The Origin of Polish on Pebbles in the Windrow Formation of Goodhue County, Minnesota

Sam Roberts
Senior Integrative Exercise
March 10, 2008

Submitted in partial fulfillment of the requirements for a
Bachelor of Arts degree from Carleton College, Northfield, Minnesota.

Table of Contents

Abstract
Introduction…….....1
Geologic Setting and Previous Work...……..……..2
Background on Polish…….……..…….....…..4
Methods…….……..…….....9
Results and Interpretations…….……13
The Origin of Polish: Gastroliths v. Ventifacts……...……..…..22
Conclusions…….……...…26
Acknowledgements…..……....….28
References Cited……...……..28

The Origin of Polish on Pebbles in the Windrow Formation of Goodhue County, Minnesota

Sam Roberts
Senior Integrative Exercise
March 10, 2008
Advisor: Clint Cowan

ABSTRACT

Extraordinarily high surface polish is exhibited by a majority of the pebbles found within the East Bluff Member of the Windrow Formation at an outcrop in Goodhue County, Minnesota. These pebbles are found loose and in conglomerates cemented by limonite. The high polish of these pebbles has previously been attributed to gastrolithic processes and water abrasion (Stauffer, 1945; Andrews, 1958). In this study, through observation and SEM analysis, a variety of characteristics of a sample of pebbles are studied in order to investigate the possibilities of gastroliths and wind abrasion as polishing mechanisms for the pebbles of the Windrow Formation. In combination with other surface characteristics such as faceting, pitting and distribution of polish, observations suggest that these pebbles were in fact polished by wind abrasion (i.e. ventifacts). Though sufficient evidence was not found to conclusively suggest that the wind abrasion occurred in a desert environment, it is possible that these pebbles were a part of a desert pavement. The polishing of these pebbles through wind abrasion in a desert environment has implications for the timing of the deposition of the East Bluff Member, suggesting a Tertiary age instead of the previously accepted Cretaceous age assigned to the entire Windrow Formation.

Keywords: wind abrasion, polish, Windrow Formation, gastrolith, facet

INTRODUCTION

The polish of rock surfaces is typically attributed to abrasion by wind (Powers, 1936; Higgins, 1956; Sugden, 1964; Christiansen, 2004; Knight, 2004; Mackay and Burn, 2004) or the milling action within the gizzard of some reptilian animals, birds, and dinosaurs (i.e. gastroliths) (Stauffer, 1945; Andrews, 1958; Hoskin et al., 1970; Darby and Ojakangas, 1980; Johnston et al., 1990; Manley, 1991; Manley, 1993; Johnston et al., 1994; Cox, 1998; Wings, 2007; Long et al., 2006).

This study attempts to specifically address the surface polish exhibited by pebbles found in the Windrow Formation (Cretaceous) in Goodhue County, Minnesota. Previous work, by Stauffer (1945) and Andrews (1958), attempts to explain the polish of pebbles within the East Bluff Member of the Windrow Formation from multiple locations in the upper Mississippi Valley region. Stauffer (1945) attributes the low polish of small pebbles to water abrasion, and the high polish of large pebbles to gastrolithic processes. Andrews (1958) discusses the entire Windrow Formation in detail, dismissing Stauffer's explanation, suggesting that the polish of pebbles of all sizes in this member was a result of the abrasive action of water. Neither Stauffer (1945) nor Andrews (1958) substantiate or support their suppositions of polishing by the action of water. I could find no studies that evaluate the action of water to polish rocks.

With modern analytical techniques, such as the SEM, and further work addressing the polish of gastroliths and ventifacts with which to compare, more in depth studies of the polished pebbles of the Windrow Formation are possible. If the cause of the polish is determined, there may be further implications. The polishing of the pebbles by gastolithic processes would be evidence for the presence of the organisms ingesting the

pebbles, despite the absence of any bone record of them. Specific identification of the organism type (e.g. dinosaurs or avian of any size) would indicate more specific or even different timing for the Windrow Formation. If these pebbles were determined to be wind polished, it may help restrict the deposition time of the Windrow Formation to a less humid period (i.e. post-Cretaceous). If the polish is inconsistent with both gastroliths and wind abraded rocks, there may be evidence that suggests another polishing process.

GEOLOGICAL SETTING AND PREVIOUS WORK

The pebbles examined in this study were collected from a deposit mapped as a part of the Windrow Formation (Thwaites and Twenhofel, 1921; Andrews, 1958; Mossler, Pers. Comm.). For the purposes of this study, Andrews' (1958) terminology will be used. The Windrow Formation is composed of two members, the lower Iron Hill Member and the upper East Bluff Member. The Iron Hill member consists of concretionary iron oxide deposits on a Paleozoic limestone bedrock. The East Bluff Member includes coarse clastic deposits, resting unconformably on the Iron Hill Member. The pebbles addressed in this paper were found within the East Bluff Member. This member can be identified by a facies that "grades from a coarse sand through a pebbly sand to a 'peanut gravel'" (Andrews, 1958). The polished pebbles of this member are vein quartz and chert, many of which exhibit polished surfaces.

The Windrow Formation is found only in the upper Mississippi Valley region, including the Driftless Area of Wisconsin and farther north into the older glaciated region of west-central Wisconsin. It is also found in the glaciated regions of southeastern Minnesota and northeastern Iowa.

The age of the Windrow Formation is unclear, sitting unconformably on Paleozoic rocks of varied ages, but with none younger than Devonian, leading to the conclusion that the formation itself can be no older than Devonian in age. The formation is overlain by rocks as young as recent topsoil and as old as Nebraskan Drift (Andrews, 1958) leading to the conclusion that it can be no younger than Pleistocene in age (Andrews, 1958). Andrews (1958) concludes that the Windrow Formation is of Cretaceous age because of correlations made with the diagnostic gravels and conglomerates that exist in Cretaceous age formations in Minnesota and Iowa.

Stauffer (1945) and Andrews (1958) are the only previous works that address the origin of the polished pebbles found in this study. Among the pebbles that are described by Stauffer (1945) as smoothed and polished by water action, he identifies large pebbles that are more highly polished and may have a different origin. These large, more polished pebbles are described as angular to subangular with uniform polish over the entire surface of the pebble, even extending into pitted areas. Through comparisons with known gastroliths from Wyoming and Utah, Stauffer (1945) suggests that these large, more highly polished pebbles, found amongst the small ones, are gastroliths.

Though Andrews (1958) does not provide a detailed explanation, he does not believe that a gastrolithic origin is feasible considering the abundance of these highly polished pebbles. He instead attributes the high polish to abrasive action in shallow, agitated waters.

BACKGROUND ON POLISH

Polish is difficult to quantify and when discussed in the literature, there is no scale for comparison. However, one example of a quantitative technique, which was beyond the scope of this study, involves the use of laser light scattering. In attempts to characterize gastrolith surface roughness, Johnston et al. (1990) developed a method using a video light scattering instrument to measure the reflection of light. A poorly polished rock scatters the light more widely, whereas a highly polished rock reflects light with more concentration. Further uses of light scattering techniques as a means for quantifying polish have occurred, however cannot be taken with confidence (Johnston et al., 1990; Manley, 1991; Manley, 1993; Johnston et al., 1994; Cox, 1998), proving that this method only marginally improves the qualitative visual estimation of polish. There is not a body of literature where any quantified technique has been used across a spectrum of polish of known origins to use as a gauge or reference. This study only implements a simple visual qualitative differentiation of the level of polish exhibited by the pebbles found.

With sufficient mobile surface particles and strong enough winds, aeolian erosion can be a significant factor in the alteration of the earth's surface (Bridges et al., 2003). The occurrence of wind abrasion is most commonly documented in hot and cold deserts, and coastal and periglacial environments (Knight, 2004). The effects of wind abrasion can be seen on rocks of all sizes, from pebbles on the millimeter scale (Higgins, 1956), to boulders and bedrock (Christiansen, 2004). Any rock affected by wind abrasion may be called a 'ventifact' (Jackson, 1997) Loose sediment and ice crystals act as the abrading material, creating grooves, pits, flutes, facets and polish, all characteristics of the surfaces

of wind-abraded rocks (Christiansen, 2004). Of these features, high polish, faceting and pitting are exhibited by the pebbles found in Goodhue County, suggesting wind abrasion as a possible explanation for the origin of these characteristics.

High polish of rocks has long been strongly associated with the action of wind-blown particles. When wind-transported saltating or suspended sand, silt or snow particles collide with rock surfaces, polish may result (Christiansen, 2004). Particles that are saltating, polish the up-wind surface of a rock only, while suspended particles may simultaneously polish multiple faces (Schlyter, 1994). Wind polishing has been documented as occurring on rocks ranging from large boulders and bedrock (Christiansen, 2004), down to granules as small as 2 mm in diameter (Higgins, 1956).

Another feature of the pebbles found in Goodhue County that suggests that wind abrasion has had an influence on their highly polished surface are the facets found on some of the pebbles. Facets are the flat faces of rocks that may form as a result of wind abrasion. Most pebbles with facets are ventifacts that have been abraded by wind in desert (Cooke et al., 1993) and periglacial (Embleton and King, 1975) environments. Though uncommon, Sheperd (2003) investigates the faceting of pebbles in a swash zone of a beach through wave abrasion in a humid, tropical environment.

The number of faces of a faceted pebble can range from one to twenty or more, some with smooth, polished surfaces, and others with pits, flutes or grooves (Higgins, 1956). Faceted rocks may vary in size from large boulders to small pebbles, and in hardness from soft limestone to igneous rocks (Sugden, 1964). While the wind erosion of stones may occur on multiple surfaces due to suspended particle abrasion, multiple facets on smaller pebbles may be attributed to their movement during this process (Sugden,

1964). In the case of rocks that have remained stationary since the formation of facets, the most abraded facet is often used, in combination with other variables, to indicate the direction, and sometimes the relative magnitude, of paleowinds (Knight, 2004). While many of the pebbles from Goodhue County have what are undoubtedly facets, the flattening of the sides of some pebbles suggest the early stages of facet formation.

A second notable cause of polish on rocks is through the digestive systems of a variety of organisms. Gastroliths are defined by Wings (2007) as "a hard object of no caloric value (e.g., a stone, a natural or pathological concretion) which is, or was, retained in the digestive tract of an animal." Typically, the sizes of gastroliths are between .1% and 3% of the length of the animal; however, particles smaller than this may have important functions in an animal (Wings, 2007). They occur in a variety of invertebrates and vertebrates, serving many purposes. Modern birds, such as ptarmigans and ostriches (Hoskin et al., 1970), and reptilians, such as crocodiles (Wings, 2007), are best known to have gastroliths. Gastrolithic function varies through species, however, the most common, and plausible uses are for the titration of food, the mixing of food, mineral supplement, stomach cleaning, and the secretion of stomach juices (Wings, 2007). The use of stones as ballast (a balancing mechanism) in aquatic animals (e.g. crocodiles and plesiosaurs) is a more controversial hypothesis for gastrolithic function (Wings, 2007). Gastroliths can be important fossils for identifying the remains of extinct animals, especially birds such as moas (Johnston et al., 1994), however they are not always found with the actual remnants of the animal they were ingested by, making them difficult to identify. While the shape and surface texture of gastroliths may be dependent on

gastrolithic function (Wings, 2007), roundness and polish are the most common physical characteristics associated with them.

Many studies have argued the undeniable connection between polish and gastrolithic processes, some even attempting to develop methods of distinguishing supposed gastrolithic polish from other types of polish. The highly polished gastroliths of modern birds with gizzards is the strongest evidence that supports that stones may be polished within the digestive tract of animals (Hoskin et al., 1970). In order to show that rounding and polishing of stones are the result of abrasion in the gizzard of birds, Hoskin et al. (1970) created scatter diagrams plotting roundness against the time of year that the rocks were found in the 92 ptarmigan gizzards. The plot shows that during the summer months the roundness of the stones tends to be low (angular) and the polish is dull, while during the winter months the roundness tends to be high (rounded) and the polish is high. This is explained by the availability of stones during the summer and scarcity during the winter. The longer the stones were in the gizzards, the more rounded and polished they became.

Other studies use the polish of pebbles to identify them as gastroliths of extinct birds, such as moas, and dinosaurs. All uses of the laser light scattering technique discussed earlier were attempts to characterize the surface roughness of suspected and known gastroliths of dinosaurs. The results were quantitative, but not necessarily convincingly diagnostic of polish origin. The primary issue with the laser light scattering is that in order for the results to be meaningful there must be confidence that the polish of gastroliths are consistently higher than that of other rock polishes (Johnston et al., 1990). While in general this may be proven to be true, gastrolith polishes vary based on the

amount of time spent in the gizzard (Hoskin et al., 1970). Non-gastroliths may also reach an unusually high polish as seen in cases of wind-abraded rocks. There is also the question of how gastroliths may be affected by various processes after they have left the gizzard (Manley, 1991). These three factors make it clear where the confusion over the identification of gastroliths may arise, and how some researchers may even falsely identify rocks as 'suspected' gastroliths.

Some studies claim that the degree of polish of stones is not of significant use in determining a gastrolith from other stones (Darby and Ojakangas, 1980). In a study by Riggs (1939), 206 stones associated with a plesiosaur were described as rounded and smooth, but with no high polish. In the study by Darby and Ojakangas (1980), all of the gastroliths found had a "masked" polish, and they believe that this may have been acquired after deposition. Other studies, such as that done by Bryan (1931), agree that gastrolithic polish was probably obtained after their use as a digestive tool.

This discrepancy over the origin of stone polish has occurred before, as demonstrated by Dorr (1966) who believes that in his study, stones previously identified as gastroliths were in fact polished as a result of wind-blown fine abrasives. He argues that without the existence of bones in the strata of these polished stones, polish cannot be confidently attributed to gastrolithic processes. This is an issue that may arise from the explanation of the pebbles found in Goodhue County as gastroliths because there have been no bones found in the Windrow Formation (Stauffer, 1945). The most widely accepted examples of gastroliths were collected directly from inside the skeletal remains of animals or within the vicinity of bones (Dorr, 1966; Long et al., 2006). However, given that many avians are proven to use gastroliths and the bones of these organisms

have low preservation potential, it is reasonable to believe that many more gastroliths exist in the record than the bones associated with them. This could apply to the Windrow Formation; however, this problems will never be solved until exact criteria for gastrolith identification are discovered. In addition to the easily decomposed skeletal remains of birds, there are a variety of possible explanations for why once any animal dies, and its body decomposes, the gastroliths within it could be separated from the bones remaining. However, there have been studies that claim to have found gastroliths in the absence of skeletal remains (cf. Brown, 1941)

Another possible cause of a high degree of polish is suggested to be through hyperconcentrated flows (Zaleha, 2005). The actual cause of the polish at the particle scale, however, is not addressed, and the conclusions of the study are based solely on context. The attribution of polish to water also occurs multiple times in the literature where other explanations do not seem possible (Bond, 1954; Zaleha, 2005), but there is no work on how and under what specific circumstances water leads to high polish. The conspicuous nature of high polish, that can make some pebbles particularly noticeable, and the lack of literature addressing water as a polishing agent, indicates that it is not a commonplace phenomenon in fluvial, lacustrine, or marine settings.

METHODS

The pebbles of this study were collected at a roadside outcrop of the Windrow Formation in Goodhue County in southeastern Minnesota (Fig. 1). The Windrow Formation does not crop out in the study area, but is restricted to subcrops (mapped by John Mossler, of the Minnesota Geological Survey,

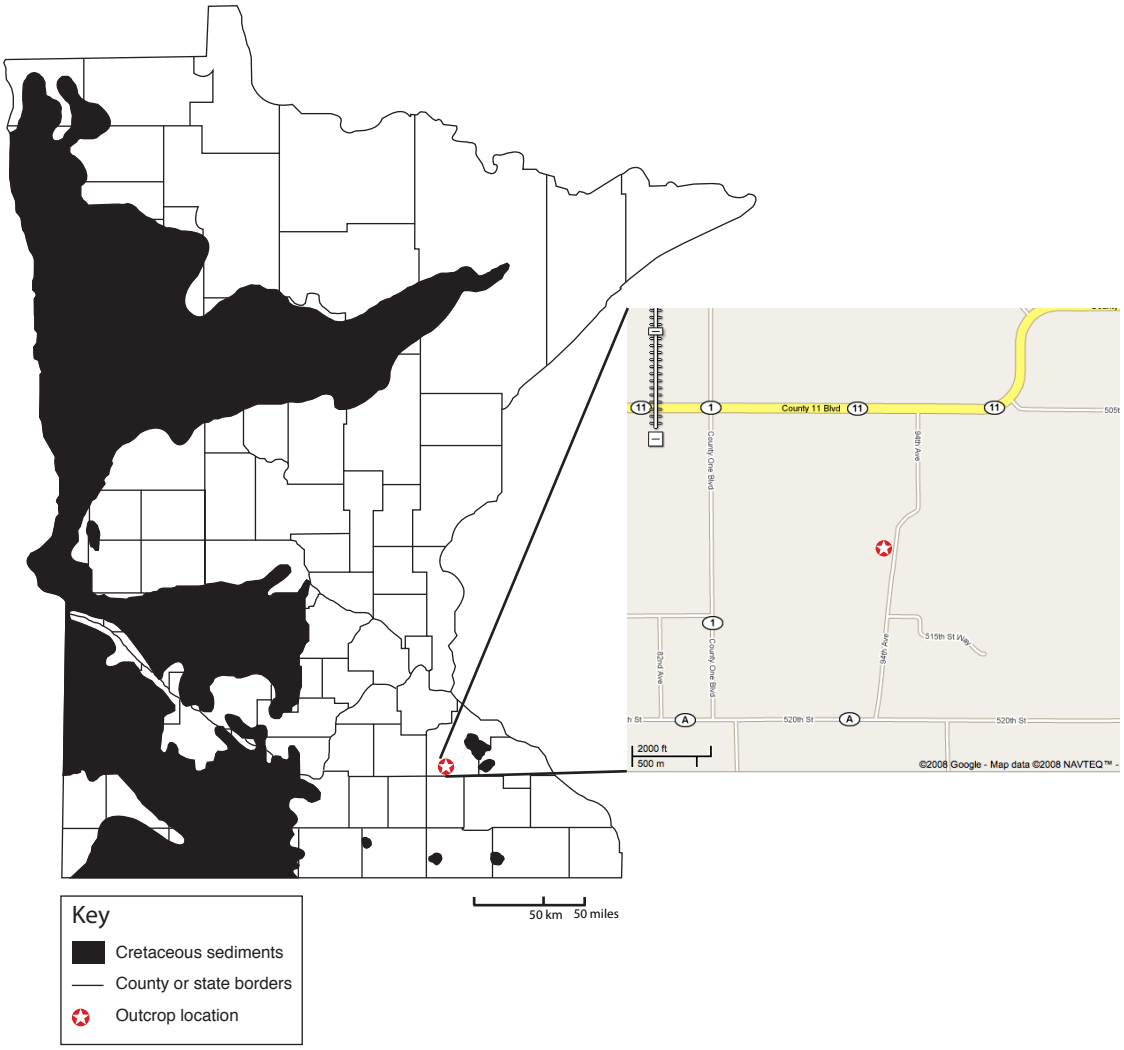


Figure 1. County map of Minnesota with red star indicating the location of the outcrop in Goodhue County (modified from Sims, P.K. and Moery, G.B., 1972). Inset map shows the location of the outcrop on 94th Ave., off of County 11 Blvd. (courtesey of Google Maps).

as the Ostrander float), including plowed fields, slumps of roadsides and hillsides. This study avoided areas with significant glacial cover. The outcrop sampled is about 15 meters in height and poorly exposed (Fig. 2). The majority of the visible pebbles of the outcrop are highly polished, a characteristic of the East Bluff Member described by Andrews (1958), and on the surface (Fig. 3), making them extremely easy to find. One of Andrews' (1958) outcrops of the Windrow Formation was in Goodhue County, leading to the conclusion that these pebbles must have very similar attributes as the ones mentioned in his study.

A five gallon bucket was filled with a sample of the Windrow Formation and as a result is not necessarily statistically representative of a sample of the formation. The sample included material from both the surface and just below the surface of the exposed outcrop. Using a sieve, grain sizes larger than 2 mm were separated, while soil, organic material and smaller grain sizes were washed away. Pebbles within the Windrow Formation are abundant. Our sample included greater than 1000 pebbles above 4 mm and many thousands of granules. The limestone fragments were removed. The remaining rocks were pebbles of grain sizes ranging from 2 mm to 25 mm, which were then sieved into size fractions (2-4 mm, 4-6.3 mm, 6.3-8 mm, 8-11.3 mm, 11.3-13.2 mm, 13.2-16 mm, 16-19 mm and 19-25 mm). Within each size fraction the polished pebbles were visually separated from the non-polished pebbles and composition of all pebbles were determined. Representative samples of pebbles and conglomerates were selected for petrography and SEM analysis. The Carleton College Hitachi S-3000N Scanning Electron Microscope equipped with an Oxford INCA microanalysis system was used.

Figure 2. Outcrop of the Windrow Formation in Goodhue County, containing the polished pebbles in both poorly and well exposed areas.

Figure 3. Polished pebbles found loose on the surface of the outcrop (finger for scale).

An acceleration voltage of 20 kV was used for all analyses. The pebbles were visually inspected and characterized according to polish, pitting, color, shape, and faceting. The polish of the pebbles was quantified using a Benjamin Moore Paints loss level chart. This means that the range of polish that was exhibited by the pebbles in each size group and color group was determined.

RESULTS AND INTERPRETATIONS

The sample collected consisted of a variety of rocks types, polished and non-polished. Within the sample collected, by weight, 60% of pebbles above 4 mm were determined to show some degree of polish on their surface, while 40% did not (Fig. 4). There were such a large number of pebbles in the size fraction from 2 mm to 4 mm that a 5%, by weight, split of these pebbles was analyzed, showing similar polish percentages with, by weight, 67% polished and 33% non-polished. The pebbles exhibited polish in all size fractions from <2 mm to 25 mm The non-polished pebbles consisted of limestone fragments, iron oxide crusts, a few basalts, a few granites and a few undetermined rock types. The polished pebbles were vein quartz and chert. The sample also included pebble to boulder sized clasts of well lithified Windrow Formation conglomerate that consisted only of the polished chert and vein quartz and were cemented by limonite (Fig. 5; Andrews, 1958).

The extraordinary polish of these pebbles is the most prominent surface characteristic exhibited and the basis for this study. Under the SEM, the relationship between the roughness and the degree of the polish of a pebble can be easily seen. The white pebble and black pebble shown in Figure 6 are of the highest degree of polish

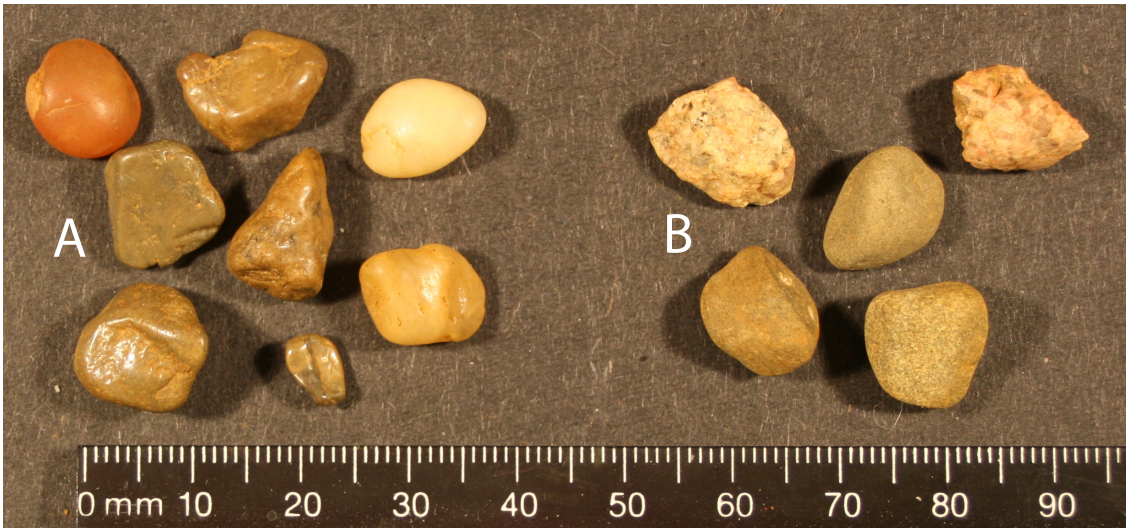


Figure 4. A comparison of pebbles found within the sample of this study.
(A) Polished pebbles. (B) Non-polished pebbles.

Figure 5. Conglomerate of polished and non-polished pebbles of various sizes.
Arrows point to some of the conspicuously polished pebbles.

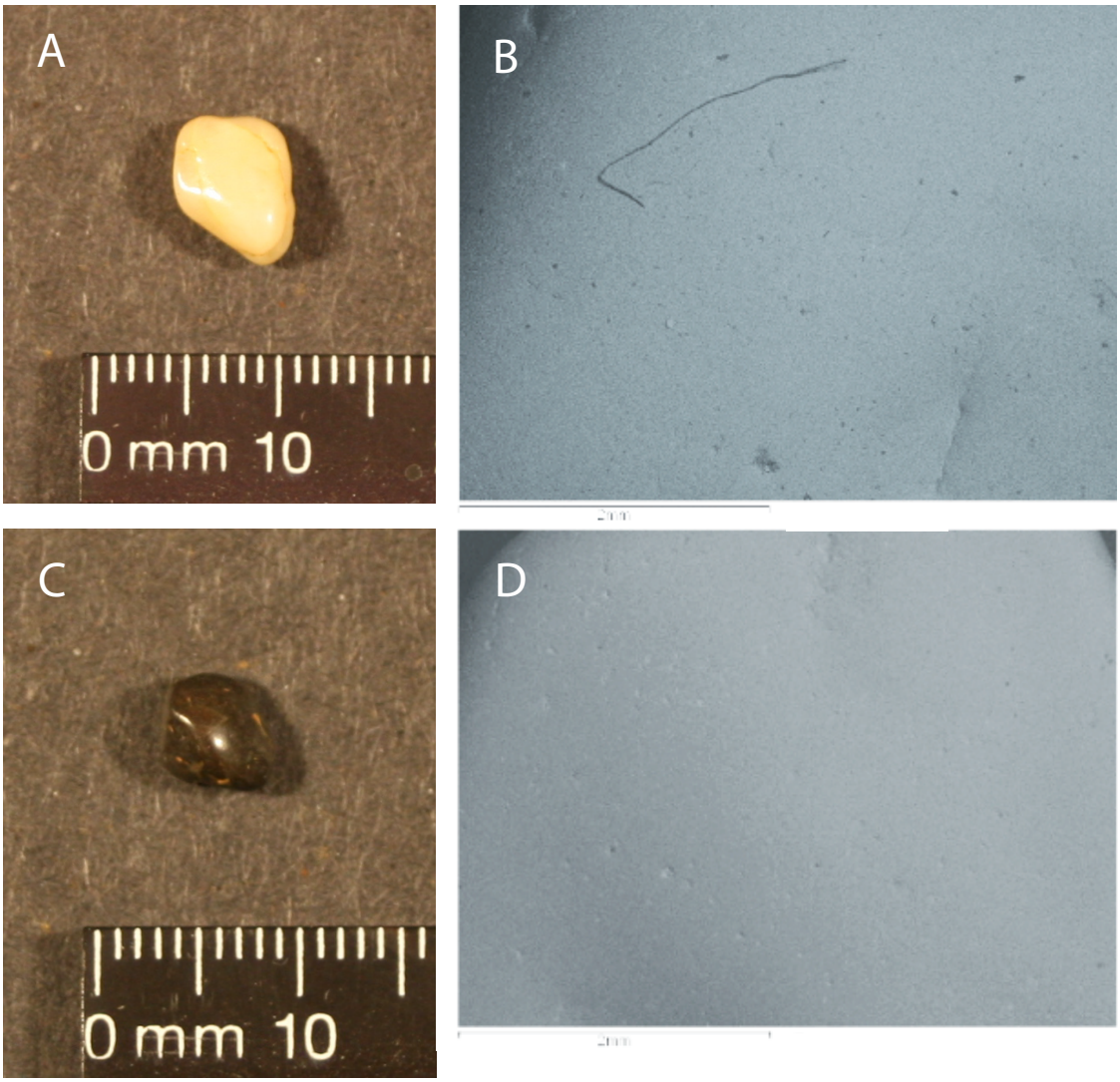
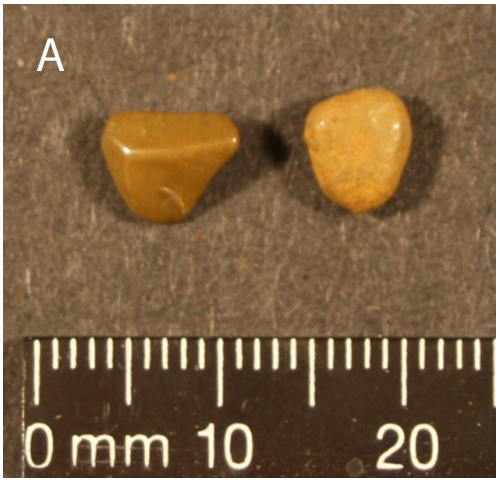


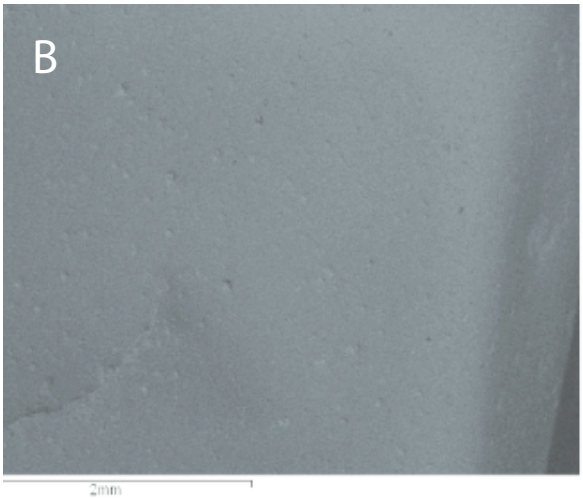
Figure 6. Highly polished pebbles from Goodhue County. (A) A polished white quartz pebble showing high polish without the use of visual aids (B) Under the SEM, an extremely minimal amount of roughness is shown on the pebble from (A). (C) A similarly polished black chert pebble. (D) The black pebble also showing little roughness under the SEM.

within the sample. SEM back scatter electron images of these pebbles show that minimal surface roughness is associated with this high polish. The comparison of two brown chert pebbles in Figure 7 show the difference in roughness of pebbles of similar color, size and composition. In back scatter electron images under the SEM, the pebble exhibiting a high polish shows extremely smooth microtopography, whereas the low polished pebble has a rough surface. In reference to SEM images Johnston et al., (1990) say that "qualitatively, the suspected moa gastroliths tend to look smoother than non-gastroliths…it is difficult, however, to obtain meaningful (or quick) quantitative measurements." While this appears to be true in this study, the SEM images are useful in simply visualizing the difference between a highly polished pebble and a low to non-polished pebble.

In this study, a pebble that is considered to be polished does not necessarily exhibit this characteristic on the entire surface of the rock. Pebbles within each size fraction from 2 mm to 11.3 mm, show a full range of polish grade, from the lowest, flat polish to the highest, lustrous polish. This indicates that within this range of pebble sizes there was no preferential polishing based on size. Pebbles within the size fractions larger than 11.3 mm, however, did not always exhibit a full range of polish.

A problem, as expressed in the literature, with surface polish is that, alone, it does not seem to be diagnostic of the specific origin of polish, which is why observations of other pebble characteristics are important. These include the facets, rims, pits, various colors, and characteristic shapes of many of the pebbles.





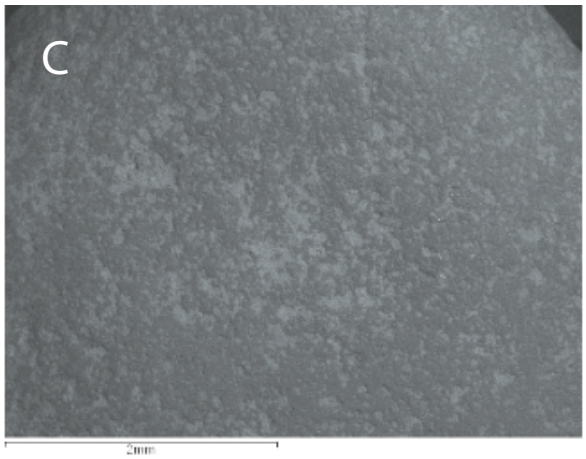


Figure 7. Two similarly colored polished chert pebbles from Goodhue County. (A) The pebble on the left exhibits a much higher polish than the pebble on the right. (B) Under the SEM, back scatter election images show that the highly polished pebble has little roughness. (C) Under the SEM, the low polished pebble shows greater roughness.

Though there are not many pebbles with facets (Fig. 8) in this sample, they do exist through a variety of colors and sizes, however, as with the highest degree of polish, are most abundant in the black, gray and brown color groups.

Petrography of thin sections of pebble conglomerates reveals the presence of orange to dark red rims around the edges of some pebbles. The number of pebbles with these rims was not determined because a representative sample was not fully analyzed for this characteristic. These rims range in thicknesses up to 2 mm and are not uniformly thick within each pebble. SEM x-ray analysis shows that these rims are the same composition as the rest of the pebble (Fig. 9). This analysis, and Andrews (1958), support that these rims are simply a light staining of the outer layer of the rock. As Andrews (1958) states, there is no coating of iron or manganese on the pebbles, despite the ferruginous matrix of limonite and are therefore suspected to be a result of weathering.

Some pebbles of the Windrow Formation also contain pits, which are circular depressions a few millimeters in depth and diameter, occurring usually on only one face or side of the pebble. Figure 10 shows the differences in the roughness of a pitted pebble with high polish and a pitted pebble with low polish. The back scatter electron images show that the polish of these pebbles can extend into the pits.

The chert pebbles range in color as blacks, grays, browns and whites. The quartz also varies in color, with clear, white, yellow, gray and pink pebbles. All of the color groupings show the highest degree of polish, however it is most abundant in the black, gray, and brown groups.

Figure 8. Faceted polished pebbles of a variety of sizes and colors.

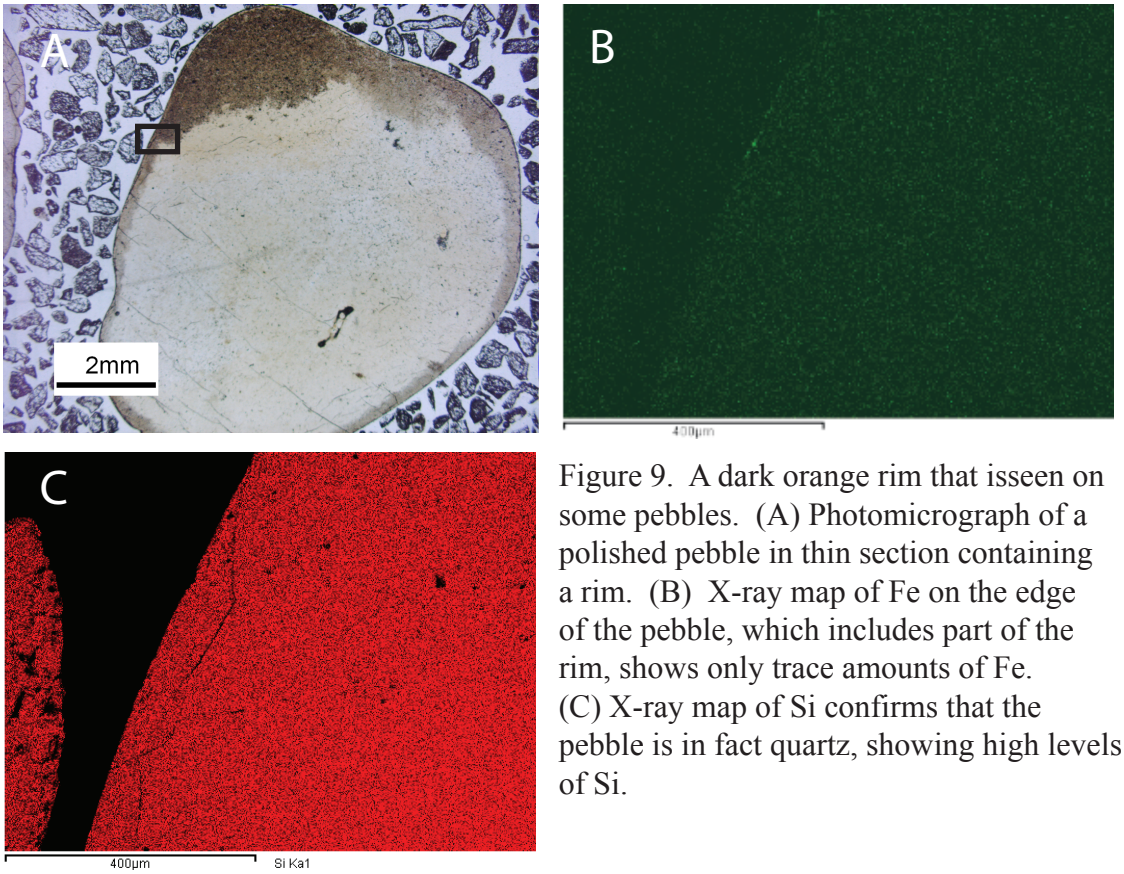
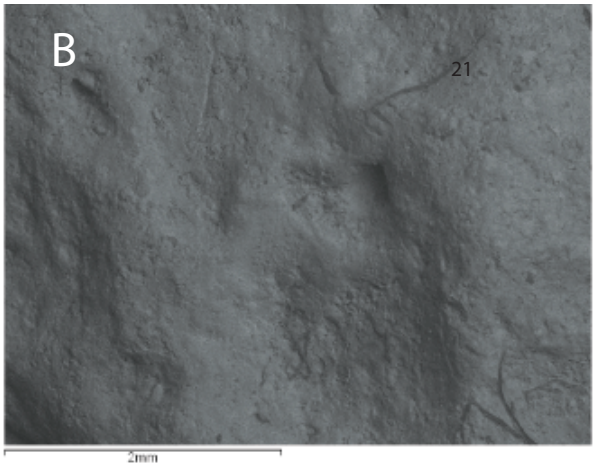


Figure 9. A dark orange rim that isseen on some pebbles. (A) Photomicrograph of a polished pebble in thin section containing a rim. (B) X-ray map of Fe on the edge of the pebble, which includes part of the rim, shows only trace amounts of Fe. (C) X-ray map of Si confirms that the pebble is in fact quartz, showing high levels of Si.



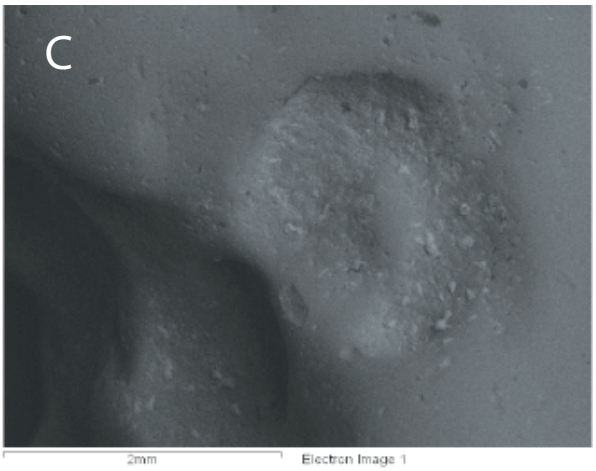


Figure 10. (A) Polished and non-polished pebbles, both showing pitting. (B) SEM back scatter electrion image of the non-polished pitted pebble, showing high roughness in comparision to (C), which is an SEM image of the polished pitted pebble. The smoothness of the polish can be seen extending into the pits of (C).

Many of the pebbles also have a distinctive shape to them. While a single shape cannot be assigned to the entire group of pebbles, even at a glance, a rounded, oval shape is the most commonly occurring amongst the white, yellow and pink quartz pebbles (Fig. 11).

The provenance of the pebbles have implications for the timing of the East Bluff Member. The limestone and iron crusts originate from the bedrock units below, and the quartz and chert pebbles can be confidently assigned to the Windrow Formation. The other non-polished pebbles within the Windrow Formation do not appear to be similar to glacial deposits in this region, based on cursory examination of local glacial deposits.

THE ORIGIN OF POLISH: GASTROLITHS V. VENTIFACTS

The pebbles found in this study are from a different portion of the Windrow Formation than studied before, exhibiting characteristics undescribed in previous work involving the pebbles of this formation. The abrasion of the pebbles by wind and the use of these pebbles as gizzard stones or gastroliths stand out as the two possible origins of polish. Each of these possibilities will be discussed below with regards to the various characteristics exhibited by the sample of pebbles collected.

Size- As mentioned earlier, rocks of all sizes, including pebbles and granules such as those in this study, are known to exhibit both polish and faceting. Within the collected sample, polish was also not preferential to size. These observations indicate that wind abrasion remains a possibility based on the size of the pebbles that were polished. Since the age of this member is still unclear, there is a large time period in which these stones could have been polished, and thus there is a large number of different types of

Figure 11. Yellow, white and pink polished quartz pebbles exhibiting a characteristic oval shape.

birds, reptiles, and dinosaurs that could have existed and used stones for digested purposes. As a result, there is a large range in sizes of stones that could have been used, setting no size limitation on the polishing of pebbles**.** Large moas were known to use stones up to 35 mm in diameter, a size much larger than any of the pebbles found in this study (Hoskin et al., 1970). The sizes of the polished pebbles do not appear to be a diagnostic feature of either process.

Polish coverage- The pebbles of the outcrop in Goodhue County are not all fully polished, with some of the pebbles showing polish on only a portion of their surface. This, however, can be explained by wind abrasion. Some of these stones could have been cemented into the ground, leaving some surfaces unexposed to the processes of wind abrasion, resulting in partial polish. Others, however, could have been loose and mobile, allowing their entire surface to be polished. The partial polish of some of the pebbles presents a problem for the explanation of these stones as gastroliths. Though the literature does not explicitly discuss this, partial polishing does not seem to be a possibility for stones in a digestive system. The entire surface of a pebble that is in the digestive system should be exposed to the same processes at all times, resulting in a uniform polish.

Polish Grade- The pebbles show a wide range of polish grade, from a very matte polish to an extremely high polish. This characteristic is not diagnostic of either process. Pebbles may be exposed to wind abrasion for varied amounts of time and intensities, causing variation in the grade of polish. They may also spend varied time in the gizzard of an animal. Some stones may have been processed for much longer than others, resulting in a higher polish, while others may have only been in a gizzard for a short

period of time before the animal's death, resulting in a lower grade of polish. Hoskin et al. (1970) use seasons to explain the variation in grade of polish for gastroliths.

Faceting- The faceting of these pebbles is best explained by wind abrasion because wind is the primary cause of this feature. While it is possible that pre-faceted stones were collected by animals, and then they were polished, these facets are in no way the result of being gastroliths. This proves that some of these pebbles underwent wind abrasion at some time.

Rims- Originally these rims were suspected to be a desert varnish, which would have further supported the idea of the polish being a result of wind abrasion in a desert environment. The lack of high levels of manganese and iron, and the scale at which the rims are occurring, indicates that desert vanish does not exist on the pebbles analyzed. However, the lack of desert varnish certainly does not mean that these pebbles were not exposed to wind abrasion. As with the facets, the light iron staining that has created the rims on some of the pebbles would have occurred before the pebbles were used as gizzard stones. Because of this, the rims found on these pebbles are also not diagnostic of gastrolithic polishing.

Pits- One common cause of pitting is through the impact of snow and sand particles against vertically aligned surfaces of stones (Knight, 2005). Pits may indicate wind abrasion, but are not distinctive of the process. Though pits are also commonly found on known gastroliths, it is still unclear as to whether this pitting occurs during the time spent in the digestive system, and for this reason is also not diagnostic of gastrolithic origin (Long et al., 2006).

Shape- The commonly occurring oval shape of the pebbles found in this study cannot be explained by wind abrasion. Though wind abrasion may alter the surface features of rocks, it does not round them, leading to the conclusion that if these pebbles were polished by wind, they must have been rounded before this process. Hoskin et al. (1970) shows that roundness is associated with the amount of time spent in the gizzard of ptarmigans. However, if these pebbles were in fact polished in a digestive tract, general roundness of these pebbles could also have occurred prior to their ingestion. Again, shape cannot be considered diagnostic of wind abrasion or gastrolithic processes.

Color- Though relating the color of the pebbles to degree of polish may not be revealing of the polishing process, it does raise interesting questions. Though it is hard to provide a good explanation for why this may be, it appears that the darker colored pebbles were preferentially or more readily polished. Since both water and wind do not favor the polishing of certain rocks based on color, it seems that the pebbles with darker color polish to a higher degree as result of an unidentified chemical process. Though the other characteristics do not favor gastrolithic processes as a polishing mechanism for the pebbles of this study, it also seems possible that the darker pebbles were preferentially chosen by gastrolith bearing organisms.

CONCLUSIONS

After an extensive review of the literature and execution of various analytical techniques, the polish of the pebbles found in the Windrow Formation in Goodhue County, Minnesota, is determined to be a result of wind abrasion. Polish can be produced through processes in the digestive tract of a variety of animals, however, the

characteristics of the pebbles found in this study disagree with this possibility and point toward wind abrasion instead. The presence of faceting does not completely discount these pebbles as gastroliths, however, facets are indicators of wind abrasion, making a strong case for wind abrasion as the polishing mechanism. One characteristic that does seem to discount gastroliths is the partial polish that is shown by some of the pebbles. This characteristic is wide spread through all colors and sizes, confirming that it is not a result of some other preferential process. As discussed earlier, partial polish is a possibility for ventifacts, but not for gastroliths.

With the assumption that these pebbles were polished by wind, it is possible that the high concentration of these rounded to angular polished stones can be explained as the remnants of a desert pavement. Though stone pavements are found in periglacial environments, they are most commonly occurring in deserts (Cook et al., 1993).

Under the assumption that these stones were polished in a desert environment, the assortment of non-polished stones has implications for the timing of this process. Based on local glacial gravels, the non-polished rocks do not seem to have originated from the glaciers of the Pleistocene. The Cretaceous can also be eliminated for the timing of this polish because it was too humid during this time for a desert environment (Dott and Batten, 1971). If these pebbles are pre-Pleistocene, post-Cretaceous ventifacts, the polish of the pebbles could be Tertiary, changing the geologic age of the upper member of the Windrow Formation.

Future work on the highly polished pebbles of the Windrow Formation should include an extensive comparison of the pebbles across multiple locations. A comparison of these

pebbles with rocks of desert pavements and known wind polished pebbles could be useful in discovering diagnostic features of this polishing process.

ACKNOWLEDGEMENTS

I would first like thank my advisor, Clint Cowan for finding me a comps project, helping me work through and organize ideas along the way and editing this paper. Without his influence, I would never have been able to sort through my pebbles with a purpose. I appreciated help from Tony Runkel, who aided in the development of the initial idea for this project, had insights on the polished pebbles of this study and still believes that they are in fact gastroliths. I would also like to thank Cam Davidson for his help in analyzing the pebbles under the SEM. Funding for the thin sections was made possible by Carleton College. I also want want to thank Tim Vick for always being available to help students, including myself, solve problem of all kinds.

REFERENCES CITED

Andrews, G. W., 1958, Windrow Formation of upper Mississippi Valley region a sedimentary and stratigraphic study: Journal of Geology, v. 66, p. 597-624.

Bond, G., 1954, Surface textures of sand grains from the Victoria Falls area: Journal of Sedimentary Petrology, v. 24, p. 191-195.

Bridges, J. C., Seabrook, A. M., D. A. Rothery, Kim, J. R., Pillinger, C. T., Sims, M. R., Golombek, M. P., Duxbury, T., Head, J. W., Haldemann, A. F. C., Mitchell, K. L., Muller, J. P., Lewis, S. R., Moncrieff, C., Wright, I. P., Grady, M. M., and Morley, J. G., 2003, Selection of the landing site in Isidis Planitia of Mars probe Beagle 2: Journal of Geophysical Research-Planets, v. 108, no. E1.

Brown, B., 1941, The Last Dinosaurs: Natural History, v. 48, p. 290-295.

Bryan, K., 1931, Wind-worn stones or ventifacts-a discussion and bibliography: National Research Counil, Report of Comittee on Sedimentation, 1929-1930, Bulletin, v. 98, p. 29-50.

Christiansen, H. H., 2004, Windpolished boulders and bedrock in the Scottish Highlands: evidence and implications of Late Devensian wind activity: Boreas, v. 33, p. 82-94.

Cooke, R., Goudie, A., and Warren, A., 1993, Desert Geomorphology: London, ULA Press, 231 p.

Cox, T., 1998, Origin of stone concentrations in loess-derived interfluve soils Paleopedology revisited: Transactions ofthe 2nd international symposium on paleopedology, v. 51, p. 74-75.

Darby, D. G., and Ojakangas, R. W., 1980, Gastroliths from an upper Cretaceous Plesiosaur: Journal of Paleontology, v. 54, p. 548-556.

Dorr, J. A., 1966, Wind polished stones:two similar sites: Papers of the Michigan Academy of Science, Arts and Letters, v. 51, p. 265-273.

Dott, R. H., and Batten, R. L., 1971, Evolution of Earth: New York, McGraw Hill, 537 p.

Embleton, C., and King, C. A., 1975, Periglacial Geomorphology: London, Arnold, 536 p.

Higgins, C. G., 1956, Formation of small ventifacts: Journal of Geology, v. 64, p. 506-516.

Hoskin, C. M., Guthrie, R. D., and Hoffman, B. L. P., 1970, Pleistocene, Holocene and recent bird gastroliths from interior Alaska: Arctic, v. 23, p. 14-23.

Jackson, J. A., 1997, Glossary of Geology: Alexandria, American Geological Institute.

Johnston, R. G., Lee, W. G., and Grace, W. K., 1994, Identifying Moa gastroliths using a video light scattering instrument: Journal of Paleontology, v. 68, p. 159-163.

Johnston, R. G., Manley, K., and Lemanski, C. L., 1990, Characterizing gastrolith surface roughness with light scattering: Optics Communications, v. 74, p. 279-283.

Knight, J., 2004, Controls on the formation of coastal ventifacts: Geomorphology, v. 64, p. 243-253.

Long, C., Wings, O., Xiaohong, C., and Sander, P. M., 2006, Gastroliths in the Triassic Ichthyosaur *Panjiangsaurus* from China: Journal of Paleontology, v. 80, p. 583-588.

Mackay, J. R., and Burn, C. R., 2005, A long-term field study (1951-2003) of ventifacts formed by katabatic winds at Paulatuk, western Arctic coast, Canada: Canadian Journal of Earth Sciences, v. 42, p. 1615-1635.

Manley, K., 1991, Two techniques for measuring surface polish as applied to gastroliths: Ichnos, v. 3, p. 313-316

Manley, K., 1993, Surface polish measurements from bona fide and suspected sauropod dinosaur gastroliths, wave and stream transported clasts: Ichnos, v. 2, p. 167-169.

Mossler, J., 2007, Minnesota Geological Survey: St. Paul, Minnesota.

Powers, W. E., 1936, The evidence of wind abrasion: Journal of Geology, v. 44, p. 214-219.

Riggs, E. S., 1939, A specimen of *Elamosaurus serpentinus*: Field Museum of Natural History, Geology Series, v. 6, p. 385-391.

Schlyter, P., 1994, Paleo-Periglacial ventifact fomation by suspended silt and snow: site studies in South Sweden: Geografiska Annaler, v. 76, p. 187-201.

Shepherd, M., 2003, Wave-faceted pebbles, Sovi Bay Beach, Viti Levu, Fiji: Zeitschrift Fur Geomorphologie, v. 47, p. 439-448.

Sims, P. K., and Morey, G. B., 1972, Geology of Minnesota: a centennial volume: St. Paul, Minnesota Geological Survey.

Stauffer, C. R., 1945, Gastroliths from Minnesota: American Journal of Science, v. 243, p. 336-340.

Sugden, W., 1964, Origin of faceted pebbles in some recent desert sediments of Southern Iraq: Sedimentology, v. 3, p. 65-74.

Thwaites, F. T., and Twenhofel, W. H., 1921, Windrow Formation; An upland gravel formation of the Driftless and adjacent areas of the upper Mississippi valley Bulletin of the Geological Society of America, v. 32, p. 293-314.

Wings, O., 2007, A review of gastrolith function with implications for fossil vertebrates and a revised classification: Acta Palaeontologica Polonica, v. 52, p. 1-16.

Zaleha, M. J., and Wiesemann, S. A., 2005, Hyperconcentrated flows and gastroliths: Sedimentology of diamictites and wackes of the upper Cloverly Formation, Lower Cretaceous, Wyoming, U.S.A: Journal of Sedimentary Research, v. 75, p. 43-54.