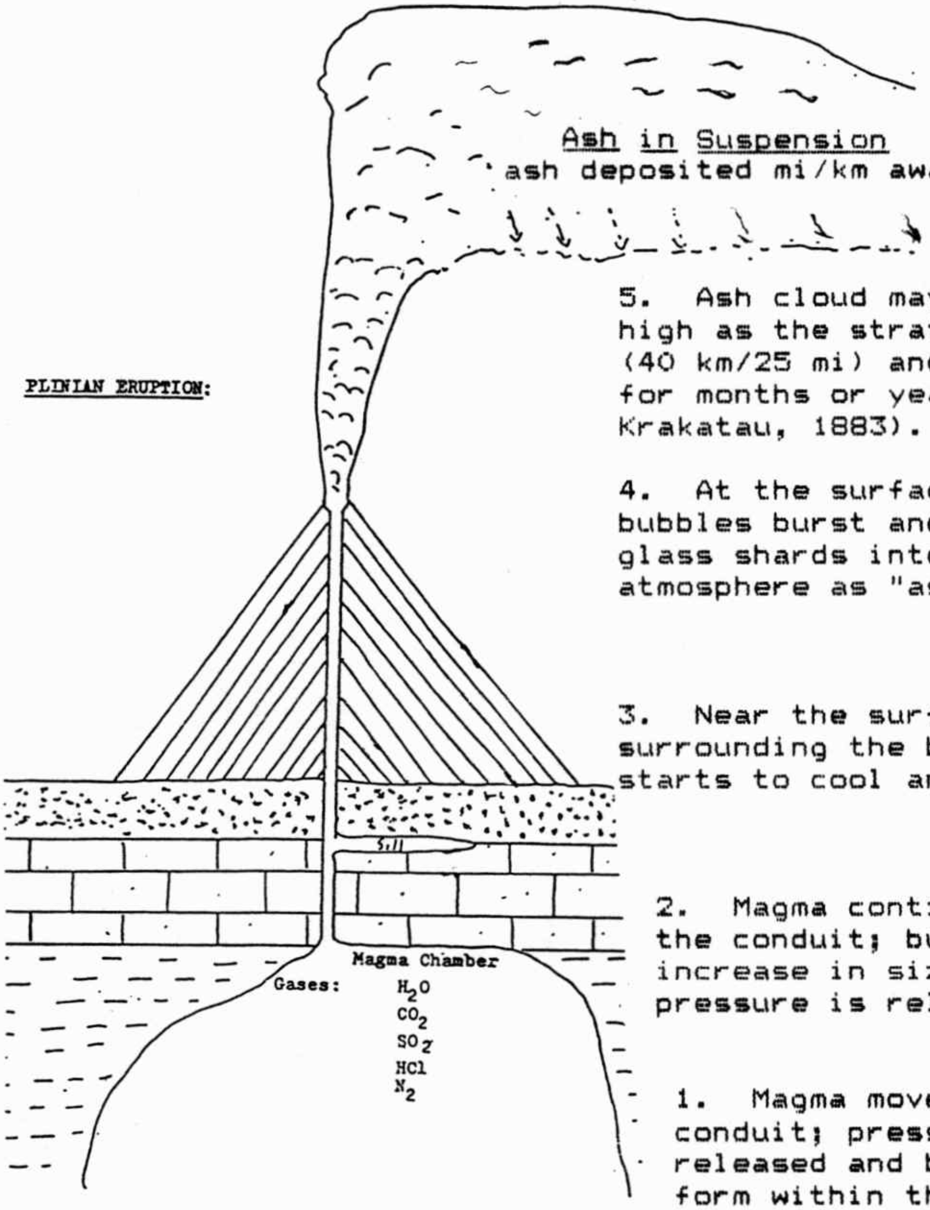
Volcanic ash is made up of pyroclastic material consisting of glass and mineral pyroclasts ejected along with various gases during an explosive eruption. Volcanic ash beds from distant sources are usually a result of Plinian (or ultraplinian) eruptions originating from a composite cone or strato-volcano (Decker and Decker, 1981; Fisher and Schmincke, 1984).

Magma contains gases such as: H_2O, CO_2, SO_4, H_2, HCl, HF, and N_2. These gases remain in solution due to the immense pressures deep within the earth. During an eruption, magma moves upward through the conduit toward the vent. As the magma moves upward, the pressure decreases and the gases begin to come out of solution and form bubbles within the magma. The bubbles increase in size as they move upward and the pressures near the surface continue to decrease. At the surface, the molten material surrounding the gas bubble cools and hardens into glass. The gas continues to expand within the bubbles as they move out of the magma. Eventually, the internal pressure of the expanding gas causes the outer coating of glass to shatter into separate shards. This material is then blown high into the atmosphere, and sometimes into the stratosphere (Fisher and Schmincke, 1984). This process is similar to someone shaking and then opening a bottle of warm beer or soda (see fig. 3).

According to a study by Retallack (1984), done in the Badlands National Park, the regional climate during the mid-Oligocene was temperate and humid with seasonal changes. Retallack (1984) also suggests the area was covered by forests with floodplain savannas. At this time, Nebraska may have had a similar ecologic setting, but there is very little sedimentological evidence to support this. Rhizo-liths within the Lower Ash bed do not appear to be large enough to have been made by full-grown trees as would be expected from a forested environment. It is possible that they were made by young trees, but most likely they were made by medium-sized plants such as bushes.

Siltstones of the Whitney Member of the Brule Formation are believed to be loessic in origin (Schultz and Stout, 1955) similar to the Pleistocene loesses of eastern Nebraska. These siltstones contain from 40 to 70 percent rhyolitic glass shards. The Gering Formation is fluvial and contains approximately 30% glass shards (Swinehart, et al, 1985). The ash beds located within these sediments were probably deposited after extremely explosively volcanic eruptions west and southwest of Nebraska threw huge amounts of pyroclastic material into the atmosphere. The 1883 eruption of Krakatau in Indonesia ejected 18 cubic kilometers of ash and pumice into the atmosphere. An explosion of this magnitude may throw pyroclastic material

FORMATION OF VOLCANIC ASH



5. Ash cloud may go as high as the stratosphere (40 km/25 mi) and remain for months or years (i.e. Krakatau, 1883).

4. At the surface (vent), bubbles burst and ejects glass shards into the atmosphere as "ash."

3. Near the surface, magma surrounding the bubbles starts to cool and harden.

2. Magma continues up the conduit; bubbles increase in size as pressure is released.

1. Magma moves up the conduit; pressure is released and bubbles form within the molten rock.

Fig. 3) Process by which violent plinian eruptions occur and volcanic ash is formed. Eruptions of this type normally take place in a composite cone or strato-volcano. The explosive effect of plinian eruptions can be compared to the effect of shaking up and then opening, a bottle of warm beer or soda.

high into the stratosphere where it may remain for months or up to years (Decker and Decker, 1981). As this material drops out of suspension in the atmosphere, it would be mixed and deposited with both eolian and fluvial sediments.

The Lower Whitney Ash is a thick, massively bedded, biotitic tuff which is chalky-white with brown burrow mottling on fresh, eroded surfaces. Older surfaces (in areas with less erosion) appear greenish-gray due to a coating of lichen which attacks and helps erode the surface of outcrops to gain mineral nutrients (Sarjeant, 1975). Much of exposed surface of the Lower Whitney Ash, which is covered with lichen, appears to be severely weathered and eroded.

Trace fossils in the Lower Whitney Ash are mainly root casts (rhizoliths) and invertebrate galleries (burrows with chambers) filled with silty ash. These trace fossils vary in color from pink to dark brown. The difference in color between ichnofossils is related to the type and amount of allogenic material filling the burrow or root cast.

The lower contact of the ash is sharp and visible on nearly all outcrops. The ash layer forms a resistant bed which usually protrudes outward beyond the surrounding Brule Siltstones (fig 4). The heaviest bioturbation appears to be located near the base of the ash, below the first silty layer or diastem. The diastems are mottled, silty ash layers which indicate some form of break in the

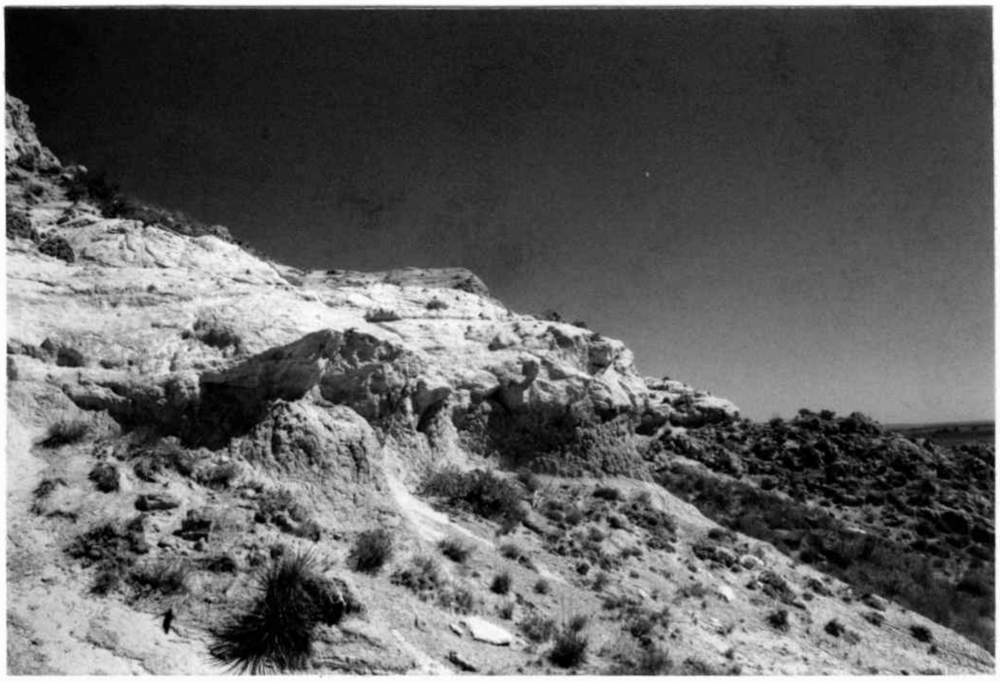


Fig. 4) The Lower Whitney Ash is exposed as a chalky-white, biotitic, massively bedded, bioturbated tuff layer. It forms a resistant bed protruding from the surrounding Brule siltstones. The upper part of the ash is usually weathered and eroded to form a low-angle ledge covered by talus. Where exposed the upper contact appears to be gradational, the lower contact is sharp and commonly well exposed. The gradational upper contact and the sharp lower contact is a result of the faster sedimentation rate of the volcanic ash as compared to the wind-blown loessic Brule Siltstones.

sedimentation of the ash, most likely due to a period of quiescence between major eruptions.

Five diastems can be located within the Lower Ash Bed, but in only one area are all five visible in a complete section. Within the diastem complex (from about 32.5 to 73.5 in./81.3 to 186.7 cm above the base) is a calcic concretion or nodular zone. The nodules range in length from about 1.0 in. (2.5 cm) to over 20.0 in. (50.8 cm). In some areas the concretions appear to either increase or decrease in size upsection.

The upper half of the ash section is heavily weathered and forms a low-angle slope covered by talus from eroded ash and siltstone. It is possible that more diastems are present in the upper portion of the ash; but only five have been recognized in this study. The condition of the ash and the talus covering it has made many of the trace fossils unrecognizable, giving the appearance that the upper section is not as heavily burrowed.

The Upper contact of the lower Whitney Ash with the Whitney Siltstone is gradational and usually occurs on a slope of a low angle and is often covered with talus; thus, in most areas it is difficult to find.

According to Izett (1981) the Lower Whitney Ash (referred to as the "Chimney Rock Ash" in his paper) is a W-type rhyolitic ash. These ashes are normally chalky-white, biotitic, and contain low percentages of glass shards with microlites. They also have 76 to 79 weight percent of SiO_2 in the glass shards. Using the method of Powell and Powell (1977), Izett calculated the temperature of the magma from which the Lower Ash originated to be about 830^{o} Centigrade which is considered to be intermediate. Izett's paper is one of the few papers which contains any laboratory studies of the Lower Whitney Ash prior to this study. Although many papers describe the ash as being a marker bed for the Whitney Member of the Brule Formation, apparently no other work has been published that gives either a detailed petrographic analysis or description of the numerous trace fossils.

METHODS OF RESEARCH

Field Method

Most of the field work for this study was done on a series of outcrops of the Lower Whitney Ash surrounding Chimney Rock. An excellent, complete section is located on the conical base of Chimney Rock (see fig. 5). There are several other sections about one-half mile (0.8 km) southeast of Chimney Rock on privately-owned land.

Chimney Rock is one of Nebraska's most famous historic monuments, and is probably the most well-known natural landmarks along the Oregon Trail. Because this is a National Historic Site, it was not possible to remove large samples from the outcrops on Chimney Rock. But, it was possible to photograph and/or sketch many of the features of interest.

Four sections were measured through the ash and small samples from specific places on the ash were obtained for petrographic analysis. The outcrops southeast of Chimney Rock are on private land; so, with permission, large blocks were removed from the outcrops for laboratory study. This collection site was used as the setting for a passion play held periodically from around 1929 to 1941. As a matter of convenience, this area will be referred to as the "Passion Play Site" (fig. 6). The ash is compact, but friable, so large blocks can be removed by cutting away the surrounding ash with a large knife or machete. Samples were carefully

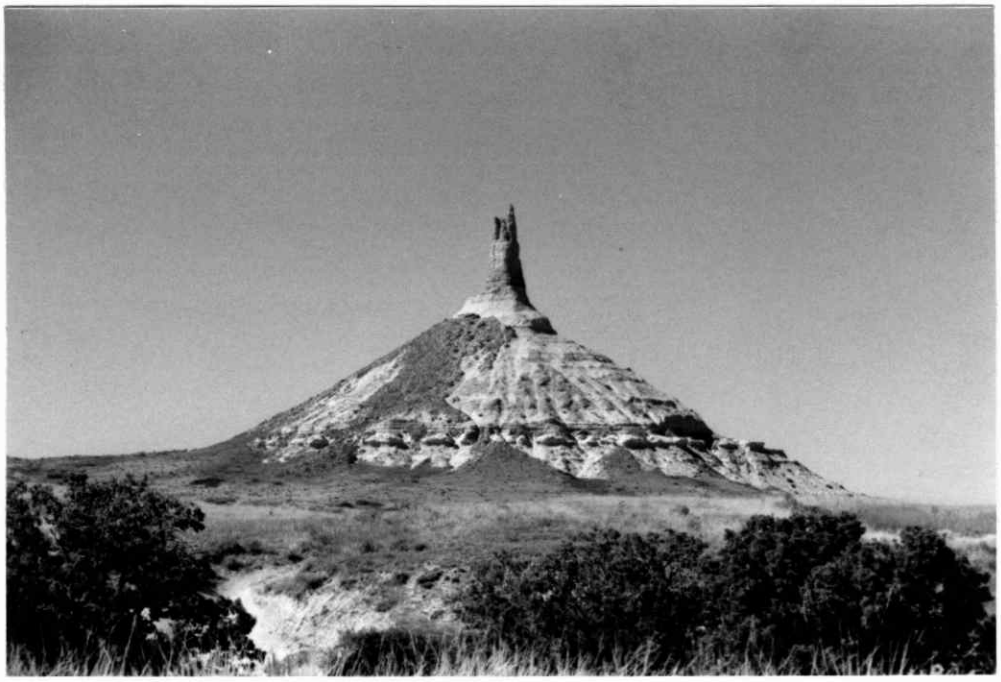


Fig. 5) The Lower Whitney Ash exposure on Chimney Rock is 10 to 11 ft. (3.1 to 3.4 m) thick and can be distinguished from the Brule Siltstones by its chalky-white color and resistant nature. The Lower Ash makes up the resistant bed located near the base of the Monument in the above photo.

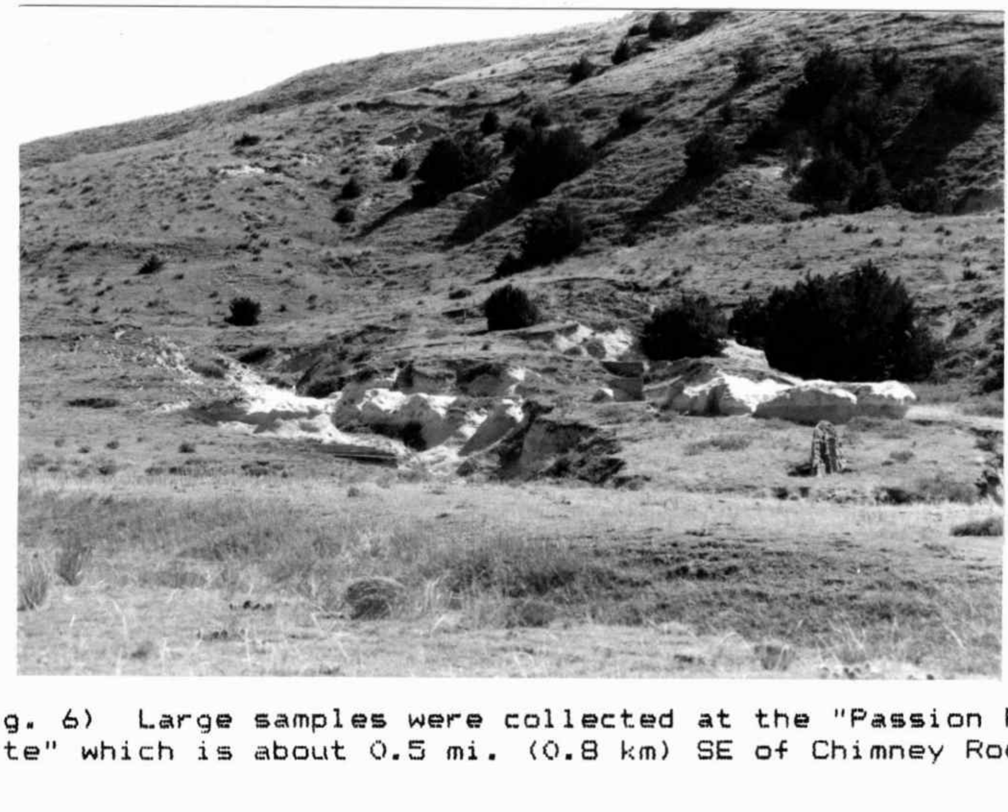


Fig. 6) Large samples were collected at the "Passion Play Site" which is about 0.5 mi. (0.8 km) SE of Chimney Rock.

selected, removed from the ash bed, and stored in pre-cleaned 35 mm film canisters. All blocks and samples were clearly labeled as soon as they were removed from the outcrop.

The thickest sections are probably located at Scotts Bluff National Monument which is about 20 miles (32.2 km) northwest of Chimney Rock. One section of ash was measured to be about 21 feet (6.4 m) thick. Sections measured on Chimney Rock ranged from 10.2 feet (3.1 m) to 11.1 feet (3.4 m) thick. The Scotts Bluff exposure has a greenish-gray appearance due to a thick coating of lichen, much more than is present on either Chimney Rock or in the Passion Play Sites. This indicates that the exposures on Scotts Bluff are older or have been subjected to less erosion than those in the Chimney Rock or Passion Play Sites. No samples were taken at Scotts Bluff because it is a National Monument and required special permission from the Park Rangers. Also, the thick lichen coating and several inches of weathered ash would have to be removed to expose a fresh surface for study.

The northernmost exposure of the Lower Whitney Ash is located in the Pine Ridge area just below Roundtop Butte. It can be easily observed from a distance, but up close it is hard to distinguish from the surrounding Whitney Siltstones. According to Schultz and Stout (1961) this exposure is about 8 to 10 feet (2.4 to 3.0 m) thick.

Laboratory Methods

Specimens taken from the Lower Whitney Ash were made into grain mount slides using Lakeside 500 thermalplastic cement. A few of these specimens were taken directly from the outcrop, most were removed from blocks of ash in the laboratory.

Grain-mount slides, were made from each sample, and a point-count study was done using a Unitron S.T.C Stage. The samples were not given an acid bath prior to making the slide, because this study includes the amount of allogenic material found within each sample. Also, the samples are clean enough that the silt and clay does not inhibit identification of the individual grains. This is true even for those samples taken from within burrow fills.

The petrographic analysis of the ash was conducted with a Zeiss Petrographic Microscope. Point-counts of 300 to 600 grains were done for each sample to determine the grain size distribution, mineralogy, and allogenic content. A total of 41 samples were taken from both the outcrops and blocks of ash. About 15,300 grains were counted from 61 slides made from these samples. With the equipment available, only grains larger than 4.0 microns (0.004 mm) could be accurately measured. However, the amount of material less than 4 microns is small enough to make it negligable and thus, not vital to this study.

Using blocks of ash brought in from the field, a series of sketches were made of various trace fossil assemblages. A 2.0 x 2.0 cm grid was placed over the area of the ash to be sketched. The sketch was made on paper with a pre-drawn grid of the same scale. Thus, each sketch is very close to the actual size and shape of the original ichnofossil (fig. 7).

By shaving away thin increments (about 2 to 3 mm thick) of ash between sketches, the 3-dimensional morphology of the trace fossils can be determined. Using a block of ash, a series of 10 sketches were made showing changes in the shape of the trace fossils as the layers of ash were cut away. A total of 14 sketches were made of trace fossil assemblages from blocks of the Lower Ash.

Accurate sketches of ichnofossil assemblages were made from color (photograph) slides using a similar method. Again, a sheet of paper with a pre-drawn 2.0 x 2.0 cm grid is used. On this paper, the image of a trace fossil assemblage is projected. Accuracy in size can be achieved by adjusting the projector's distance to the paper and comparing the item used for scale in the photograph with the actual item (such as a hammer, ruler, etc...). Thus, the trace fossil assemblage could be accurately traced directly onto the paper with the pre-drawn grid. Size and shape of the trace fossil sketches are very close to the originals. Fifteen sketches of ichnofossil assemblages were made from

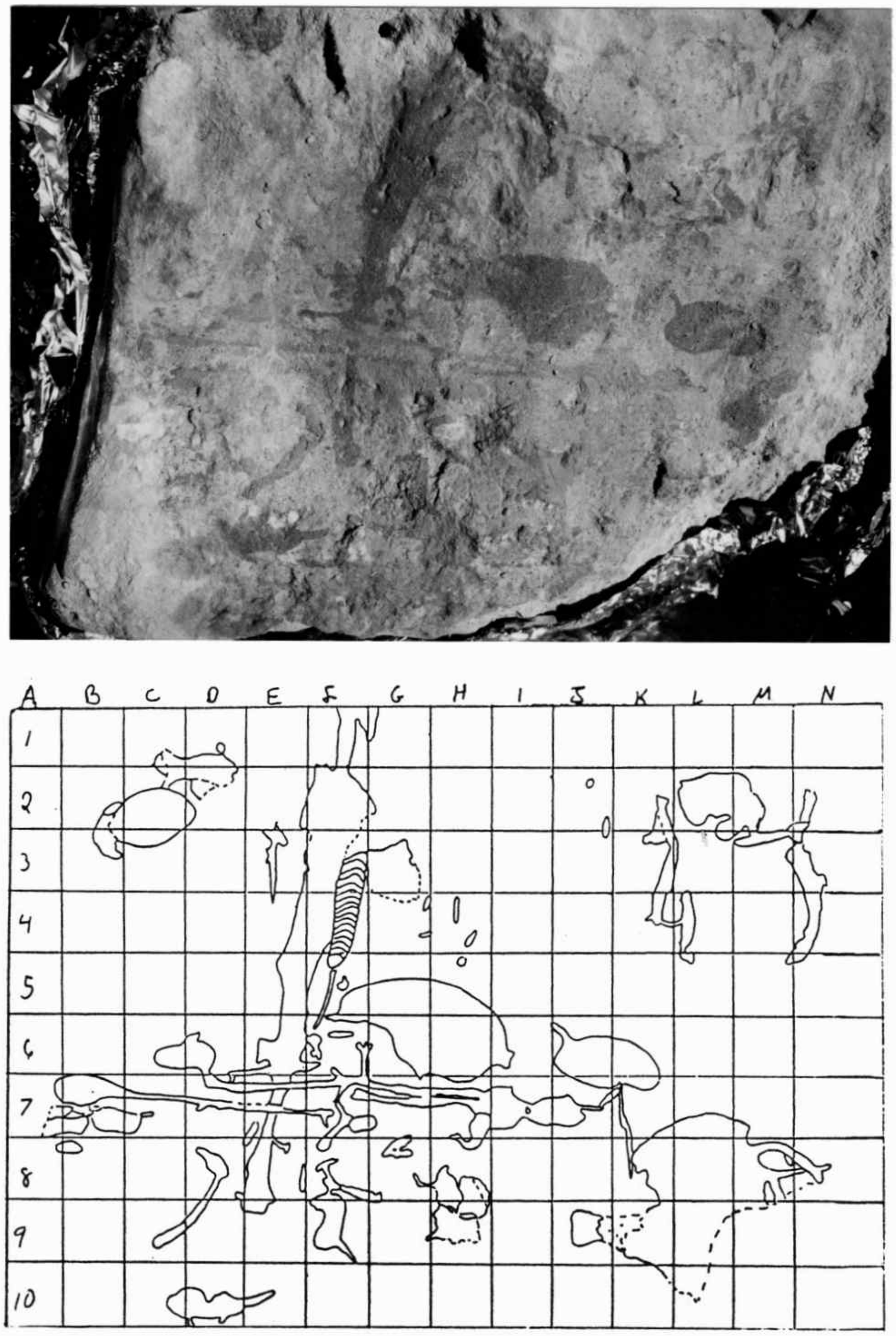


Fig. 7) Sketches such as this were made from blocks and slide photos of heavily bioturbated area, especially near the base of the ash bed. This block was removed 10 to 17 in. (25 to 43 cm) above the base. Each square is 2.0 cm on a side in the above sketch.

nine slides using this method.

With these 29 sketches and four blocks of ash, about 343 trace fossils were described and measured, many are individual specimens, but some are probably interconnected. A general size distribution was determined by measuring the widths of each burrow and rhizolith, and by measuring the length (along the longest axis) of each chamber. Differences in color and allogenic content were used to separate each trace fossil within an assemblage into its age relative to surrounding trace fossils. Thus, assigning it to a "generation" of biogenic activity within a single assemblage.

SEDIMENTOLOGY OF THE LOWER WHITNEY ASH

Ecologic Setting

The Lower Whitney Ash is a vitric, rhyolitic tuff. However, the type of ecologic setting of western Nebraska during the Oligocene is uncertain. The over- and underlying siltstones of the Whitney Member of the Brule Formation are considered to be of loessic (eolian) origin (Schultz and Stout, 1955). The Lower Whitney Ash is probably an airfall deposit because it contains a very small amount of allogenic material. If it was deposited in water, such as by a river or a lake, there would be a higher percentage of silt and other material within the ash bed. Also, there is no evidence of subaqueous deposition within the Whitney Siltstones above and below the Lower Ash bed.

Nearly all areas of the ash appear to be massively bedded. Any primary bedding that may have existed would have been destroyed by extensive bioturbation. Many volcanic ash beds are deposited with primary massive bedding (Fisher and Schmincke, 1984). However, one block of ash eroded from Chimney Rock shows evidence of very thin laminae which are about 1.0 to 2.0 mm thick. Unfortunately, this is the only part of the ash which displays any type of bedding, and it could not be determined from where on the outcrop this block had come.

A study done on the burrowing activity of staphylinid beetles on the Loup and Platte Rivers in Nebraska (Smith and Hein, 1971) shows that the insects slow down their burrowing activity at lower temperatures. At 20° C (68° F) the beetles worked sluggishly, constructing their burrows at less than one per hour. At 35° C (95° F) the beetles worked nearly four times as fast. Although this does not tell us what temperature the area had during the mid-Oligocene, it does indicate that warm temperatures are favorable for extensive biogenic activity.

Stratigraphy of the Lower Ash

Four sections were measured on Chimney Rock (fig. 8). The thickest section was measured as 11.1 feet (3.4 meters) on the west-southwest side. The thinnest section was measured on the north-northeast side as 10.2 feet (3.2 meters). Sections were also measured on the north-northwest side (11.0 feet/3.4 meters) and the south side (10.6 feet/3.2 meters) on Chimney Rock.

The basal contact of the ash bed with the Whitney Siltstone is sharp and slightly calcic in some areas. It is usually heavily bioturbated near the base, and has both rhizoliths and invertebrate galleries. About 32 inches (81.0 cm) above the base is a horizontal layer of mottled silt and clay (fig. 9) approximately 4.0 in. (10.2 cm) thick. This mottled layer can be traced laterally to all sides of Chimney Rock and even to an outcrop in the Passion

STRATIGRAPHIC SECTIONS OF THE LOWER WHITNEY ASH

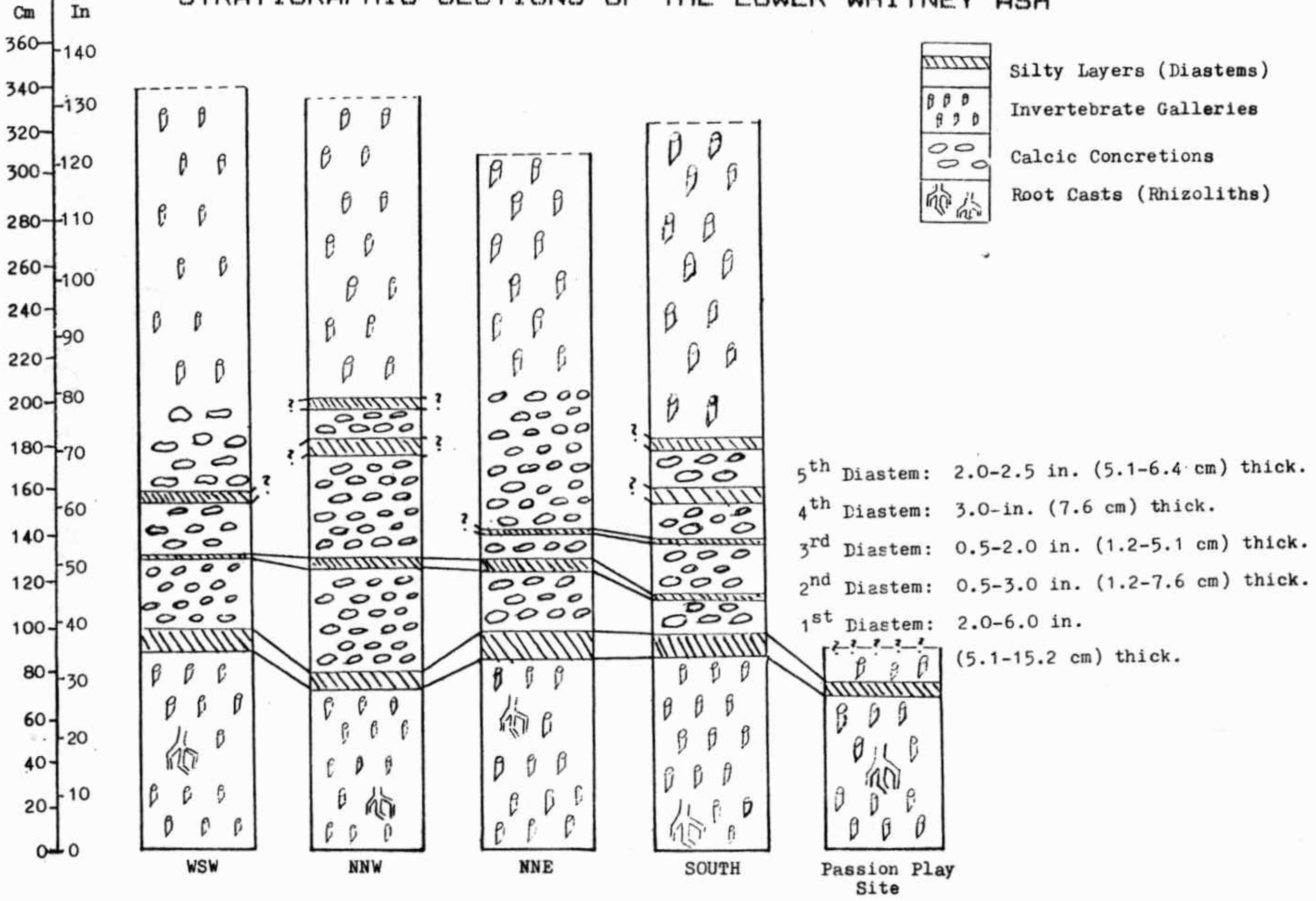


Fig. 8) Four sections of the Lower Whitney ash were measured on Chimney Rock. Note how well the recognizable diastems can be correlated from one section to another. The nodular zones begin above the first (lowermost) diastem and end at about the level of the fifth diastem, even in sections where this diastem is not recognized.

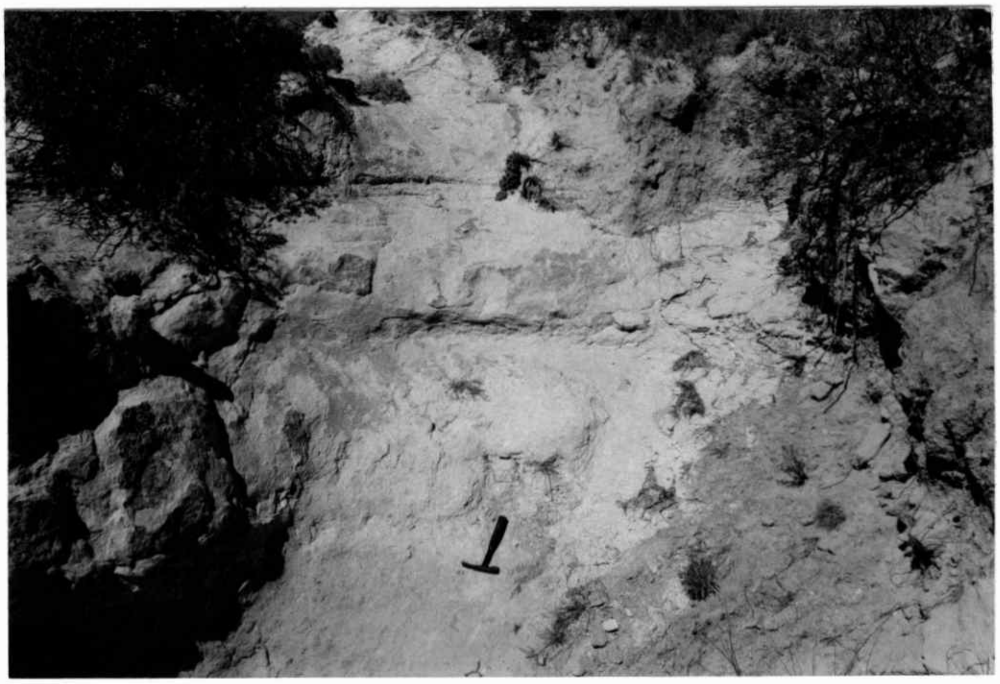


Fig. 9) The diastems occur as horizontal, mottled, silty layers which can be traced laterally from one section to another. The correlated diastems do not vary in elevation by more than 8.5 in. (21.6 cm).

The first or lowermost diastem (9b-next page) is approximately 32.0 in. (81 cm) above the base. It is the thickest of the layers at about 4.0 in. (10.0 cm) and is visible on all outcrops of the Lower Ash. This diastem can be traced from Chimeny Rock to the Passion Play Site about 0.5 mi. (0.8 km) away.

The second diastem (9a-next page) is about 48.5 in. (123.0 cm) above the base. This layer is about 2.0 in. (5.1 cm) thick and is also recognizable on all four measured sections on Chimney Rock.

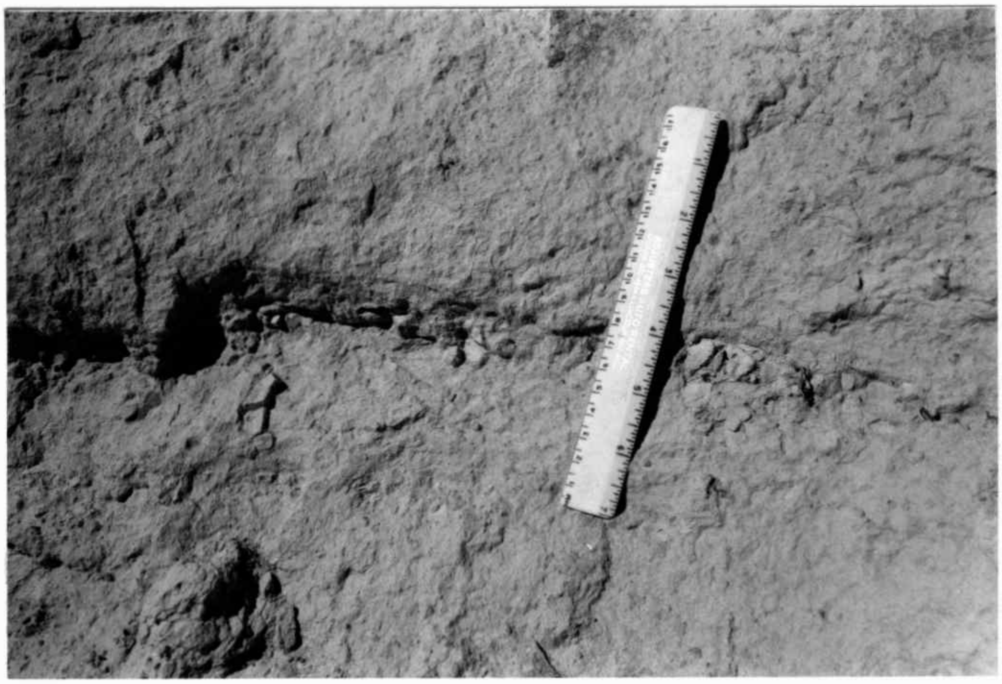


Fig. 9a) The second diastem is about 16.5 in. (42 cm) above the first diastem and can be located on all four measured sections of Chimney Rock.

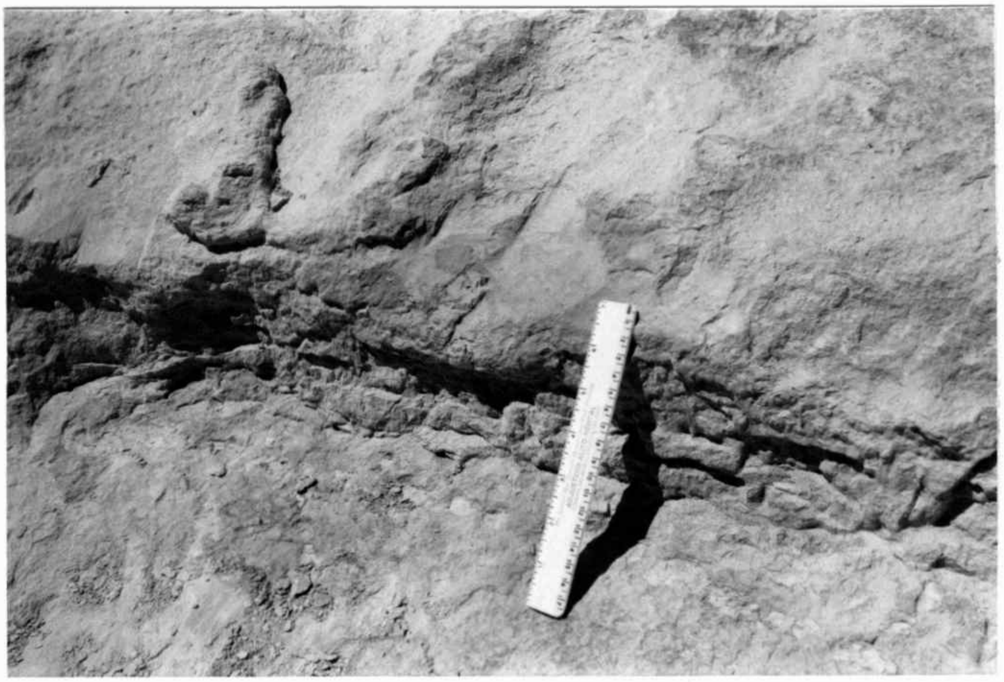


Fig. 9b) The first diastem is about 32 in. (81 cm) above the base of the ash and can be located on all four measured sections of Chimney Rock and on outcrops in the Passion Play Site 0.5 mi. (0.8 km) away.

Play Site one-half mile (0.8 km) away. This first layer is the thickest of at least five visible horizons. The other layers are thinner, between 0.5 to 3.0 in. (1.3 to 7.6 cm) thick.

The next horizontal layer is about 48.5 in. (122.9 cm) above the base. The third layer is approximately 56.9 in. (144.5 cm) and the fourth is 65.0 in. (165.1 cm) above the basal contact. The top mottled layer is at about 73.5 in. (186.7 cm). These horizontal layers represent a break in the sedimentation, such as a minor unconformity or diastem, between volcanic eruptions. There is no apparent soil development to suggest the existence of a paleosol. The volcanic eruptions and subsequent ashfalls only lasted a short time, from a few hours to a few weeks. The period of time between eruptions, during the accumulation of these diastems, was probably less than a couple of years; thus, it was not long enough for good pedogenic structures to form (fig. 10).

The diastems located within the Lower Whitney Ash were formed as allogenic dust (silt and clay) settled onto the surface of the ash during periods of quiescence between ashfalls. The first diastem would have formed after ash stopped falling after the initial eruption. At this time, allogenic silt was brought in (most likely by wind) and deposited onto the surface of the ash, similar to how the siltstones of the surrounding Brule Formation were formed.

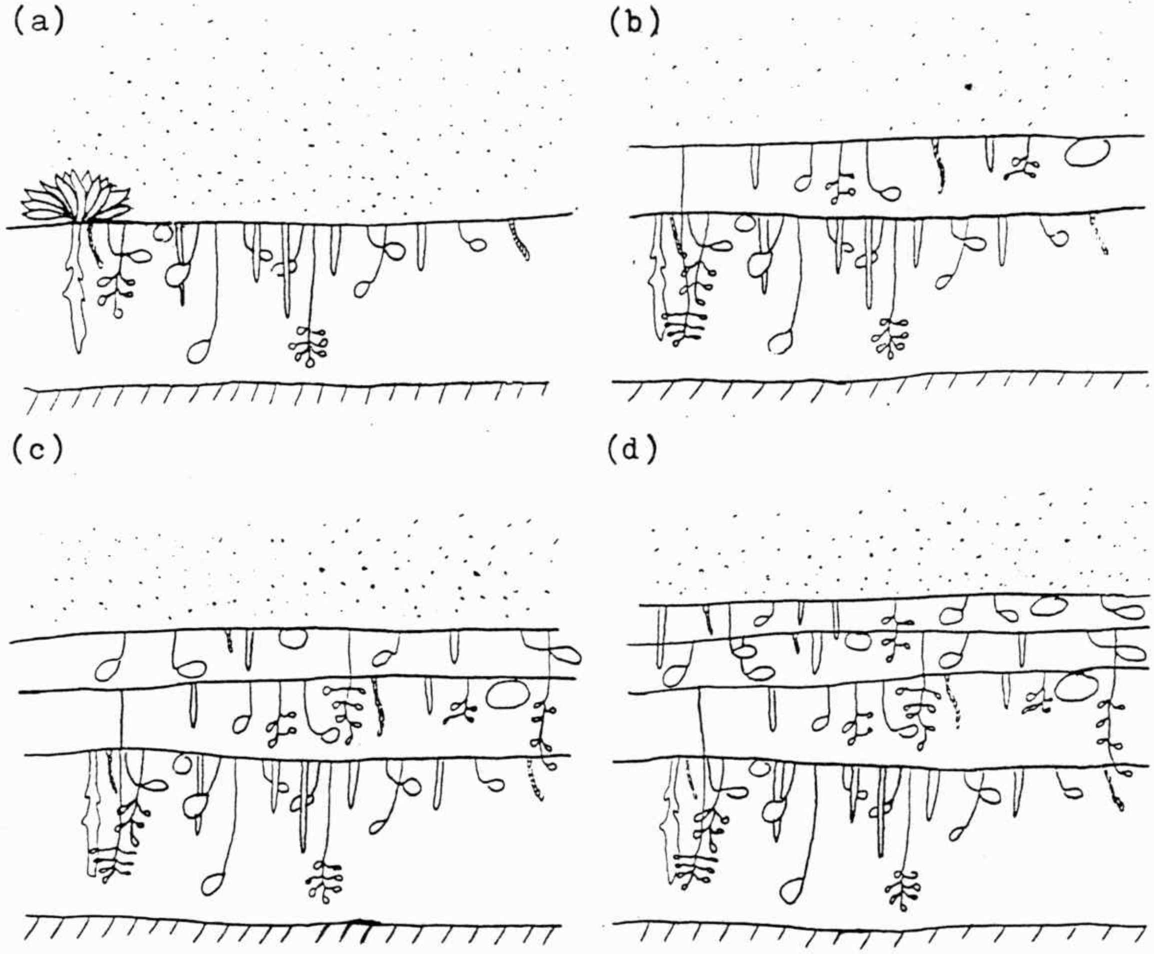

CONSTRUCTION OF DIASTEM COMPLEX

Fig. 10) After the second ashfall (a), the next ash bed (b) was probably bioturbated by several generations of biogenic activity. After each subsequent ashfall, a diastem was formed during a period of quiescence between eruptions (c). Five distinct diastems can be recognized within the Lower Whitney Ash (d). Note the thickest sequence is at the base, this indicates a thicker ashfall. The associated diastem is also thicker than the others which suggests a longer period of time before the next eruption. Thus allowing more allogenic material to accumulate on the surface of the ash.

Very few trace fossils can be recognized within the diastem complex, but numerous calcic concretions can be found within the thin ash layers between the diastems. It has been suggested that there may be a connection between the formation of concretions and the presents of trace fossils.

The diastems were formed as silt was deposited on the surface of the ash bed, it may have been rapidly stabilized by small plants. But, the short time between eruptions would probably not have allowed vegetation to become extensive enough to form a pedogenic horizon or soil. The first (lowermost) diastem is the thickest, so it represents the longest break between volcanic eruptions during the time the source area was active and/or the climatic conditions were favorable to bring the volcanic ash into Western Nebraska. This diastem can be traced to all areas of Chimney Rock and to the outcrops in the Passion Play Site. At this site the first diastem is located 27.0 in. (68.6 cm) above the base of the ash. The height of this diastem from the base fluctuates from 28.1 in. (71.4 cm) on the north-northwest section, to 34.6 in. (87.9 cm) on the west-southwest section. This is true for all of the recognizable diastems and their associated ash layers. The reason for this is probably due to topographic differences of the ground's surface during the ashfall. The falling pyroclastic material blankets the area and conforms to the topography. Heavy rains and slides may cause the ash to flow into low areas such as valleys. Thus, thicker ash deposits may be found in topographically low areas; whereas, hills and other high areas would have thin ash deposits (Williams and McBirney, 1979). None of the diastems which can be correlated from one section to another vary by more than 8.5 in. (21.6 cm) in elevation from the base of the ash.

During the petrographic analysis of the ash, it was discovered that the basal 4.0 in. (10.2 cm) of ash contains more pumice than bubble wall shards (about 56% pumice to 44% bubble wall shards). At 5.5 in. (14.0 cm) above the base, the amount of bubble wall shards increased to approximately subequal amounts with the pumice. At 14.0 in. (35.6 cm), the bubble wall shards increased to become more common than pumice (about 59% bubble wall shards to 41% pumice).

This increase in bubble wall shards upsection suggests a decrease in viscosity (due to an increase in temperature) of the magma from which the ash originated. This would occur as cooler material (from the top of the magma chamber) is blown out of the vent and replaced with hotter material from deeper within the magma chamber. Thus, the pumiceous layer (near the base of the ash) is a result of the explosive cooler, viscous material from the surface of the magma chamber. The increase in bubble wall shards indicates an increase in temperature of the magma from deeper within the chamber (fig. 11).

It may be possible to use this method to separate the Lower Ash into individual volcanic eruptions. Samples were carefully removed from the ash surrounding the diastems and

BUBBLE WALL/PUMICE RATIO

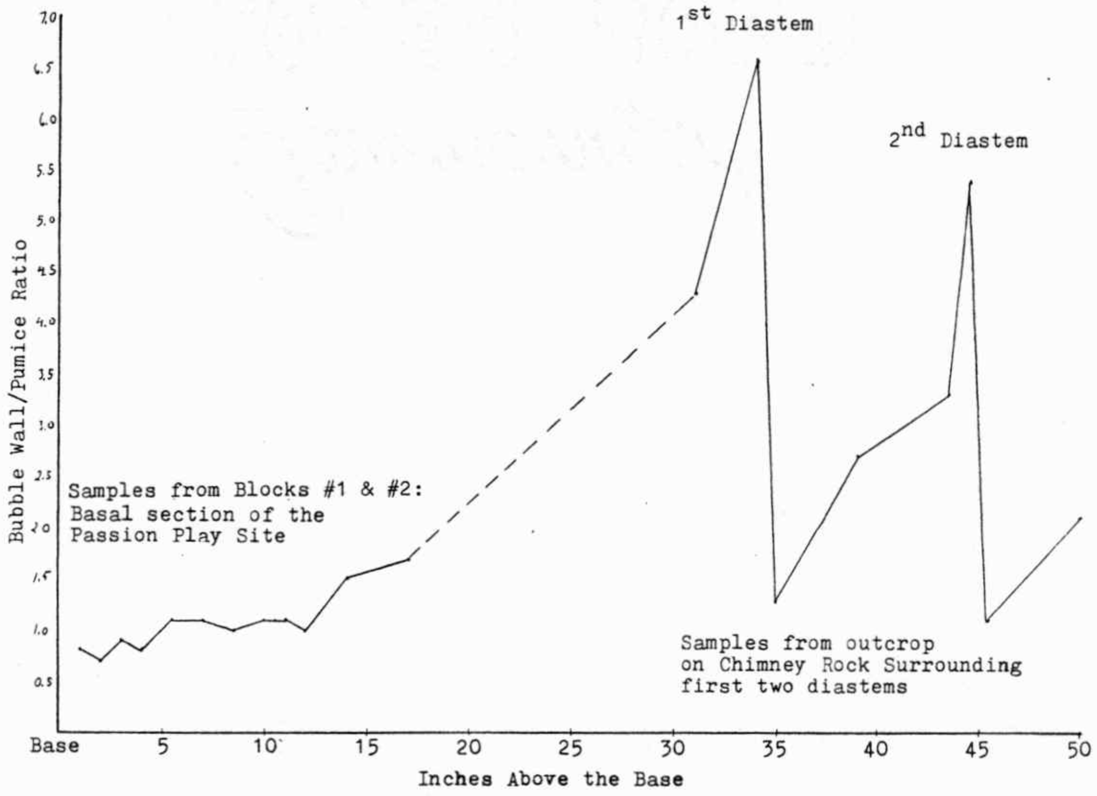


Fig. 11) Samples taken from the base of the ash bed in the Passion Play Site show a gradual increase in bubble wall shards upsection. The increase is much more dramatic in samples taken from Chimney Rock within the ash surrounding the first two diastems. This suggests that at the start of an eruption, cool, viscous magma is ejected as pumice. This is soon replaced by hot, less-viscous material from deeper within the magma chamber which is ejected as bubble wall shards.

subjected to a petrographic analysis. The difference in bubble wall to pumice is very large within the first diastem (about 87% bubble wall to 13% pumice). At 1.0 in. (25.0 cm) above the diastem, the pumice increases to about 43% and the bubble wall content drops to 57%. Above this, at 4.0 in. (10.2 cm) above the first diastem, the bubble wall content again increases to about 73% and the pumice content drops to 27%. A similar pattern was observed during a petrographic analysis of samples taken surrounding the second diastem about 44.5 in. (113.0 cm) above the base (see fig. 11).

At the beginning of an eruption, such as that described in the Sedimentology section, the material near the top of the chamber would be the first to be ejected. This material is cooler and more viscous than the molten rock found deeper within the magma chamber. This cool, viscous material would be ejected as pumice and is the first to be deposited after the eruption, thus forming a pumaceous layer at the base of the bed.

After the (cool, viscous) upper material has been blown out, hotter, less viscous material (from deeper within the magma chamber) is ejected in the form of bubble wall shards. Thus, the highest amounts of pumice should be located at the base of an ash layer from a single eruption. For each new eruption, after a period of time allowing the material near the top of the magma chamber to cool down, a sequence such as that described above should be repeated.

Although there does appear to be a pattern here, this data is based on only two sampled areas 0.5 miles (0.8 km) apart. The basal ash was sampled on the Passion Play Site, and the diastems were sampled on Chimney Rock. To truly substantiate this hypothesis, more ash samples would need to be taken from other sections and a similar petrographic analysis done with these samples.

Within the layers of ash between the diastems are numerous calcic concretions of various sizes and shapes (fig. 12). Most are roughly ovoid to globular with randomly oriented knobs. The concretions range in size from less than 1.0 in. (2.5 cm) to over 20.0 in. (50.8 cm).

The concretion (or nodular) zone begins just above the first diastem and extends upward to about the level of the fifth diastem. In some areas they appear to vary in size within the vertical section. In the west-southwest section, the concretions seem to increase in size above the third diastem which is about 61.0 in. (154.9 cm) above the base. The north-northwest section shows no major changes in the size of the concretions. The north-northeast and south sections have a large concretion zone between the first and third diastem. Above the third diastem in this section, about 55.0 in. (139.7 cm), the concretions appear to decrease in size. No concretions are present above the fifth diastem. There is no apparent reason as to why the

Fig. 12) Calcic concretions are only found within the thin layers of ash of the diastem complex. These nodules were probably originated from some type of soil-forming process similar to that which produces concretions in paleosols.

concretions increase or decrease in size within a specific section, especially since there is no correlation from one section to another in regard to changes in nodular size.

The Lower Whitney Ash is generally massive and weathered in many areas. The massive, weathered surface within the concretion zone makes it difficult, if not impossible, to determine when the concretions were formed. If bedding were visible within the ash bed, it could be used to determine when the concretions were formed in relation to the deposition of the ash. If the bedding laminae cut through a concretion without curving around it, this would indicate that the concretion formed after the sediment was buried and compacted. Whereas, if the laminae curve around the concretion, this would suggest early formation of the concretion prior to burial and compaction of the sediment (Ehlers and Blatt, 1982). Unfortunately, even in thin-section, there appears to be no evidence of laminae within the concretions.

In thin section, the concretions appear to be made up of volcanic ash "cemented" with $CaCO_3$. Near the edges, small silt grains can be seen which appear similar to those observed within the burrow fill. These may be fecal pellets. If these unusual silt grains (which were also found during the petrographic study of the burrow fill) are fecal pellets, this would suggest that there may be a connection between the concretions and the trace fossils.

Ichnofossils may be present, but are not recognized within the nodular zone. According to a study by Berner (1968), decaying matter may aid in the precipitation of minerals such as calcite. Also, in many areas, trace fossils may be preserved as "precompactional nodules or nodule protuberances" (Hallam, 1975). This is caused by the decreased porosity of the burrow fill (as compared to the matrix) which controls the flow of pore fluids causing minerals (such as calcite) to precipitate in these areas of lowered porosity. Thus, there could be some connection between some of the concretions and the trace fossils located within the Lower Whitney Ash.

Many of the smaller concretions are about the size of a normal chamber from most of the invertebrate galleries, but some of the nodules are nearly twice as large as the largest chambers. One possible explanation is that the larger concretions were formed in an area with two or more coalescing chambers, which caused the calcite to be precipitated in a larger area than in areas with only a single chamber. The source of the calcite filling the concretions is, as of yet, unknown. Most likely it was brought in by the water flowing through the ash which produced the concretions.

There is little evidence other than this to explain the existence of these calcite concretions. There appears to be a possible connection with the trace fossils, which would explain why few are recognized within the nodular zone. The nodular zone is only located between the first and fifth diastems where the ash beds are relatively thin, generally less than 22.0 in. (55.9 cm); the ash below the first diastem is about 32 in. (81.0 cm) and the ash above the fifth diastem is about 53.7 in. (136.4 cm) thick.

Usually, concretions are formed in subaqueous environments, but calcic nodules often form in association with soil horizons in eolain environments (Ritter, 1978). These concretions are probably an early diagenetic feature which began forming soon after the ash was deposited and grew prior to the deposition of the following ash layer.

Modern erosion of the upper portion of the ash bed has left most areas with a low, nearly horizontal slope. In places, the concretions have weathered out of the outcrop as the ash was deflated to form a lag deposit of calcic nodules. Very few trace fossils can be recognized within the diastem complex, but can be observed in the thicker layer of ash above the fifth diastem. The ichnofossils are not as common or appear as diverse as in the ash below the first diastem. This may be due to the heavier weathering of the upper half of the ash. The trace fossils in this part of the ash seem to only be made up of invertebrate galleries. Rhizoliths were not recognized in the upper part of the ash bed.

The upper contact on the Lower Whitney Ash with the

Whitney Siltstone is usually covered by talus, so it is often difficult to identify. In places that the upper contact is exposed, it appears gradational. The accumulation of wind-blown silt and clay is much slower than that of airfall pyroclastic material. This is why most volcanic ash beds have a sharp lower and a gradational contact. As the ash falls, it quickly blankets the landscape and generally develops a distinct layer of pyroclastic material. Afterward, allogenic material slowly settles on top of the ash layer's surface. This often allows the ash to become intermixed with the silt and clay. Thus, resulting in a gradational contact with the upper sedimentary beds (Fisher and Schmincke, 1984). This also explains why the diastems have a mottled silty appearence.

PETROGRAPHY

Samples used in this study included both clean, unburrowed ash and silty, burrowed ash (see table 1). During the point-count study, each grain was measured, identified, and any distinguishing features (such as glass crusts, twinning, etc...) were recorded. The grains were then counted, categorized, and percentages were calculated for each sample. The categories include: grain size distribution, mineralogy, and allogenic content.

Grain Size Distribution

The grain size distribution of the basal 12.0 inches of the Lower Whitney Ash ranges from very fine silt to coarse sand (material from 4 to 1000 microns). The amount of clay sized material (less than 4 microns) is very small for most of the samples. Only three grains of very coarse sand size (greater than 1000 microns/1.0 mm) were found.

In nearly all of the samples, the largest percentage of grains were between very fine silt and coarse sand (31 to 125 microns) size (fig. 13). The amount of material in each direction (less than 31 microns) and greater than 125 microns) decreases to form a smooth "bell curve", with the lowest percentages at the very fine silt and coarse sand size fractions. With only a couple of exceptions, this appears to be the trend for all of the samples studied, including both clean and burrowed samples.

GRAIN SIZE ANALYSIS OF CLEAN ASH

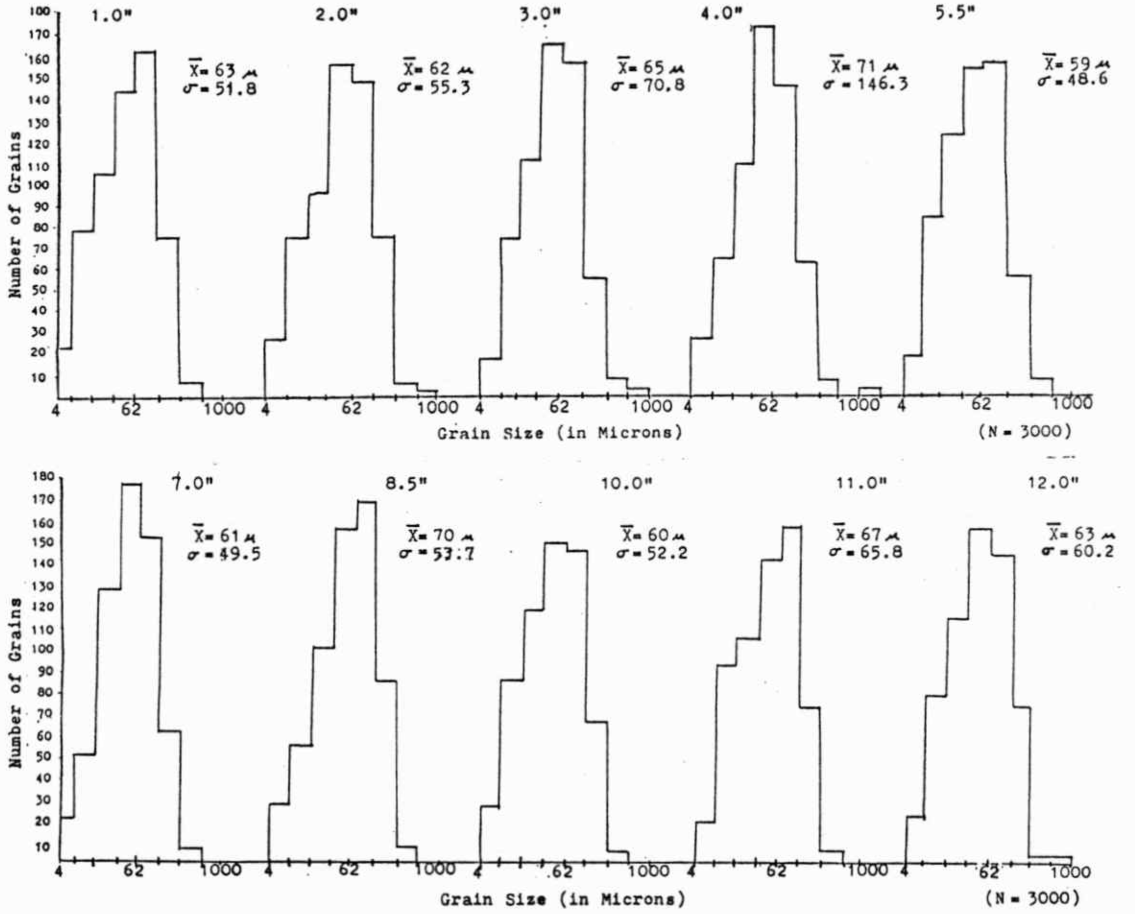


Fig. 13) Grain size destribution of the Lower Ash is generally between 4 and 1000 microns (1.0 mm = 1000 microns). The above samples were taken from a block of ash removed from the base of the Lower Ash in the Passion Play Site. The histograms above represent the lowermost 12.0 in. (30.5 cm) of the section. The mean ($\bar{X}$) and the standard deviation (σ) are also noted in the above histograms.

Note the uniformity of the grain size distribution in these samples along with the wide range in grain size. The wide range in grain size is due to the forming of clusters made up of very fine silt- to clay-sized particles "glued" together during an eruption (either by sulfuric acid or elecrostatic forces). The clusters are carried along with the coarser grain-sized materials where they fall out of suspension and break apart. Thus being deposited along with the coarser silt-sized material.

Volcanic ash beds commonly have a very wide range in grain size. During a violent eruption, the pyroclastic material may form into aggregates or "clusters" high in the atmosphere. These clusters contain material ranging from clay to coarse sand which may be "glued" together, either by sulfuric acid or electrostatic forces. These are very fragile and break apart as they hit the ground (Rose, 1987). Thus, giving the ash bed an unusually wide grain size distribution

Volcanic Glass

Most volcanic ash beds contain either bubble wall or pumice shards depending on the temperature and viscosity of the magma. Volcanoes with a very high temperature and low viscosity magma produce bubble wall shards; whereas, volcanoes with a low temperature, high viscosity magma produce pumice glass shards. Magmas with an intermediate temperature and viscosity should produce both bubble wall and pumice shards (Izett, 1981). Ash beds of this type are relatively uncommon.

Volcanic glass makes up 85 to 95 per cent of the Lower Whitney Ash. The glass is rhyolitic with a refractive index between 1.497 and 1.50. The magma had a proposed intermediate temperature of 830 °C according to Izett (1981) which allowed both bubble wall and pumice shards to form (fig. 14).

Fig. 14) The Lower Whitney Ash contains both bubble wall (above) and pumice (below) glass shards. This is probably because the ash originated from a magma of intermediate temperature (about 830°C).

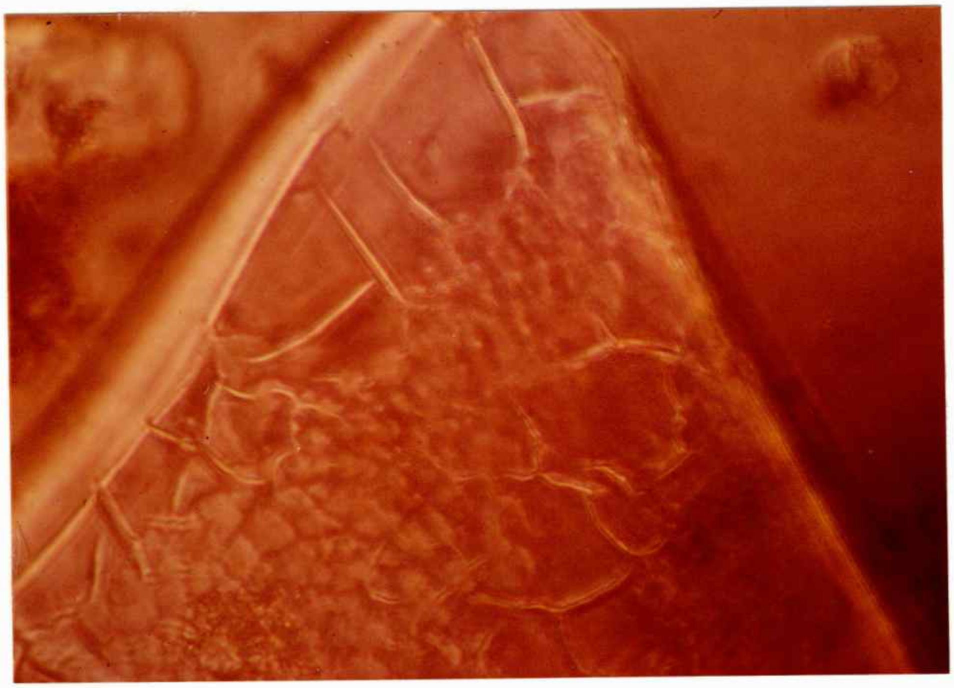
As observed in the Lower Whitney Ash, it may be possible to determine where individual eruptions begin by locating highly pumiceous layers with gradual increases in bubble wall shards upsection. This method can only be used on ash beds such as this which originated from a magma of intermediate temperature. Petrographic studies on ash associated with the silty diastems indicates a similar situation which suggests that the Lower Whitney Ash was deposited from a series of eruptions instead of one massive event.

Mineralogy

Mineral crystals make up about 5 to 15 percent of the Lower Whitney Ash. The composition may vary slightly between samples, but the ash samples generally contain the following minerals (in decreasing abundance): biotite, plagioclase, quartz, sanidine, hornblende, and accessory minerals such as opaque Fe/Ti-oxides (magnetite/ilmenite), zircon, apatite, and possibly some pyroxenes (most likely augite).

Many of the crystals exhibit a glass crust along the edge or coating the grain (fig. 15). These glass crusts are the remains of chilled magma adhering to the mineral which crystalized prior to the eruption. The magma is quickly chilled as it is ejected out of the vent during a violent eruption (Fisher and Schmincke, 1984). The glass crust may form as pumice or platy bubble wall remnants.

Fig. 15) Magma adhearing to mineral grains during an eruption are quickly chilled at the surface to form a glass crust surrounding or coating the mineral crystals. The above photo shows a euhedral biotite grain with a glass crust surrounding the edge. The photo below shows a plagioclase grain with a glass coat.



Both types are very resistant and usually remains after the grain hits the ground. The presence of a glass crust is an excellent indication that the mineral grain is of volcanic origin.

The most common mineral in the Lower Whitney Ash is biotite which makes up approximately 2.6% of the ash. Large crystals (up to 1.5 mm) can be observed throughout the ash bed. Under the microscope, the biotite crystals are commonly green to brown, sometimes euhedral, and may show good cleavage planes. Small, thin crystals are often pleochroic.

Plagioclase is almost as common as biotite and makes up about 2.4% of the ash. These crystals are colorless in plain polarized light and usually gray under crossed polarizers. Some plagioclase crystals show good compositional zoning. Euhedral crystals are present but extremely rare. Less than 30% of the plagioclase crystals show twinning under crossed polarizers, and unfortunately, none of the plagioclase grains observed had suitable twinning for mineral identification. Due to the silicic volcanic source, the plagioclase is probably oligoclase or andesine (Ehlers and Blatt, 1982; Williams and McBirney, 1979).

Quartz and sanidine each make up a little over 1% of the ash. Both appear similar to plagioclase in plain polarized light and are often gray to yellow under crossed polarizers. Quartz, sanidine, and plagioclase must usually be identified by their interference figures. A few of the sanidine crystals show good cleavage planes and at least two crystals appear to have Carlsbad twinning.

Hornblende crystals make up less than 1% of the ash. These crystals are green to brown, elongate, and usually pleochroic. Many are euhedral with good cleavage planes. Often, the ends appear to be spiked, probably due to partial dissolution. A small amount of pyroxene (possibly augite) may also be present, but the observed crystals were too small to accurately identify.

Accessory minerals make up about 0.5% of the ash and include Fe/Ti-oxides, zircon, and apatite. The Fe/Ti-oxides (probably magnetite and/or ilmenite) are opaque, rarely euhedral, and although uncommon, are present in nearly all samples in small amounts. In plain polarized light, zircon and apatite are both colorless, prismic, euhedral, and have very high relief as compared to the Lakeside cement (refractive index = 1.54). These crystals can be distinguished from one another by their interference figures. Also, zircon has a higher birefringence, so it is more colorful than apatite, which appears gray under crossed polarizers.

Most of the minerals observed show some sort of glass crust. It is these crystals which can be positively identified as being of volcanic origin. Minerals which do not exhibit a glass crust generally appear very similar to those that do; so it can be assumed that most of the grains counted in this study are of volcanic origin and derived from the same source.

Allogenic Content

Most of the allogenic content of the Lower Whitney Ash consists of silt and a little clay adhering to the grains (and often filling the vesicles of the pumice shards). Silt grains are included in this study, but the clay particles are too small to be accurately counted and measured. A small percentage of allogenic calcite occurs in some areas, and only five chert grains were identified.

Samples taken from the base of the ash bed appears to have higher amounts of allogenic material than samples taken upsection. Samples taken 1.0 in. (2.5 cm) above the base have allogenic contents close to 5%. At about 12.0 in. (30.5 cm), the amount of allogenic material is closer to 3%. Above this, the allogenic content decreases to about 1%.

The higher amounts of silt at the base may be a result of slight intermixing of ash with the Whitney Member silts during the initial ashfall; or, it may be due to the extensive bioturbation found at the base of the ash. It is very easy to get some of the silt from within trace fossils when taking samples of clean, unburrowed ash. So these basal "clean" samples may be slightly contaminated by silt from surrounding ichnofossils. The higher silt content of the trace fossils gives them a darker color than the clean, unburrowed ash. The darkest trace fossils have clear, distinct boundaries; but, often, lighter colored ichnofossils have boundaries which are less distinct. Thus, it is very difficult to get clean samples in many areas near trace fossil assemblages.

TABLE 1: PETROGRAPHY

	Block 1	Block 2	Block 3	Block 4	Block 5
(Clean Ash)					
Glass:	267	259	276	256	280
bubble wall:	142	112	190	114	270
pumice:	134	147	86	112	73
Minerals:	20	31	21	41	17
biotite:	6	10	5	16	6
plagioclase:	5	8	5	11	4
quartz:	4	3	3	3	3
sanidine:	2	4	3	6	3
hornblende:	2	3	2	3	-
accessories:	1	3	1	2	1
Allogenics:	4	9	3	3	3
	(N=300)	(N=300)	(N=300)	(N=300)	(N=300)
(Burrowed Ash)					
Glass:	246	256	262	229	250
bubble wall:	179	188	171	116	180
pumice:	67	77	91	113	67
Minerals:	27	28	28	48	20
biotite:	8	7	8	12	6
plagioclase:	6	7	7	12	5
quartz:	6	3	3	5	1
sanidine:	2	5	4	6	2
hornblende:	4	3	4	9	4
accessories:	1	1	2	4	2
Allogenics:	27	7	10	23	30
	(N=300)	(N=300)	(N=300)	(N=300)	(N=300)

Table 1 shows the glass, mineral, and allogenic content of samples taken from five blocks of the Lower Whitney Ash. Note the higher amount of allogenic material within the burrowed ash samples.

TRACE FOSSILS

Trace Fossils are an important tool in studying the geologic history of a specific area. They can often be used to increase our knowledge of the morphology as well as the geologic and geographic range of different groups of organisms (Osgood, 1975). And, according to Frey (1975), trace fossils "generally reflect behavioral adaptations to specific environmental conditions; thus, particular assemblages of trace fossils tend to be characteristic of given environmental regimes." Those assemblages reoccur through time whenever certain environmental conditions are present.

The trace fossils found within the Lower Whitney Ash are made up of root casts (rhizoliths) and invertebrate gallery systems (burrows with chambers) which are filled with silty ash (fig. 16). The mineralogy and grain size analysis of the burrow-fill is similar to the clean ash but contains more allogenic material (mostly silt).

Rhizoliths

The rhizoliths are vertical, tubular, and from 2.0 to 3.0 cm in diameter. These root structures are generally several centimeters long and taper downward such as the light colored vertical ichnofossils in the photos in fig. 16 and in the sketches in figs. 21 and 23. Many appear to have small horizontal branches. Unfortunately, the basal ends of the observed rhizoliths were not exposed so it is difficult to say if they ended in bifurcations. These root

Fig. 16) Note the diversity in size, shape and color of the trace fossils within the assemblage. The light colored ichnofossils are older and contain less allogenic material than younger, dark colored trace fossils.

casts appear to be similar in size to others studied by D'Alessandro, Ekdale, and Picard (1987) in Eocene fluvial deposits in Utah. They may also be similar to medium-sized rhizoliths studied by Bown (1982) in Oligocene floodplain deposits in Egypt.

The character of the root is dependent on hereditary factors within the genus or species of the plant, but the form of the root is generally controlled by the environment. For example, roots in an arid environment form an extensive system to search for moisture (Sarjeant, 1975). Root casts in the Lower Ash do not appear to be laterally extensive or very deep, so they probably grew in an area with a nearby source of water. The shallow nature of the root casts in the ash bed may also be related to the fine-grained material in which they grew. Plants growing in coarse-grained material tend to have deeper roots (Sarjeant, 1975). The silty ash filling the rhizoliths is almost always light brown with low allogenic contents, but the boundaries are usually sharper than most light brown gallery systems.

Invertebrate Galleries

The invertebrate galleries are made up of burrows and/or chambers filled with silty ash. The burrows are usually tubular, and range in size from 1.0 to 20.0 mm in diameter. Chambers, which are also referred to as calies (Bown, 1982) or cells (Ratcliffe and Fagerstrom, 1980), are probably some type of dwelling structures which are usually larger than the connecting burrows. These chambers are normally ovoid to elongate, with some being irregularly shaped. These may be from 0.75 to over 10.0 cm along the longest axis (fig. 17).

There appears to be no correlation between the size of the burrows and the size of the chambers from which they originate. Most of the burrows are 2.0 to 3.0 mm in diameter, burrows of this size are associated with chambers of all sizes and shapes. Some form very complex patterns of interconnecting burrows and chambers. A few of the burrows branch into other burrows the same size or smaller. The burrows may be up to several centimeters long, but usually only a small portion of the burrow is exposed on the surface of the outcrop. Since only a small section of the burrow is exposed, the measured widths of these burrows are less accurate than those measured in cross-section.

Only one meniscate burrow was located during this study. It was roughly vertical and about 1.3 cm in diameter. Other menisate burrows undoubtedly exist within the Lower Whitney Ash near Chimney Rock. But, like most of the trace fossils, some features (such as menisci) may be difficult to identify; thus, making the meniscate burrow hard to recognize. The meniscate specimen located during this study was found in a block of ash removed from the outcrop. The specimen was not recognized as a meniscate

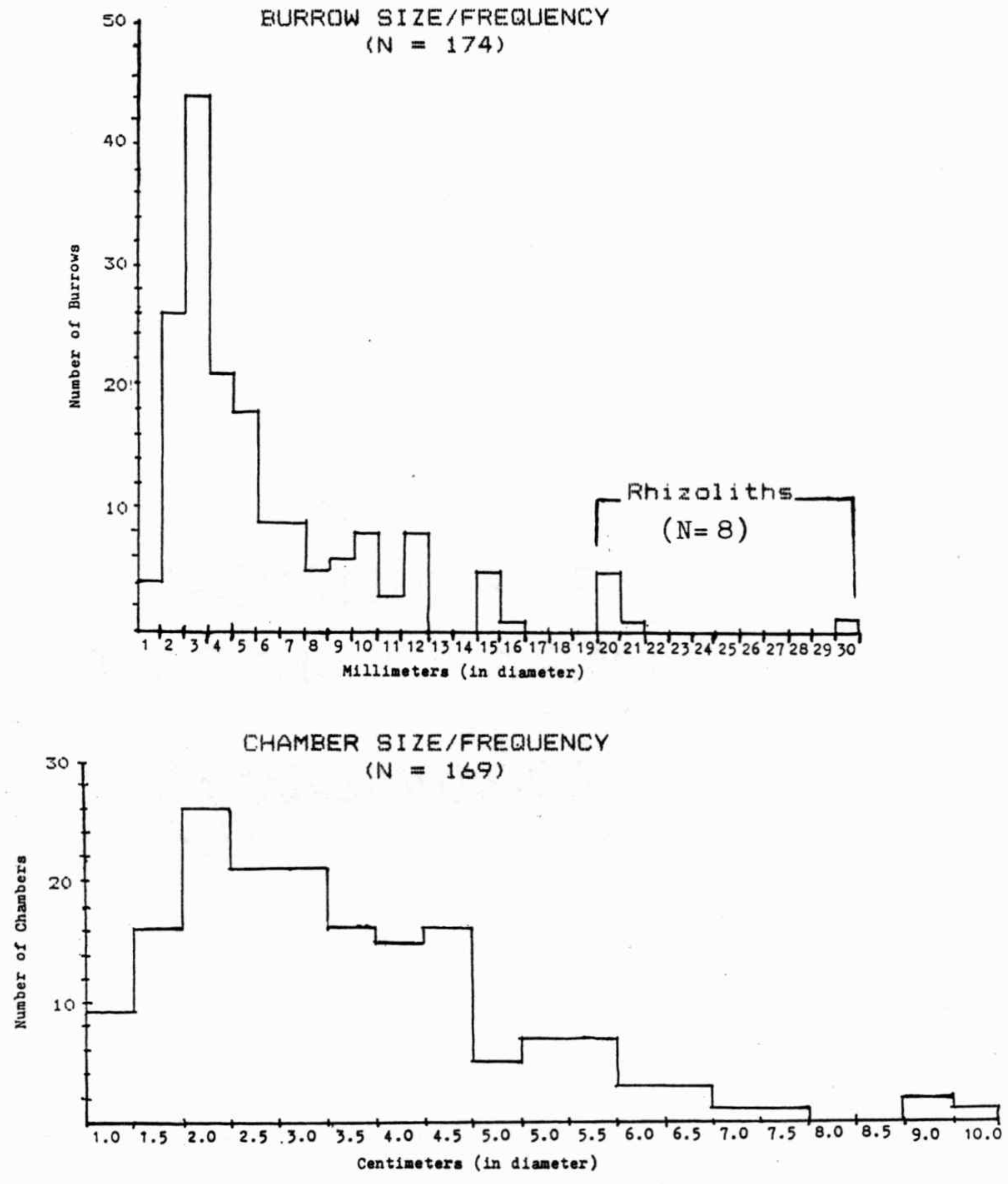


Fig. 17) Chambers were measured along the A-axis and burrows were measured along the B-axis. Most of the trace fossils were observed and measured on a 2-dimensional surface, so not all of the measurements may be totally accurate unless measured in cross-section.

burrow until a detailed sketch was being made of the trace fossil assemblage on the ash block. The trace fossils are easier to see and identify if the ash is saturated with water, boundaries and other features can be brought out and recognized if the ash is moist.

The trace fossils range in color from pink to various shades of brown. The pink ichnofossils are made up of very fine silt to almost clay-sized material (generally less than 8 microns). These are not very common and appear mostly near the base of the ash bed. The reason for the concentration of such fine-grained material in these trace fossils is unknown at this time. The other trace fossils, which vary from light to dark brown, are made up of silt- to sand-sized material (greater than 4 microns). The color of each ichnofossil is a direct result of the allogenic content of the burrow fill. Dark brown trace fossils contain more silt than light brown specimens.

Light brown gallery systems usually have faint, irregular boundaries with the surrounding ash. In some very light colored trace fossils, the boundaries are so indistinct as to make it nearly impossible to locate the boundary and distinguish the burrow fill from the clean ash. Petrographic analysis of the light brown galleries show that the burrow fill contains 1.5 to 6.0 percent silt.

Dark brown gallery systems usually have clean, well-defined boundaries with the surrounding ash. They have a silt content from 4 to over 10 percent. Often, dark brown galleries cut-across or truncate light colored trace fossils. This, along with the difference in silt content, suggests that the dark brown ichnofossils are younger or of a later "generation" than the lighter, older trace fossils. There appears to be no difference in grain size between the silty burrow fill of the trace fossils and the surrounding clean ash (fig. 18). This indicates that the ash making up the burrow fill is the same as that surrounding the trace fossils, except it contains more allogenic material.

Trace Fossil Assemblages

Ichnofabrics are generally made up of more than one "trace suite" or generation located within the same sediment. Two or more generations of biogenic activity occur adjacent to one another, forming a "composite ichnofabric" (Bromley and Ekdale, 1986). The younger trace fossils are generally better preserved than older specimens which may be poorly preserved if they are preserved at all.

Sometime after the initial ash fall ended, the first generation of biogenic activity began as invertebrates started burrowing into the new, fresh ash. After these gallery systems were abandoned, they were filled with slightly silty ash (fig. 19). At this time, very little allogenic material had been blown onto the surface of the ash, thus forming the light brown trace fossils.

GRAIN SIZE ANALYSIS OF BURROWED ASH

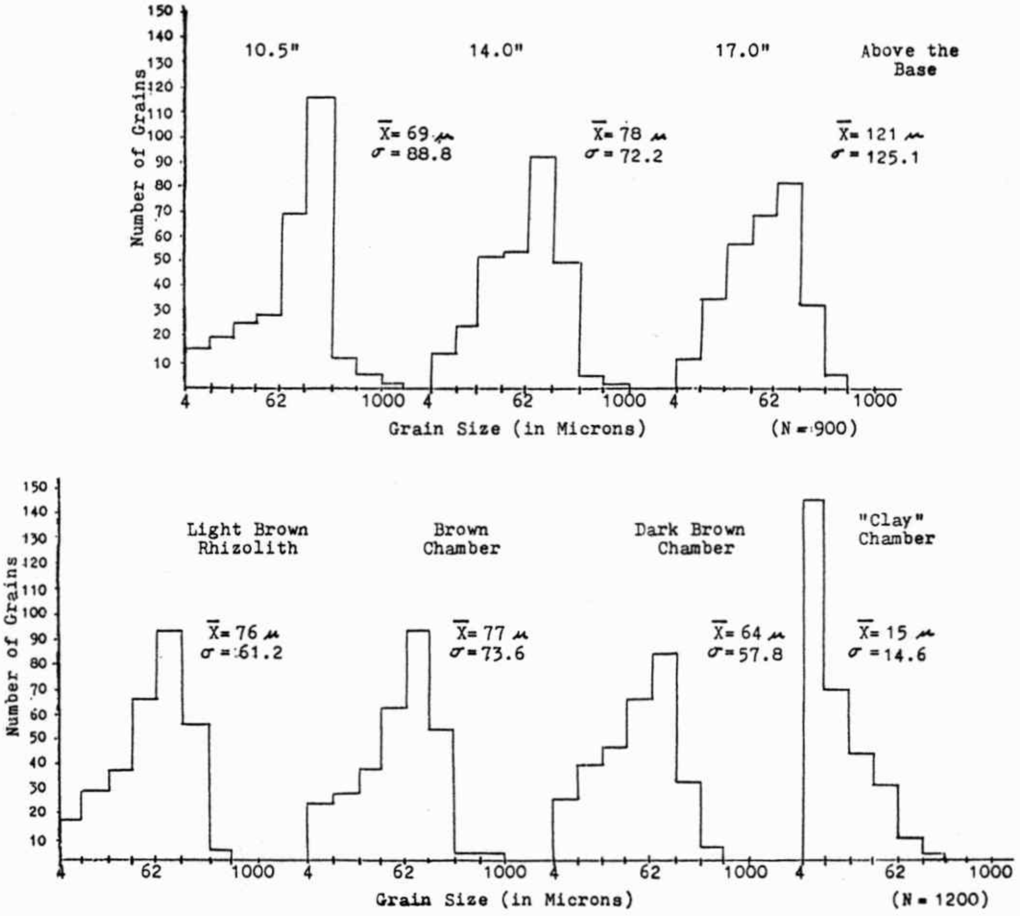


Fig. 18) The grain size distribution of clean, unburrowed samples can be compared to silty, burrowed samples. Most of the samples studied have a similar grain size distribution with the highest percentage between coarse silt to very fine sand (31 to 125 microns).

THe similarity between the clean, unburrowed ash and the silty, burrowed ash suggests that the burrow fill is made up mostly of ash from the surface of the ash bed. The one exception is the "clay chamber" which, for some unknown reason, contains a high concentration of very fine grained materials (generally less than 8 microns).

DIASTEM CONSTRUCTION

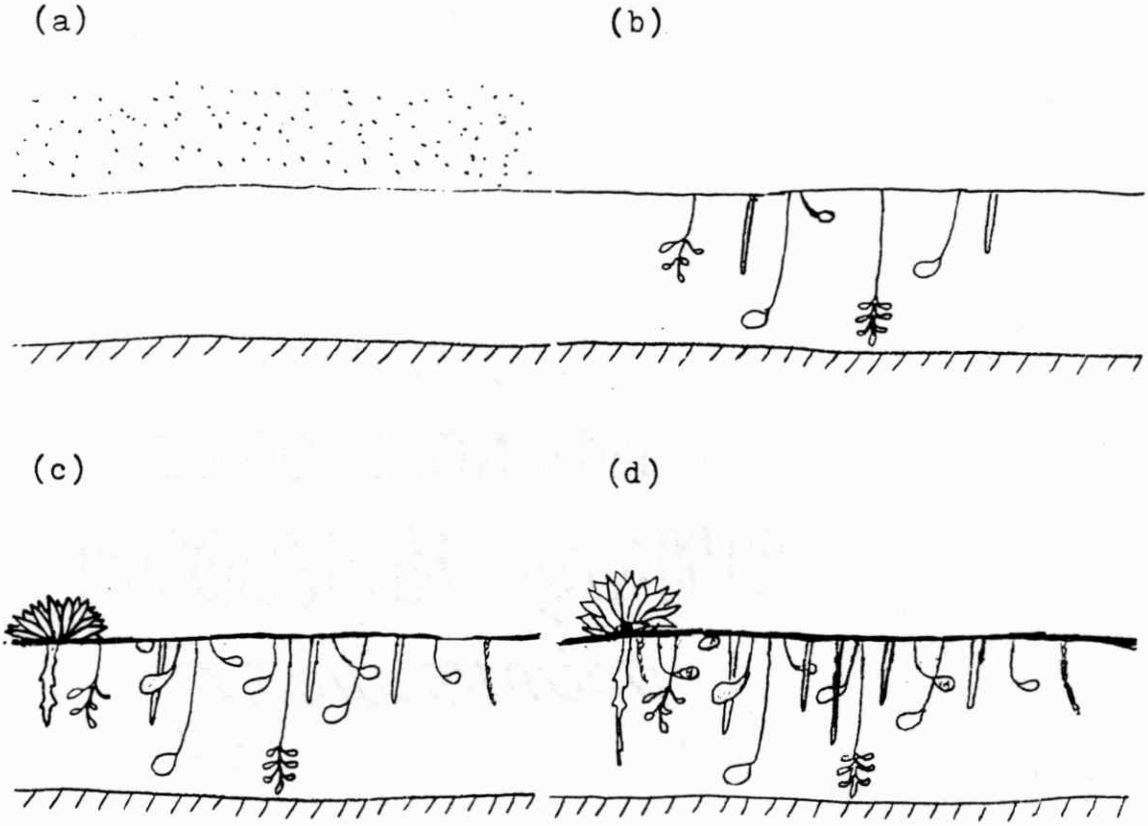


Fig. 19) This schematic diagram shows the accumulation of allogenic material onto the surface of the ash. The silty surface indicates a break in the sedimentation of the pyroclastic material. The diastem formed as silty and clay settled on the surface of the ash. After the initial ashfall (a), the ash bed is soon inhabited by invertebrate organisms (b) and eventually be plants (c).

As the allogenic material accumulates, the diastem thickens. Silty ash from the diastem fills the burrows as they are abandoned. The burrow-fill in the later generations of trace fossils (c) and (d) becomes darker as the diastem thickens. Up to three generations can be observed in some assemblages.

Eventually, new generations of galleries were made adjacent to the older trace fossils. By the time these galleries were abandoned, a thicker layer of allogenic material had accumulated on the surface of the ash. So, the sediment from the surface filling in these newer galleries contained more silt than the surface material which filled the early trace fossils. Since this material has more silt, it is darker in color (fig. 20). In some areas, as many as three generations of biogenic activity can be recognized due to the cross-cutting relationships and the differences in color and silt content between separate trace fossils.

The rhizoliths near the base of the ash always appear to be light brown and of an early generation. The plants from which the root casts originated probably grew sometime after the first ashfall. But, it would seem that the root casts, which were preserved, did not form until sometime after the second ashfall. Thus, it may be possible that these rhizoliths are of an early generation of the second ashfall. According to the measured sections, most of the subsequent ashfalls were much thinner than the initial ashfall. Most were probably from 10.5 in. (26.7 cm) to about 22 in. (55.9 cm) thick. If the plant had been killed during the following ashfall, it would eventually decompose and the root cast would soon be filled with slightly silty (light brown) ash.

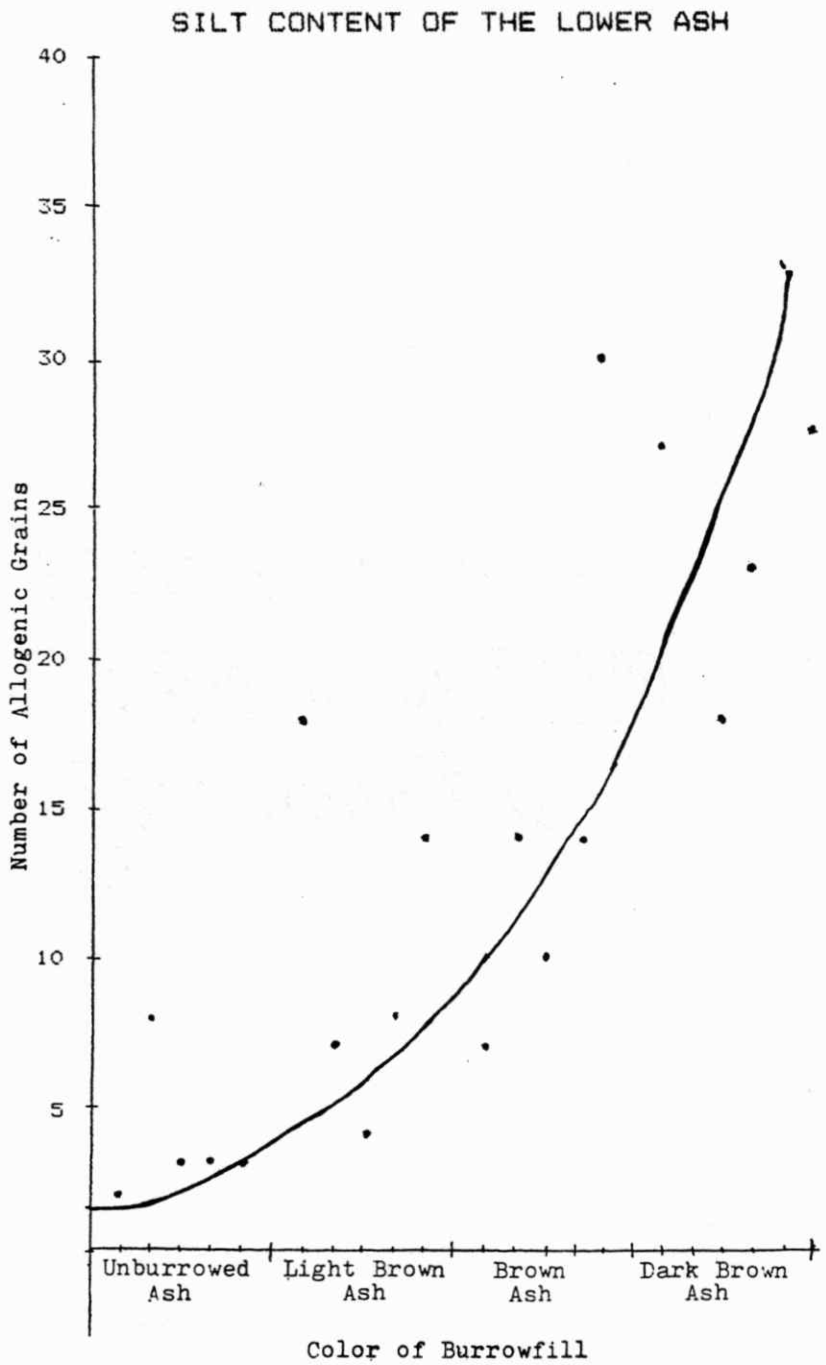


Fig. 20) Note the increase in the allogenic content as the ichnofossils become darker. The older, light colored trace fossils were filled early, before much silt and clay had accumulated on the surface of the ash. The older, dark colored trace fossils were filled later, after a thicker layer of allogenic material had accumulated onto the surface of the ash bed.

Composite ichnofabrics are typically associated with marine sediments, different types of trace fossils are observed as changes in the sediment occur over time (Ekdale, Bromley, and Pimberton, 1984). The Lower Whitney Ash is unique in that it is of terrestrial origin with a distinct composite ichnofabric. The changes in the Lower Ash are not a result of subsurface diagenesis but of the accumulation of allogenics on the surface of the ash. There appears to be no change in the types of ichnofossils found in each generation; the same types of organisms probably produced each new generation.

Possible Ichnogenera

As of yet, exactly what plants made the rhizoliths or what organisms produced the gallery systems are unknown. Due to the friable, uncemented nature of the Lower Whitney Ash, all of the trace fossils appear on a flat, 2-dimensional plane. Unfortunately the rhizoliths are too poorly preserved to accurately determine the specific type of plant from which the root cast originated. However, it may be possible to determine the type of organisms made the galleries by comparing those in the Lower Ash with others found in surrounding areas and in sediments of similar age.

Stanley and Fagerstrom (1974) conducted a study of beetle burrows found within the Late Oligocene and Miocene sandstones at Scotts Bluff National Monument. These beds are about 5 to 8 million years younger than the Lower

Whitney Ash, but evolutionary changes of many types of insects are probably very small, even when compared to the same groups living today (Ahlbrandt, Andrews, and Gwynne, 1978). In their 1974 study, Stanley and Fagerstrom made comparisons of burrows located in the sandstones of the Arikaree Group with modern beetle burrows in floodplain deposits along the Platte River. According to a study by Swinehart and Loope (1981), some of the sandstones of the Arikaree (such as the Monroe Creek Formation) are actually eolian deposits which contain many of the trace fossils studied by Stanley and Fagerstrom (1974). Many of the trace fossils in the Arikaree are associated with volcanic ash lenses.

These beetle burrows are normally branched, cylindrical to ellipsoidal, and form tunnels 2.5 to 5.0 cm in diameter. These are probably of the ichnogenus Palaeophycus (Stanley and Fagerstrom, 1974; Ratcliffe and Fagerstrom, 1980). Other beetle burrows described are vertical, unbranched, cylindrical shafts without a terminal chamber or cell. These form in populations ranging from 1.0 to 10.0 mm, these are most likely of the ichnogenus Skolithos. Several meniscate burrows made by deposit feeders (probably oligocaetes) were also described from Scotts Bluff (Stanley and Fagerstrom, 1974).

In a study of trace fossils done on paleosols in the White River Group of Badlands National Park, South Dakota

Dakota by Retallack (1984) trace fossils in this study were made by bees and dung beetles. Near-spherical chambers with short, branching burrows were described as belonging to the ichnogenus Pallichnus. These trace fossils are about 1.2 to 2.1 cm in diameter and were hypothesized to be the pupal cells and brood burrows of dung beetles. Tear (or globular) shaped chambers located on deep vertical shafts are described as the ichnogenus Celliforma. These are 20.0 mm long, 9.0 to 11.0 mm in maximum diameter and often taper to 7.0 mm near a short, flairing entrance tube. These are hypothesized to be the larval cells of bees and wasps (Retallack, 1984; Ekdale, Bromley, and Pemberton, 1984).

The two studies described above are within 200 miles (321.8 km) to the Chimney Rock area and are both in sediments 20 to 30 million years old. So, it is possible that all these sediments were deposited in a similar environment. Many of the trace fossils described in these two studies appear to be similar to many observed in outcrops of the Lower Whitney Ash. For example, the ichnogenera Pallichnus and Celloforma appear to be similar to some galleries observed in the Lower Ash Bed (figs. 21 & 22).

Also, some specimens of Skolithos as described by Stanley and Fagerstrom (1974) may be found on outcrops of ash on Chimney Rock and the Passion Play Site (figs. 23 & 24). Skolithos are described as single, unbranched,

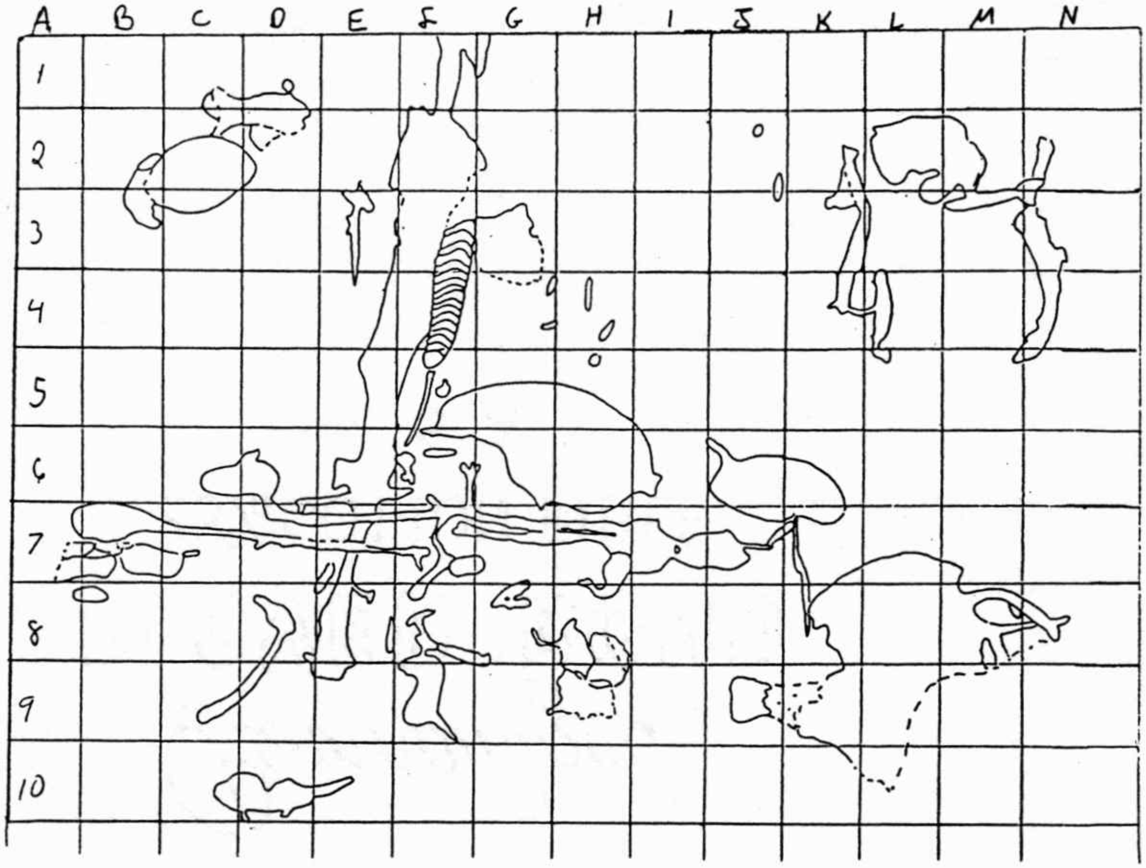


fig. 21) The above sketch was made from Block #1 taken from the Passion Play Site about 10 to 17 in. (25 to 43 cm) above the base of the Lower Ash on a vertical face on the outcrop.

The following ichnogenera are found in the above sketch (see also the photo and sketch in fig. 7, p. 18):

Skolithos = (F-5), (E-8), (H-4), (J-2).

Celliforma = (D-6), (B-7), (I-7), (F-7), (J-6).

Muesteria = (F-3).

Note also the rhizolith which begins at (G-1) and ends at (E-8). Also notice how some of the younger ichnofossils cut-across older specimens, such as the Celliforma cutting across the rhizolith (E-7). All of the Celliforma above may have been made by burrowing bees except the specimen located at (J-6) which is larger and may have been made by a wasp.

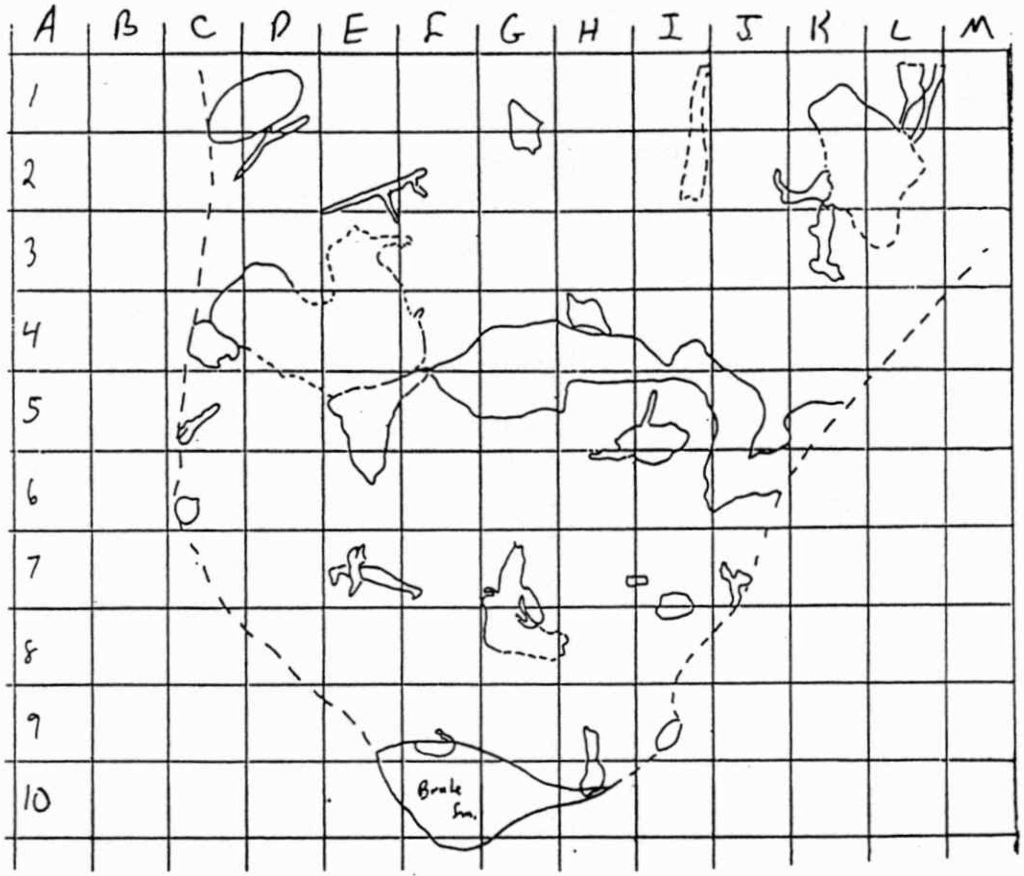


Fig. 22) The above sketch was made from Block #2 taken from the base of the Lower Whitney Ash Bed at the Passion Play Site.

This sketch contains the following ichnogenera:

Palaeophycus = (E-5) to (K-5).

Skolithos = (I-1).

Celliforma = (I-5).

Note the cross-cutting relationships of the older trace fossils by younger specimens. The base of the block is made up of the underlying Whitney Member siltstone.

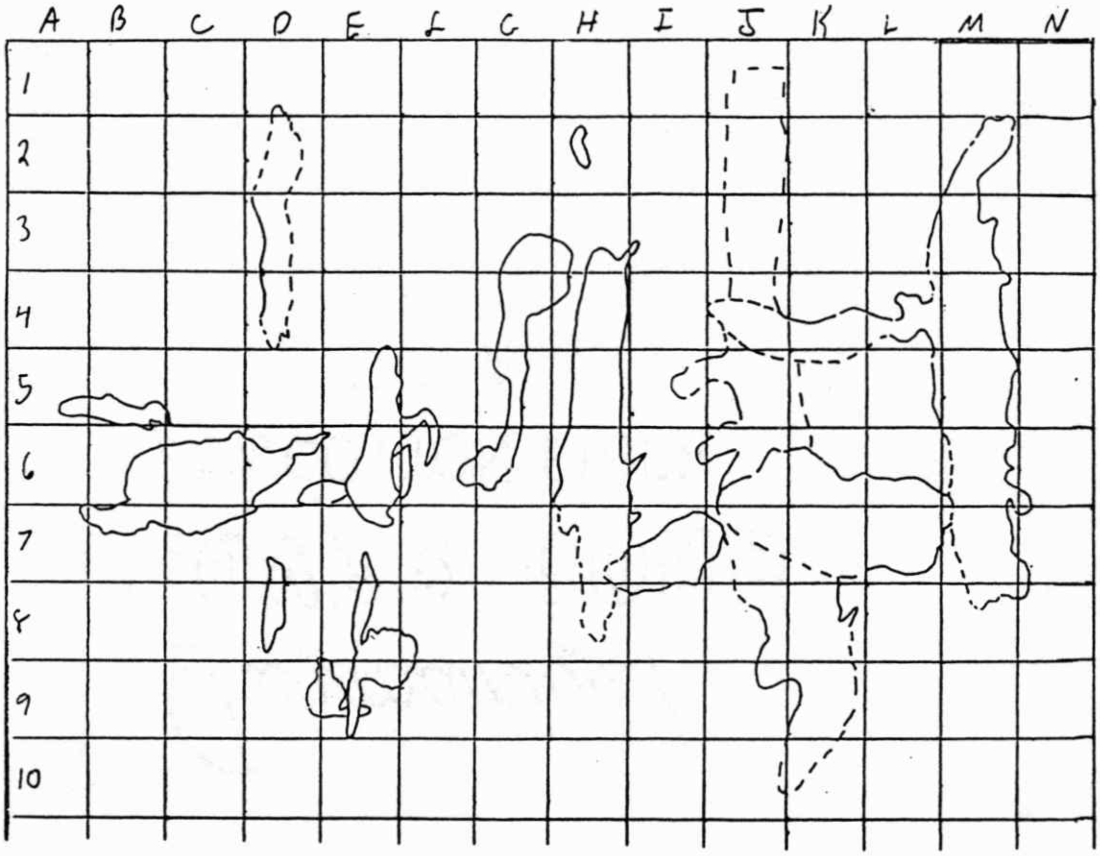


Fig. 23) This sketch was made from a photographic slide taken at Chimney Rock (see lower section of the bottom photo of fig. 16, p. 48). This sketch contains the following ichnogenera:

Celliforma = (C-6) probably made by a wasp.

Pallichnus = (E-8), (E-9).

Note the cross-cutting relationship of the Pallichnus specimens (E-9).

There are also four rhizoliths in the above assemblage: (D-1) to (D-4), (H-3) to (H-8), (J-1) to (J-10) and (M-2) to (M-8).

Note the cross-cutting relationships of the rhizolith by the large unidentified chamber (J-6).

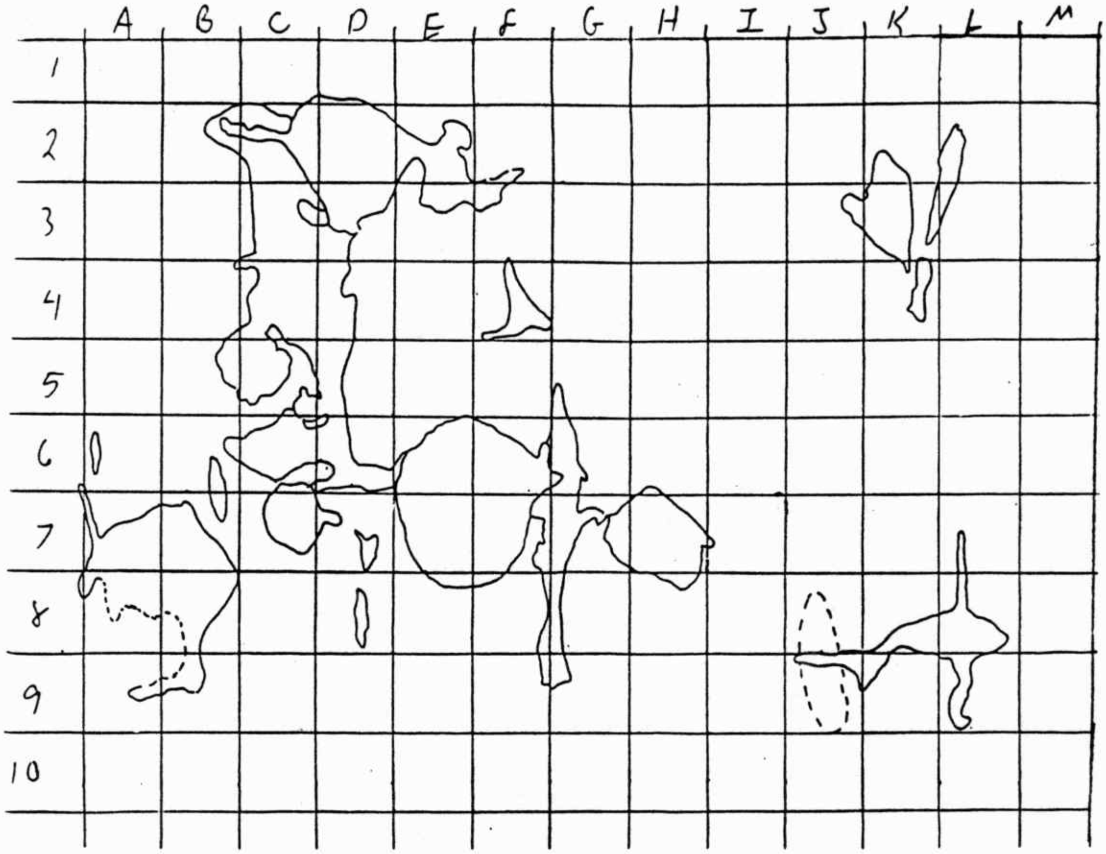


Fig. 24) This sketch was also made from a photographic slide taken at Chimney Rock.

The above assemblage contains the following Ichnogenera:

Skolithos = (A-6), (B-6), (D-8), and possibly (L-2).

Celliforma = (L-8).

Pallichnus = (C-7).

Note the cross-cutting relationships between the large, round, unidentified chamber in the center and also note the unidentified ovoid trace fossil being cut-across by the Celliforma specimen (J-9).

cylindrical to subcylindrical burrows which may be lined or unlined straight to curved, and usually vertical but may be inclined. They range from 1.0 to 11.0 mm in diameter and generally have structureless burrow fill (Alpert, 1974). Specimens located in the Lower Ash are only 1.0 to 6.0 mm in diameter and are mostly vertical, but a few are inclined. Skolithos burrows were probably made by insects such as beetles. Some may have been produced by insect larva (Stanley and Fagerstrom, 1974; Ratcliffe and Fagerstrom, 1980; and D'Alessandro, Ekdale, and Picard, 1978). The galleries in this study have been measured in a 2-dimensional plane that may not intersect the maximum gallery diameter. So the measured widths may not necessarily be representative of the actual gallery diameters.

Another trace fossil described earlier which may be found in the Lower Whitney Ash are those referred to as Palaeophycus (fig. 22). These burrows are generally horizontal, cylindrical, and sinuous. They range in diameter from 0.5 to 5.0 cm and rarely have branches (D'Alessandro, Ekdale, and Picard, 1987; Stanley and Fagerstrom, 1974; and Ratcliffe and Fagerstrom, 1980). Those which may be preserved in the Lower Ash appear to be horizontal, cylindrical, and some appear sinuous where more than a few centimeters are exposed. The specimens located in the Lower Ash generally range in diameter from approximately

1.5 to 2.5 cm. Palaeophycus are believed to have been made by either insects or possibly crustaceans (D'Alessandro, et al, 1987; Stanley and Fagerstrom, 1974; and Ratcliffe and Fagerstrom, 1980).

Trace fossils described by Retallack (1984) as the pupal cells and brood burrows of dung beetles are referred to as the ichnogenus Palluchnus (fig. 24). These consist of near-spherical chambers about 1.2 to 2.1 cm in diameter with short, branching burrows. A couple of chambers located in the Lower Ash may belong to this ichnogenera. These specimens are subspherical, have attached (possibly branching) burrows, and are approximately 1.1 to 1.6 cm in diameter.

Retallack (1984) also described the larval cells of bees in the badlands known as Celliforma. These are tear-shaped chambers about 20.0 mm long and 9.0 to 11.0 mm in diameter with deep vertical burrows. Wasp galleries are similar to bee galleries, but have chambers 20.0 to 40.0 mm in length (Ratcliffe and Fagerstrom, 1980).

Solitary wasp galleries from Oligocene sediments in Egypt (Bown, 1982) are 5.0 to 8.0 cm long, 7.0 to 9.0 mm wide, and thicken to 1.0 to 2.1 cm at the base. At the end is a circular or oblate to ellipsoidal chamber 1.7 to 2.1 cm high and about 3.5 cm long. These galleries are usually located at a 75 degree angle to the horizontal.

The modern digger wasp Ammobia constructs galleries made up of burrows 12.0 to 18.0 cm long, circular, and 2.5 cm in diameter. Two to six tunnels, 2.5 to 5.1 cm long, may radiate from the burrow and end in an oval chamber 3.8 to 5.1 cm long and 1.9 cm wide (Jacot, 1940). A solitary asp Bembex makes smaller galleries than the Ammobia described above. It makes galleries 6.0 mm in diameter about 25.4 cm long, but with no terminal chamber. These are usually found at 45° angles to the horizontal (Bryson, 1939). Thus, there is some diversity in the shapes of galleries produceed by different species of wasps. This is probably true for many families of insects and other invertebrates living during the Oligocene. The specimens of Celliforma made by wasps in the Lower Whitney Ash (figs. 21 & 23) are ovoid, about 3.5 cm long with entrance tunnels as large as 8.0 mm in diameter.

It is possible that some complex galleries which appear on outcrops of the Lower Ash may have been formed by ants and subterranean termites. These nests consist of galleries which form a somewhat diffuse network of galleries enlarging in places for form spaceous chambers (Noirot, 1970). Subterranean termites may live either partially or entirely below the surface of the soil. These termites produce liquid feces, so no preservable fecal pellets remain (Rohr, Boucot, Miller, and Abbott, 1986).

In a study of the Oligiocene sediments of the Jebel Qatrani Formation of Oligocene age in Egypt, Bown (1982) describes what may be the subterranean nests of termites (ichnospecies _Termitichnus_ _gatranii_). These are made up of sediment-filled galleries 3.0 to 7.0 mm in diameter with spherical to oblate chambers 10.0 to 75.0 cm long. These are similar to modern compound galleries and commected nests of subterranean fungus-growing termites. Other galleries similar to _Termitichnus_ form in clusters into the hundreds and are interconnected by numerous, branching burrows which are flattened to spherical in cross-section. These appear similar to the nests of leaf-cutting/fungus-growing ants such as the _Atta_ (Jacoby, 1952, 1955).

Meat ants (_Iridomyrmex_) were common during the Oligocene (Wilson, 1971). Modern specimens (from Australia) form galleries made up of vertical shafts which are circular and approximately 1.5 cm in diameter near the entrance. About 2.0 to 3.0 cm below the surface, they form irregular galleries which branch outward and downward and become wider and larger with depth. These galleries are irregularly oval with flat floors and domed roofs 7.0 by 5.0 cm long and up to 1.5 cm in height. The connecting tunnels also have flat floors which are 1.5 to 2.5 cm wide with a domed roof 1.5 cm high. Vertical shafts are circular and 9.0 to 11.0 mm in diameter (Ettershank, 1968).

Galleries located in the (early Miocene) Sheep Creek Formation in western Nebraska are made up of volcanic ash-filled shafts and branching tunnels 5.0 to 15.0 cm long and 3.0 to 10.0 mm in diameter. These may have been made by harvester ants (Thomasson, 1982). Ants are probably the most important soil movers of all modern insects (Jacot, 1940). This may also have been true during the mid-Tertiary.

One exposure of the Lower Whitney Ash appears to contain an extensive gallery system similar in size and construction to the ant and/or termite galleries described earlier. The tunnels or burrows extend both vertically and horizontally and are about 0.5 to 1.5 cm in diameter. Some have small chambers 2.5 to 5.0 cm long and are about 1.5 cm in height. One large chamber which appears to be associated with this gallery system is roughly circular and about 5.5 cm in diameter (fig. 25).

The size of the galleries in this assemblage are similar in size to those described by Ettershank (1968) made by meat ants. They also appear similar in construction to galleries made by <u>Atta</u> or leaf-cutting/fungus-growing ants (Jacoby, 1952, 1955; Bown, 1982) or possibly by subterranean termites (Bown, 1982). However, the outcrop on which this assemblage is exposed on a low-angle slope so the gallery system is cut at an oblique angle of about 30^{o} to the horizontal. Since this gallery system was

ANT OR TERMITE NEST

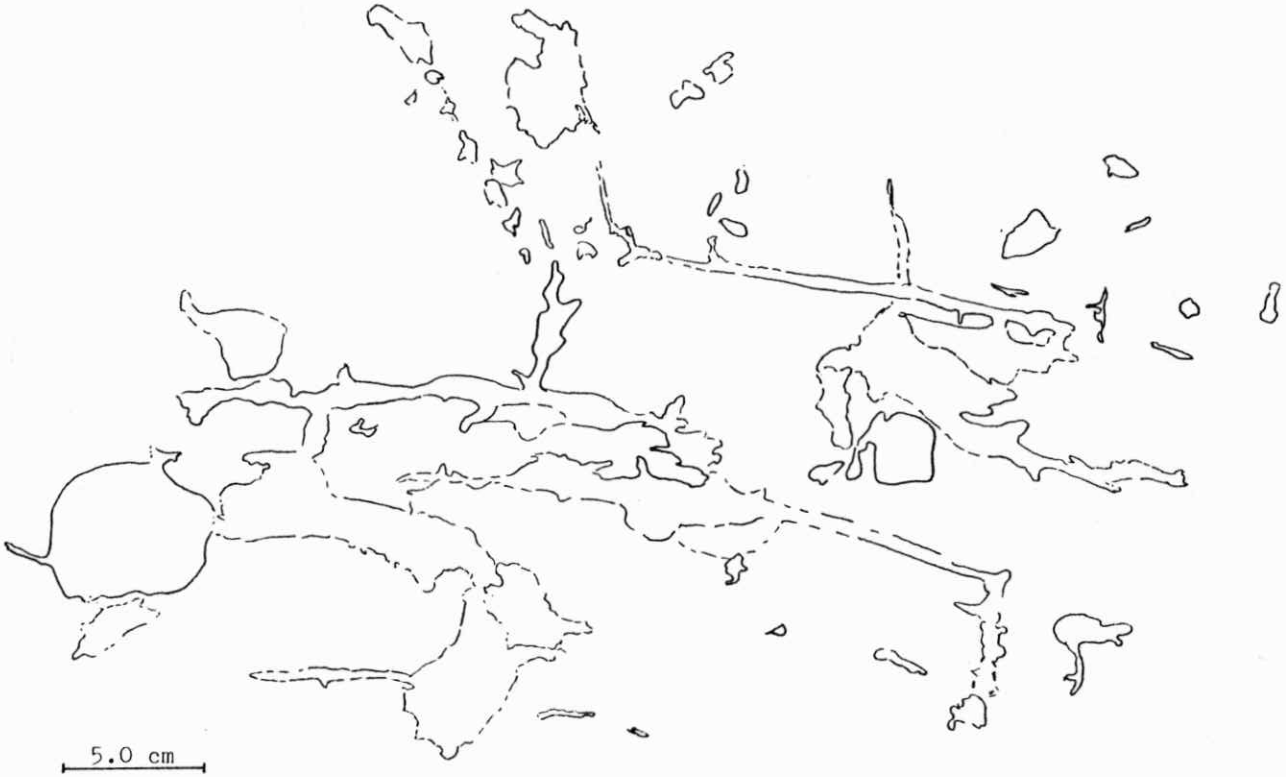


Fig. 25) The above gallery system may have been made either by leaf-cutting/fungus-growing ants or by subterranean (leaf-cutting/fungus-growing) termites (ichnogenus Termitichnus, Bown, 1982). Note the extensive, complex gallery system made up of interconnecting tunnels or burrows.

not observed on a vertical face, the burrows and chambers did not appear to have flat floors as described by Bown (1982) and illustrated by Jacoby (1952, 1955).

Many of the ant or termite galleries are very extensive, having been constructed and expanded over many generations (Wilson, 1971). The specimen from the Lower Whitney Ash (fig. 25) is located below the first diastem on Chimney Rock. So it is possible that only a few generations of ants or termites lived in this gallery system prior to its being filled with silty ash. Thus, it is probably not as large as many nests described in most papers due to the shorter time it was used.

All Hymenoptera (bees, wasps, ants, and termites) are commonly found in dry woodlands and grasslands (Jacot, 1940). Thus, the environment in which these galleries were formed was most likely eolian as suggested by the loessic origin of the Whitney Siltstones lying above and below the Lower Ash bed.

Only one specimen of a meniscate burrow has been recognized in this study. More of these burrows undoubtedly exist in the Lower Ash, but have not yet been located or recognized. Studies have been done on meniscate burrows in nearby areas. Scotts Bluff National Monument by Stanley and Fagerstrom (1974) and Frey, Pemberton, and Fagerstrom (1984).

Other studies include work done on meniscate burrows in: nonmarine Miocene sediments in Wyoming (Toots, 1967), freshwater limestones of the Brule Formation (Oligocene) in western Nebraska Edwards, 1975), fluvial deposits of Eocene age (D'Alessandro, Ekdale, and Picard, 1987), and some braided stream deposits of Cretaceous/Tertiary age (Bracken and Picard, 1984) in Utah. Some have even been described in a volcanic ash bed in the Split Rock Formation (Miocene) of Wyoming (Toots, 1975).

The meniscate specimens described in these papers are mainly of two ichnogenera: Ancorichnus which is tubular, circular to subellipsoidal in cross-section, with a thick wall lining, and a diameter of about 1.0 to 10.0 mm (Frey, Pemberton, and Fagerstrom, 1984; D'Alessandro, Ekdale, and Picard, 1984); And Muensteria, often called Taenidium (Toots, 1967; D'Alessandro and Bromley, 1987) which is similar to Ancorichnus except it does not have a wall lining and often has rounded instead of straight menisci. Also, Ancorichnus is almost always oriented horizontally; whereas, specimens of Muensteria may be oriented vertically or horizontally. Muensteria ranges from 2.0 to 15.0 mm in diameter (D'Alessandro, Ekdale, and Picard, 1987); (Bracken and Picard, 1984); and (Squires and Advocate, 1984).

The meniscate burrow located and recognized from the Lower Whitney Ash (see fig. 21) is vertically oriented, approximately 9.0 mm in diameter, and does not appear to have a wall lining. The specimen is light brown, and not well preserved; the menisci only show up if the ash is saturated with water. It would be impossible to accurately determine what deposit feeders inhabited the Lower Ash from only one specimen. But with the size, menisci shape, and vertical orientation of this single burrow, it would seem most likely that this specimen is that of the ichnogenera Muensteria.

Most meniscate burrows are believed to have been made by deposit feeders such as oligochaetes or similar worms (D'Alessandro, et al, 1987; Squires and Advocate, 1984; and Frey, Pimberton, and Fagerstrom, 1984). Some meniscate burrows have been attributed to arthropods such as insects and their larvae (Frey, Bromley, and Pimberton, 1984; Frey, Pemberton, and Fagerstrom, 1980).

Pellets

Unusual silt grains found in the gallery systems may be fecal pellets or microcoprolites (fig. 26). These are ellipsoidal dense, and between 30 tO 165 microns (0.03 to 0.165 mm) along the longest axis. They can be distinguished from normal silt grains by their shape, compact appearance, and sharper outlines. The grains described here appear similar to an ichnospecies of fecal pellet known as Coprulus oblongus. This is the most common type of fecal pellet, but its origin is the hardest to determine (Ekdale, Bromley, and Pemberton, 1984). The pellets are

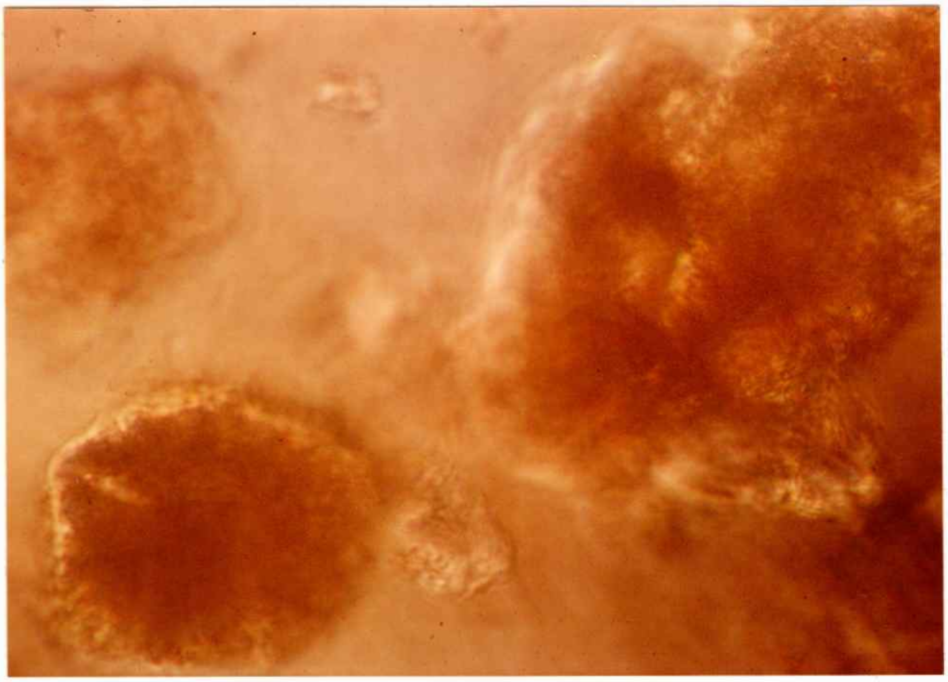
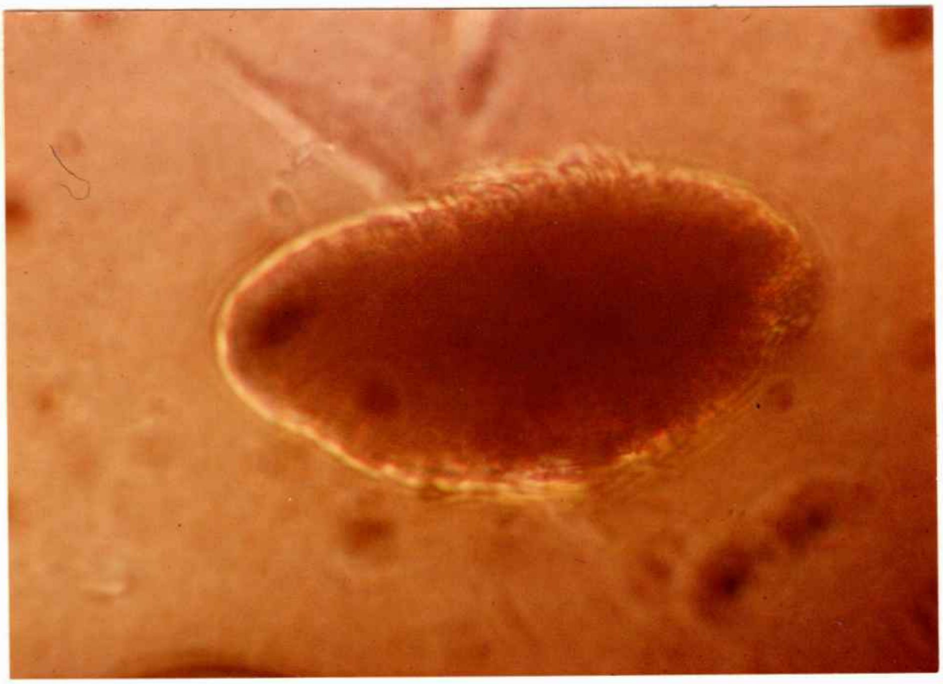
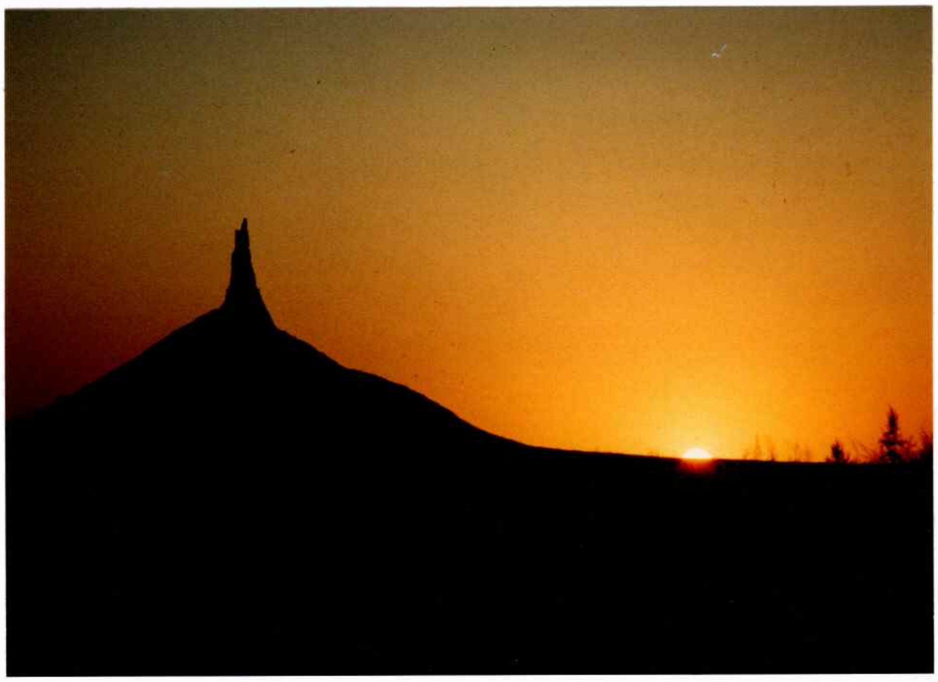


Fig. 26) Normal silt grains (above) as compared to a pellet (below). These may be fecal pellets formed by invertebrate organisms which inhabited the burrows. They are probably of the common Ichnospecies of fecal pellet known as Coprulus oblongus.



only found in samples taken within the burrow fill and make up a very small part (generally less than 5%) of the total allogenic content.



CONCLUSIONS

1. The Lower Whitney Ash is a thick, biotitic airfall deposit laid down over several thousand square kilometers of western Nebraska during the mid-Oligocene. Due to the configuration of the ash, with the thickest edge toward the southwest and the thinning toward the east and northeast, the Lower Ash probably originated from a southwestern source. The rhyolitic composition of the ash and its age make the San Juan Volcanic Field in southern Colorado the most likely source.

2. The Lower Whitney Ash was deposited in a series of at least six separate violent eruptions. This is obvious due to:

    a) Rhizoliths from medium-sized plants are present near the base of the ash bed.

    b) Five horizontal layers of silty, mottled ash are recognized as a diastem complex from about 32 in. (81.0 cm) to 73.5 in. (186.7 cm) above the base of the ash. These layers represent a break in the sedimentation of the ash between separate eruptions. The silty layers were formed during these periods of quiescence by the accumulation of allogenic silt and clay on the surface of the ash. More diastems may be present, but not recognized.

3. The grain size of the lower 12.0 inches appears to be mainly from very fine grain silt (4 microns) to coarse sand (1.0 mm). The highest percentage appears to be between the coarse silt and very fine sand range (32 to 125 microns). The mean is between 59 and 71 microns in length.

4. Bioturbation has destroyed any primary bedding. However, based on petrographic anallysis of ash at the base and on either side of the diastems, it may be possible to separate the ash into different units, each possibly the product of an individual eruption. Highly pumiceous layers exist at the base of the ash and just above the first two diastems. Above these pumiceous layers, the amount of bubble wall shards increases. This is probably due to an increase in temperature and a decrease in the viscosity of the magma as cool, viscous material from the top of the magma chamber is ejected and replaced by hotter, less viscous material from deeper within the earth. This could only be used for ash beds originating from a magma of intermediate temperatures which produced both pumice and bubble wall shards.

5. The Lower Whitney Ash is heavily bioturbated in some areas, the trace fossils are made up of rhizoliths and invertebrate galleries which are filled with silty ash. The galleries were not all made at the same time, but form a "composite ichnofabric." In some places, up to three

generations of biogenic activity can be recognized. This is based on:

a) Differences in color relating to the silt content of the individual trace fossils. Older, light trace fossils were made soon after the ash was deposited and very little allogenic material had accumulated on the ash surface. Younger, dark colored trace fossils were made sometime later as more allogenic material accumulated on the surface.

b) Older, light colored trace fossils are often cut across or truncated by younger, dark colored gallery systems.

6. The gallery systems are diverse in size and shape. Many can be compared to ancient and modern burrows located in near-by areas. Most of the galleries were probably made by insects (adult and larvae) such as beetles, bees, wasps, ants, and possibly termites. Only one meniscate burrow was recognized during this study.

REFERENCES

Ahlbrandt, T.S.. Andrews, S., and Gwynne, D.T., 1978, Bioturbation in Eolian Deposits: Journal of Sedimentary Petrology, v. 48, p. 839-848.

Alpert, S.P., 1974, Systematic Review of the Genus Skolithos: Journal of Sedimentary Petrology, v. 48, p. 661-669.

Berner, R.A., 1968, Calcium Carbonate Concretions Formed by the Decomposition if Organic Matter: Science, v. 159, p. 195-197.

Bown, T.M., 1982, Ichnofossils and Rhizoliths of the Nearshore Fluvial Jebel Qatrani Formation (Oligocene) Fayum Province, Egypt: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 40, p. 255-309.

Bracken, B., and Picard, M.D., 1984, Trace Fossils from Cretaceous/Tertiary North Horn Formation in Central Utah: Journal of Paleontology, v. 58, p. 477-487.

Bromley, R.G., and Ekdale, A.A., 1986, Composite Ichnofabrics and Tiering of Burrows: Geological Magazine, v. 123, p. 59-65.

Bryson, H.R., 1939, The Identification of Soil Insects By Their Burrow Characteristics: Kansas Academy of Science, v. 42, p. 245-253.

D'Alessandro, A., and Bromley, R.G., 1987, Meniscate Trace Fossils and the Muensteria-Taenidium Problems: Paleontology, v. 30, p. 743-763.

D'Alessandro, A., Ekdale, A.A., and Picard, M.D., 1987, Trace Fossils in Fluvial Deposits of the Duchesne River Formation (Eocene), Unita Basin, Utah: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 61, p. 285-301.

Decker, R., and Decker, B., 1981, Volcanoes: San Francisco, W.H. Freeman and Company, 244 pp.

Edwards, P. 1975, Invertebrate Burrows in an Oligocene Freshwater Limestone: Contributions to Geology, v. 14, p. 7-8.

Ehlers, E.G., and Blatt, H., 1982, PETROLOGY Igneous, Sedimentary, and Metamorphic: San Francisco, W.H. Freeman and Company, 732 pp.

Ekdale, A.A., Bromley, R.G., and Pemberton, S.G., 1984, Ichnology: Trace Fossils in Sedimentary and Stratigraphy: Society of Economic Paleontologists and Mineralogists Short Course, 15, 317 pp.

Ettershank, G., 1968, The Three-Dimensional Gallery Structures of The Meat Ant *Iridomyrmex purpureus*: Australian Journal of Zoology, v. 16, p. 715-723.

Fisher, R.V., and Schmincke, H.U., 1984, Pyroclastic Rocks: New York, Springer-Verlang, 472 pp.

Frey, R.W., 1975, Relm of Ichnology, In: R.W. Frey (Editor) The Study of Trace Fossils: New York, Springer-Verlang, p. 13-38.

Frey, R.W., Pemberton, S.G., and Fagerstrom, J.A., 1984, Morphological, Ethological, and Environmental Significance of the Ichnogenera *Scoyenia* and *Ancorichnus*: Journal of Sedimentary Petrology, v. 58, p. 511-528.

Hallam, A., 1975, Preservation of Trace Fossils, In: R.W. Frey (Editor), The Study of Trace Fossils: New York, Springer-Verlang, p. 55-63.

Izett, G.A., 1981, Volcanic Ash Beds: Recorders of Upper Cenozoic Silicic Pyroclastic Volcanism in the Western United States: Journal of Geophysical Research, v. 86, p. 10200-10222.

Jacoby, M., 1952, Die Erforschung des Nestes der Blattschneider-Ameise *Atta sexdens rubropelosa* Forel: Zietschrift Angewandte Entomologie, v. 34, p. 145-169.

Jacoby, M., 1955, Die Erforschung des Nestes der Blattschneider-Ameise *Atta sexdens rubropelosa* Forel (mittels des Ausguss Zerfahrens mit Zement): Zeitschrift Angewandte Entomologie, v. 37, p. 129-152.

Jacot, A.P., 1940, Thw Fauna of the Soil: The Quarterly Review of Biology, v. 5, p. 28-58.

Lipman, P.W., 1975, Evolution of the Platoro Caldera Complex and Related Volcanic Rocks, Southern San Juan Mountains, Colorado: United States Geological Survey Professional Paper 852, p. 1-128.

Noirot, C.H., 1970, The Nests of Termites, in Krishna, K., and Weesner, F., Biology of Termites: New York, Academic Press, p. 73-120.

Osgood, R.G., Jr., 1975, The Paleontological Significance of Trace Fossils, In: R.W. Frey (Editor), The Study of Trace Fossils: New York, Springer-Verlang, p. 87-108.

Powell, R. and Powell, M. 1977, Geothermometry and Oxygen Barometry using Coexisting Iron-Titanium Oxides - A reappraisal: Mineralogical Magazine, v. 41, p. 257-263.

Ratcliffe, B.C., and Fagerstrom, J.A., 1980, Invertebrate Lebensspuren of Holocene Floodplains: Their Morphology, Origin, and Paleoecological Significance: Journal of Paleontology, v. 54, p. 614-630.

Retallack, G.J., 1984, Trace Fossils of Burrowing Beetles and Bees in an Oligocene Paleosol, Badlands National Park, South Dakota: Journal of Paleontology, v. 58, p. 571-592.

Ritter, D.F., 1978, Process Geomorphology: Dubuque, Ia., Wm. C. Brown Co. Pub., 603 pp.

Rohr, D.M., Boucot, A.J., Miller, J., and Abbott, M., 1986, Oldest Termite Nest from the Upper Cretaceous of West Texas: Geology, v. 14, p. 87-88.

Rose, W.J., Jr., 1987, Active Pyroclastic Processes Studied with Scanning Electron Microscopy, In: J.R. Marshall (Editor), Clastic Particles, Scanning Electron Microscopy and Shape Analysis of Sedimentary and Volcanic Clasts: New York, Van Nostrand Reinhold Company, p. 136-155.

Sarjeant, W.A.S., 1975, Plant Trace Fossils, In: R.W. Frey (Editor), A Study of Trace Fossils, New York, Springer-Verlag, p. 136-179.

Schultz, C.B., and Stout, T.M., 1955, Classification of Oligocene Sediments in Nebraska: University of Nebraska State Museum Bulletin, v.4, p. 17-52.

Schultz, C.B., and Stout, T.M., 1961, Field Conference on the Tertiary and Pleistocene of Western Nebraska: Special Publication University of Nebraska State Museum, 55 pp.

Smith, N.D., and Hein, F.J., 1971, Biogenic Reworking of Fluvial Sediments by Staphylinid Beetles: Journal of Sedimentary Petrology, v. 41, p. 598-602.

Squires, R.L., and Advocate, D.M., 1984, Meniscate Burrows from Miocene Lacustrine-Fluvial Deposits, Diligencia Formation, Orocopia Mountains, Southern California: Journal of Paleontology, v. 58, p. 593-597.

Stanley, K.O., and Fagerstrom, J.A., 1974, Miocene Invertebrate Trace Fossils from a Braided River Environment, Western Nebraska, U.S.A.: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 15, p. 63-82.

Stout, T.M., DeGraw, H.M., Tanner, L.G., Stanley, K.O., Wayne, W.J., and Swinehart, J.B., 1971, Guidebook to the Late Pliocene and Early Pleistocene of Nebraska: University of Nebraska Conservation and Survey Division, Lincoln Nebraska Geological Survey, p. 70.

Swinehart, J.B., and Loope, D.B., 1987, Late Cenozoic Geology Along the Summit to Museum Hiking Trail, Scotts Bluff National Monument, Western Nebraska: The Decade of North American Geology Field Guides for Nebraska, University of Nebraska-Lincoln, p. 13-18.

Swinehart, J.B., Sounders, V.L., DeGraw, H.M., and Diffendal, R.F., Jr., 1985, Cenozoic Paleogeography of Western Nebraska, In: Cenozoic Paleogeography of the West-Central United States, Society of Economic Paleontologists and Mineralogists Symposium #3, p. 209-229.

Thomasson, J.R., 1982, Fossil Grains Anthoecia and Other Plant Fossils from Arthropod Burrows in the Miocene of Western Nebraska: Journal of Paleontology, v. 56, p. 1011-1017.

Toots, H., 1967, Invertebrate Burrows in the Non-Marine Miocene of Wyoming: Contributions to Geology, v. 6, p. 93-96.

Toots, H., 1975, Distribution of Meniscate Burrows in Non-Marine Tertiary Sediments of Western U.S.: Contributions to Geology, v. 14, p. 9-10.

Williams, H., and McBirney, A.R., 1979, Volcanology: San Francisco, Freeman Cooper and Company, 397 pp.

Wilson, E.O., 1971, The Insect Societies: Belknop/Harvard, Cambridge, Mass., 548 pp.