Review by G.B. Morey
Sat down with him in my office
10-8-03

Geology of the Kensington Rune Stone

Reviewed on 10-9-03
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Introduction

This report presents the results of an investigation into the geologic aspects of a stone slab artifact called the Kensington Rune Stone or KRS. In addition to documenting the physical features of the stone, the geologic attributes were used to assign the age of the inscription. The investigation began on July 3, 2000, and included both field and laboratory work. Fieldwork consisted of a site visit to where the stone was discovered on a farm near Kensington, in west-central Minnesota, in 1898 and the collection of chip samples from tombstones in the Hallowell Cemetery in Hallowell, Maine. Laboratory analysis was performed at American Petrographic Services Inc. in St. Paul, Minnesota, and at the Materials Laboratory at Iowa State University in Ames, Iowa. We also performed research into the history of the KRS at the Minnesota Historical Society (MHS). Where appropriate, portions of relevant documents are reproduced in this report.

General Description of the Physical Features

The laboratory work performed is essentially the same as what a pathologist does when performing an autopsy. The only difference is that the "body" in this case is a 202-pound (91.6 kg) slab of very hard stone. During the course of the examination, we consider the large-scale features first and progressively examine increasingly smaller-scale features through microscopy. The basic parameters of the stone are documented first.

Approximate Dimensions	Weight
31" (79 cm) x 16" (41 cm) x 5 ½" (14 cm) thick	202 (91.6 kg)

Figure #1: Overall view of the "face" side of the KRS that contains the first nine lines of the inscription.

Actually it is The release of these factors.

The stone is tabular in shape and is roughly the size of a common tombstone. The overall angular shape of the stone was produced by roughly parallel fracture planes that developed while the stone was still in the bedrock. Intense pressure and stress from deep within the earth over millions of years produced these orderly fractures called **joints**. A few of these joint fractures cut across the face of the KRS and are parallel to each other.

Figure #2: A prominent joint fracture runs across the face side of the stone <u>at a shallow angle</u>. relative to what datum?

The flat and elongate stone exhibits three distinct types of surfaces. The first is bluish-gray in color and does not exhibit any observable glacial striations. The first nine lines of the inscription are carved into this surface. For discussion purposes we'll call this surface the "face" side. The face side also exhibits a second set of smaller scale fracture planes called **cleavage**, that exhibit a repeatable, sub-parallel orientation. These fracture planes are produced by intense pressure from within the earth that aligned, newly formed micas and other elongate minerals. Five distinct cleavage planes are visible on the face side of the KRS.

Similar or diverse orientation?

Figure # 3: Sunlight at a low angle highlights five distinct cleavage planes that step upward along the "face" of the stone. The long vertical step between two cleavage planes cuts across six lines of the inscription at a high angle.

Cleavage played an interesting role during the original carving of the inscription that caused the carver to change plans as he went along. The first line of the inscription begins at the far upper left side of the stone. The second line is indented about 3" and begins on the upper side of the step between two cleavage planes. Close inspection of this area reveals where a character was carved that appears to have caused a piece of the rock to spall off when it was stuck. Presumably, the carver began the second line at the far left edge but lost part of the first word when the rock broke off along the cleavage plane below. This area is called the "Oh Shoot" area. The third line was also started on the upper area. Confidence in the stability of the rock was apparently restored and the fourth line was started at the far left edge.

Figure #4: A relatively large piece of rock spalled off along the lower cleavage plane as the second line of the inscription was being carved.

Whoever carved the inscription definitely had to be mindful of the unpredictable nature of fractures and spalling caused by the inherent aspect of cleavage in the stone.

Figure #5: A pit was created when two runes were carved in the area between two cleavage planes.

Another prominent feature on the face is the white triangle-shaped area in the lower left side of the stone. This very thin layer (1-2 mm thick) is comprised of a coarse-grained crystalline calcite (CaCO3) that moved along the joint fracture system, parallel to the face side of the stone, and was deposited by solutions in the crack. Within the calcite are elongate chlorite [(Mg, Fe, Al)6 (Al, Si)4 O10 (OH)8] minerals, which exhibit a preferred orientation that is parallel to the long axis of the stone. This calcite was likely deposited millions of years ago when the KRS was still part of the bedrock.

Solutions moved along "..." & deposited cr. gr. cal.?

what does this say about paragenesis? is this chlorite ‖ to some other planar feature in rock? Or it is a very late orientation implying that calcite not a late-forming mineral

Figure #6: The white triangle-shaped area is hydrothermal calcite. This calcite was deposited by hot solutions that moved along the joint fracture system when the stone was still in the bedrock.

what is "hot"?

Is it the chlorite that causes you to call the calcite hydrothermal?

The hydrothermal calcite is important because several characters were carved into this area. The weathering of calcite, a relatively soft mineral (3 on the Mohs hardness scale which ranges from 1 to 10), is much different than the rest of the rock, which is considerably harder. Microscopic examination using reflected light revealed little difference between the texture and apparent weathering of the calcite both around and within the carved characters. Further study of the weathering of the characters within the calcite area is strongly recommended.

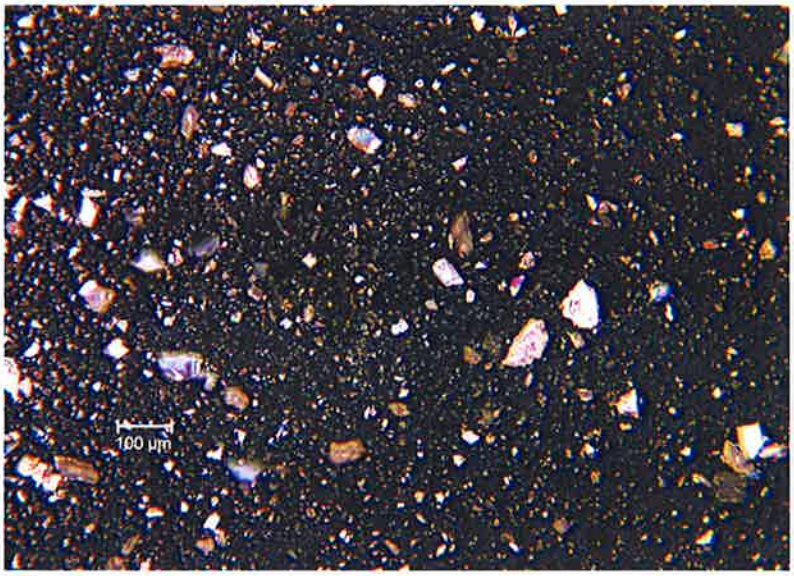


Figure #7: A sample of the hydrothermal calcite was scraped off from the white triangle-shaped area on the face side of the stone. The relatively coarse-sized, angular grains exhibit 3rd order birefringence colors when reviewed under cross polarized light.

The back side of the stone exhibits some very interesting features. A fiber-optic light source was directed at a very low angle across the back side of the stone. What immediately became apparent are relatively deep (1 to 5 mm) glacial striations that run roughly parallel to the long axis of the stone. ~~Since~~ no other sides of the KRS exhibit striations, it appears that the scratches were made while the stone was still a part of the bedrock. The glacier likely dragged rocks frozen at the base of the ice over the bedrock creating the striations. The tabular-shaped stone was later dislodged from the bedrock and incorporated within the body of glacial ice. The stone was then transported, presumably into the Kensington area, and then deposited when the glacial ice melted roughly 12 to 15 thousand years ago. basis, reference or what?

Time Term Because or Inasmuch as

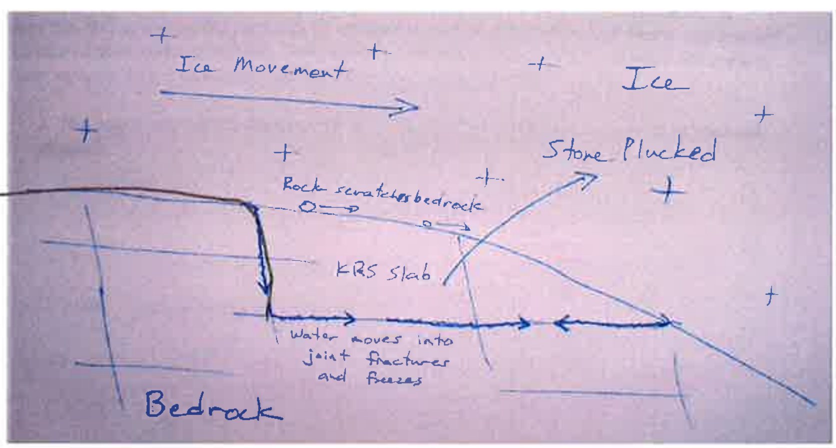


Figure #8: The likely origin of the KRS involved the back side being striated when the stone was still part of the bedrock. The stone was then plucked and carried within the body of the ice with little or no abrasion occurring. The ice eventually melted and the stone was deposited as a surface glacial erratic.

Figure #9: The relatively deep glacial striations on the back of the KRS are highlighted by low angle fiber-optic light.

Two peculiar white lines extend across the glacial surface. These are roughly parallel, undulating, and branch off at three locations. These appear to have been formed by the roots of the tree under which the KRS was found. The white lineation closest to the middle of the stone turns downward over the relatively steep and rounded opposite side.

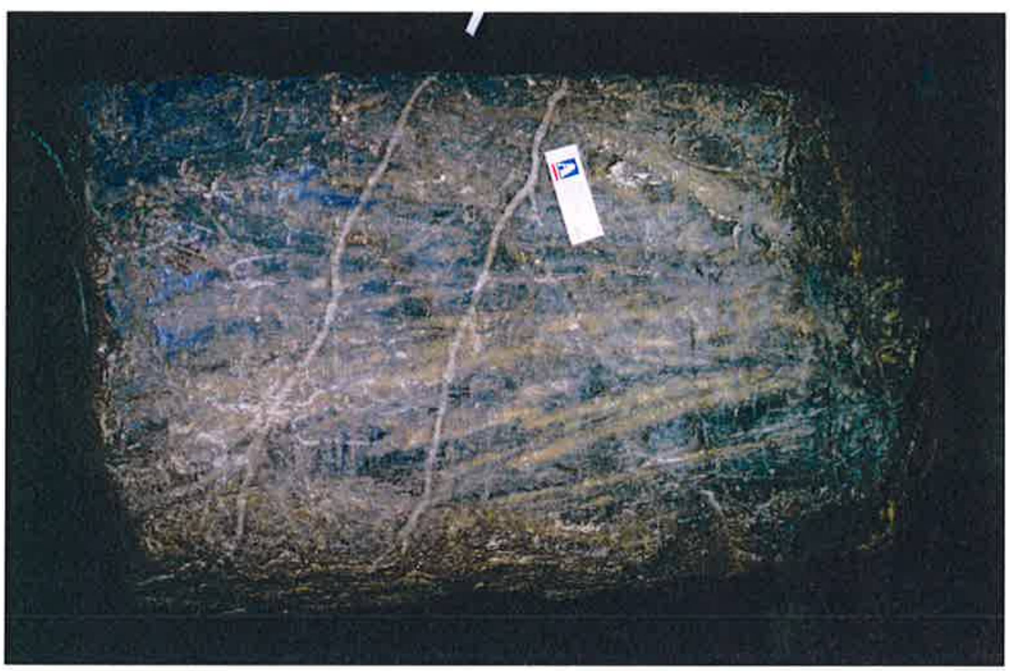


Figure #10: Two white, roughly parallel, undulating and branching lineations trend across the glacial surface and down the opposite side.

Figure #11: One lineation apparently would have continued beyond the bottom edge of the stone (in this orientation).

On the sharp, tapered end of the glacial side are intermittent areas of yellowish-white coatings of secondary calcite. This calcite is much finer-grained than the hydrothermal calcite on the face side. After the glacier melted away (approximately 12 thousand years ago), percolating groundwater deposited secondary calcite on the surface of the stone. Numerous sand grains are bound within the coatings, which are commonly found on glacial erratics.

So this calcite cross-cuts the vein calcite? or age relationship based on occurrence?

Figure #12: Yellowish-white, secondary calcite coatings speckle the tapered end of the glacial side of the stone. Percolating groundwater formed the coatings.

Figure #13: A heavy calcite coating on a granite glacial boulder was found at Rune Stone Park in Kensington, Minnesota. Many glacial erratics with calcite coatings were observed near the site where the KRS was discovered.

Another type of surface coating was observed that is white in color and found primarily along the top edge of the split side of the stone. These deposits are scattered within several rune grooves and word separators. Scrapings of the material were reviewed under polarized light and indicate that the coatings are comprised entirely of gypsum. Several plaster casts of the stone were reportedly made in the 1940's by the Smithsonian Institution in Washington D.C.

ref.

Figure: #14: Intermittent white coatings of gypsum occur within a word separator on the split side of the KRS.

Close examination of the sharpest edge, where the glacial side and the side containing the last three lines of the inscription meet, reveals at least six indentations. These rounded, conchoidal fracture-like areas appear to be related to purposeful impact.

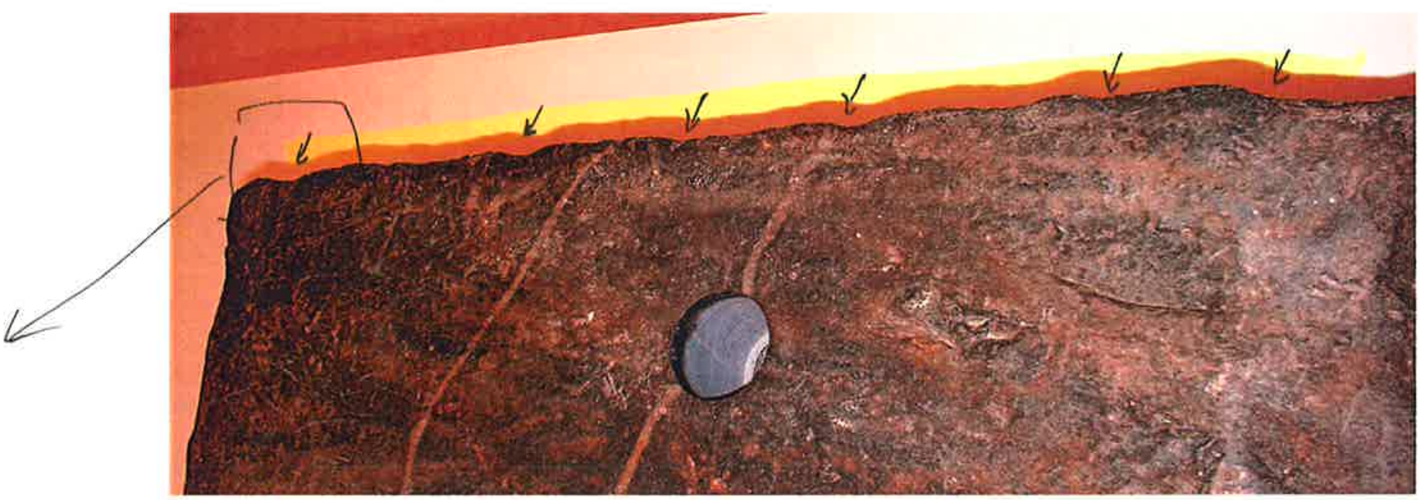


Figure #15: At least six indentations (arrows) along the sharpest edge appear to be related to purposeful impact.

Figure #16: This rounded, conchoidal-like fracture along the sharpest edge of the stone appears to have been produced by purposeful impact.

The side of the stone containing the last three lines of the inscription has an appearance that is different than all the other surfaces of the stone. The color of this surface is a slightly darker bluish-gray and has a rougher overall texture. It appears that the stone was purposely shaped, or "dressed" prior to the inscription being carved, since seven of the nine lines on the face side begin immediately adjacent to the left edge. We have identified this surface as the "split" side. In December of 2000, professional letter carver Janey Westin was asked to examine the KRS. She agreed that the conchoidal fractures along the edge were consistent with purposeful impact and that the entire split side had been dressed prior to carving the last three lines of the inscription.

An important aspect of the stone is the weathering characteristics of the different surfaces. All of the surfaces that have been weathering since being transported and then deposited by glaciers have a similar appearance. These surfaces have a light bluish-gray color with noticeable small-scale pitting. The pitting is caused by complete dissolution of the softer and less stable minerals, micas, pyrite and calcite. These surfaces have been exposed to weathering for at least 12,000 years, the approximate age of the last glacial activity. The split side surface has a darker overall gray color and does not exhibit the prominent pitting observed on the glacial surfaces. This surface appears to have been exposed to weathering for a significantly shorter length of time.

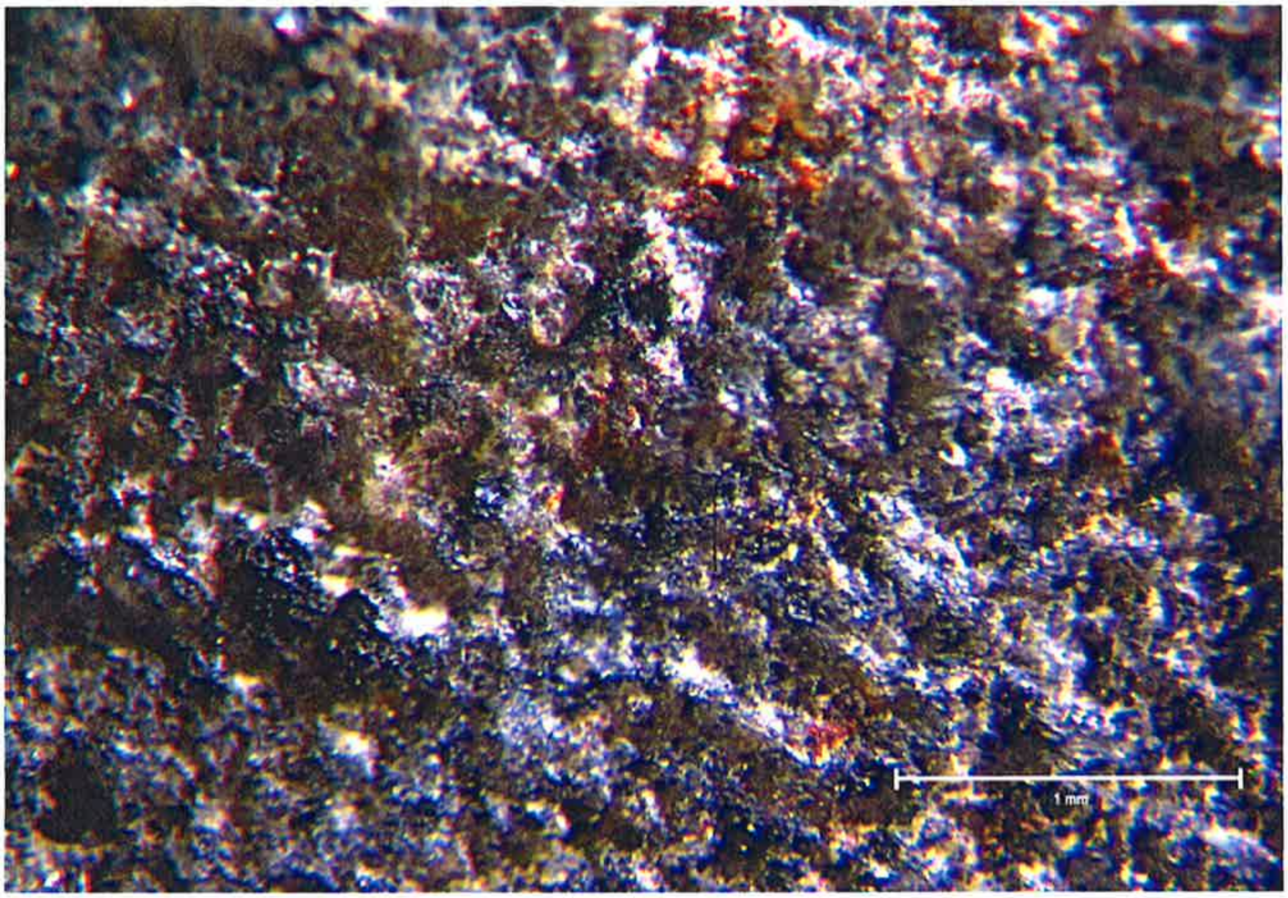


Figure #17: The glacial surfaces of the stone exhibit a lighter overall blue-gray color with noticeable pitting. This surface represents at least 10,000 years of weathering.

Figure #18: The split side of the stone that contains the last three lines of the inscription and the Holand "H", which was carved by Hjalmar Holand in 1907. The dark gray color and rougher texture of this surface is different than all the other glacial-aged weathered surfaces.

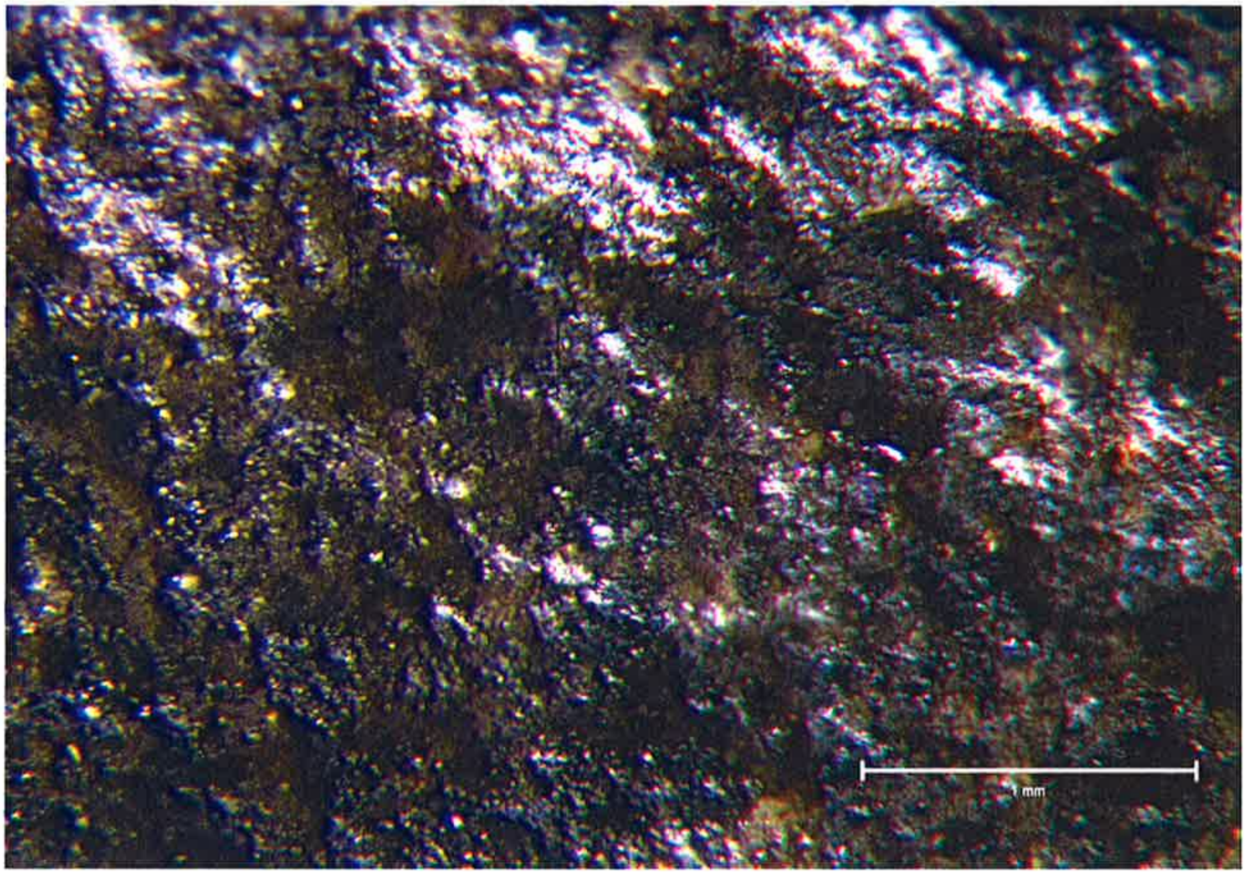


Figure #19: The split side surface is a darker gray color and does not exhibit the prominent pitting of the glacial surfaces. This surface represents a weathered appearance that developed over a much shorter period of time than the other surfaces of the stone.

The Inscription

There are twelve lines in the original inscription that are comprised of 287 individual carved characters. The first thing that jumps out when examining the inscription is the relatively fresh appearance of the carved characters. The deepest parts of the grooves were scraped out with a sharp instrument with sufficient force to remove all weathering products that were previously present. In addition, this "**retooling**" crushed the constituent minerals in the stone, which turned white and thereby created the fresh appearance. This gives the casual viewer the impression that the inscription was recently carved. However, close examination reveals an obvious difference in the color and texture of the areas adjacent to the deepest parts of the grooves. These surfaces have the same darker gray color as the split side of the stone and represent spots where flakes of rock spalled off immediately adjacent to the main grooves at the time the stone was originally carved. This **flaking** is observed to some degree on nearly every character on the face side.

Figure #20: The deepest parts of the grooves on the face side have been re-tooled with a sharp instrument. This has crushed the incipient minerals, which then turned white giving the inscription a fresh appearance. The darker gray areas adjacent to the retooling were produced by pieces of rock that flaked off when the original inscription was carved. These flaked surfaces have the same properties as the entire split side, which indicates that they were created at the same time.

All of the original rune-form grooves on the face side and approximately 75% of the rune-forms on the split side have been lightly scratched or completely retooled. The retooling on the face side appears to have been done with greater force than the split side. This is perhaps due to easier access to the face side. The retooling apparently occurred shortly after its reported discovery in November of 1898. There are four pieces of evidence that strongly support this assertion:

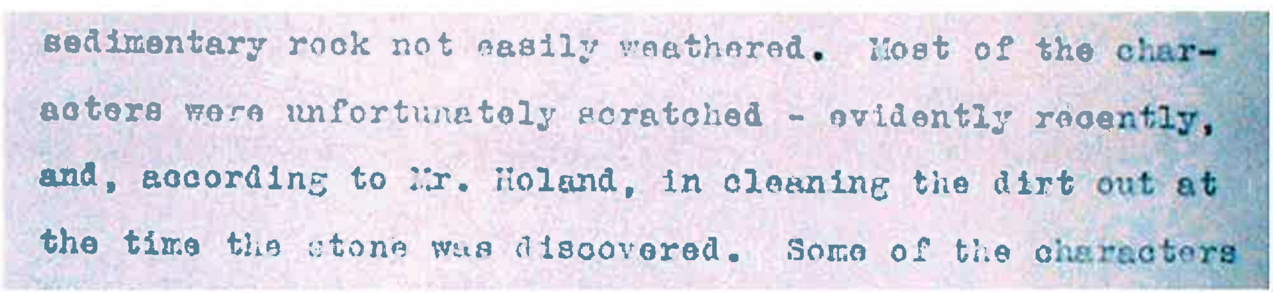
1. On March 3, 1899, after having studied the KRS for two days, Professor George Curme of Northwestern University was quoted in the Chicago newspaper, The Skandinavien: "Wherever the characters of the inscription have not been disturbed, they have precisely the same color as the general surface of the stone."

2. Close inspection of photographs taken of the KRS in March of 1899 appears to show the retooling was present at that time. The Steward photographs clearly show that the runes had already been cleaned at that time.

Figure #21: Retooling of the split side of the inscription is apparent by the light color of the characters in this photograph taken by John F. Steward in March of 1899.

3. On page 19 of Professor Winchell's April 19, 1910 report, he wrote, "This difference was said to be due to the fact that the runes on the edge had been filled with mud and had been cleaned out with a nail."

4. W. O. Hotchkiss, the Wisconsin state geologist, reported in an April 4, 1910 letter that the runes were scratched out shortly after its discovery.



sedimentary rock not easily weathered. Most of the char-
acters were unfortunately scratched - evidently recently,
and, according to Mr. Holand, in cleaning the dirt out at
the time the stone was discovered. Some of the characters

Figure #22: W. O. Hotchkiss letter to Upham dated April 4, 1910

There is one other character on the stone that was carved relatively recently. In 1907, Hjalmar Holand reported carved an "H" into the split side toward the bottom end of the stone. This character does not exhibit any observable weathering features.

Roughly a dozen characters on the split side of the stone do not appear to have been retooled at all. A few other characters on the split side appear to have been weakly retooled. What becomes apparent is that these original characters have the same color, texture and weathering features as the entire side into which they were carved. This similarity is consistent with the dressing of the side, and the original carving of the characters having been performed at about the same time. These characters are important because they exhibit weathering features such as iron oxide deposits. Iron oxide deposits developed from the decomposition of the mineral pyrite (FeS2). These deposits were observed within the original carved runes that were not retooled and speckled intermittently throughout the entire split side surface. Also observed within some of the original grooves are small (~ 0.5 mm), iron oxide-coated pits that represent pyrite crystals that have completely weathered away. The timing of these weathered pyrite pits was unknown until a fortuitous control sample, the "AVM Stone", was recently discovered. Attributes of that same will be briefly discussed below.

Timing of when the pyrite → Fe oxides?

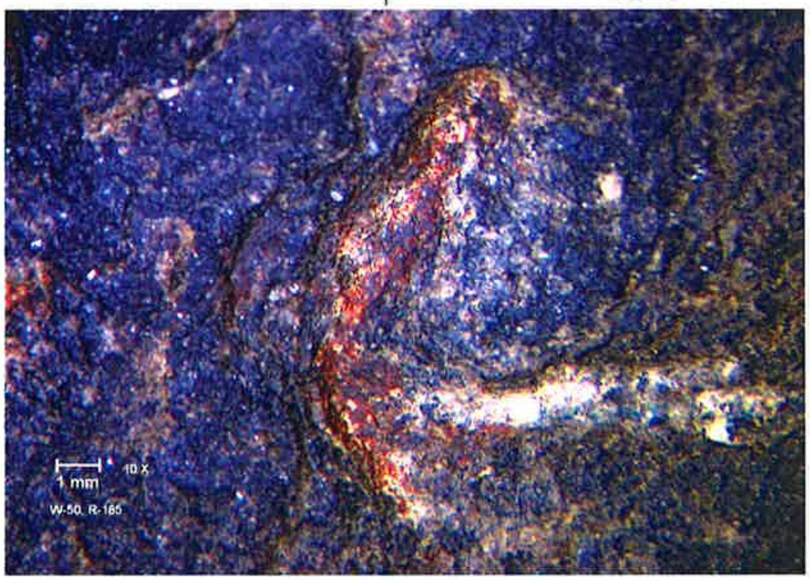


Figure #23: Rust-colored iron oxide deposits within an original character on the split side.

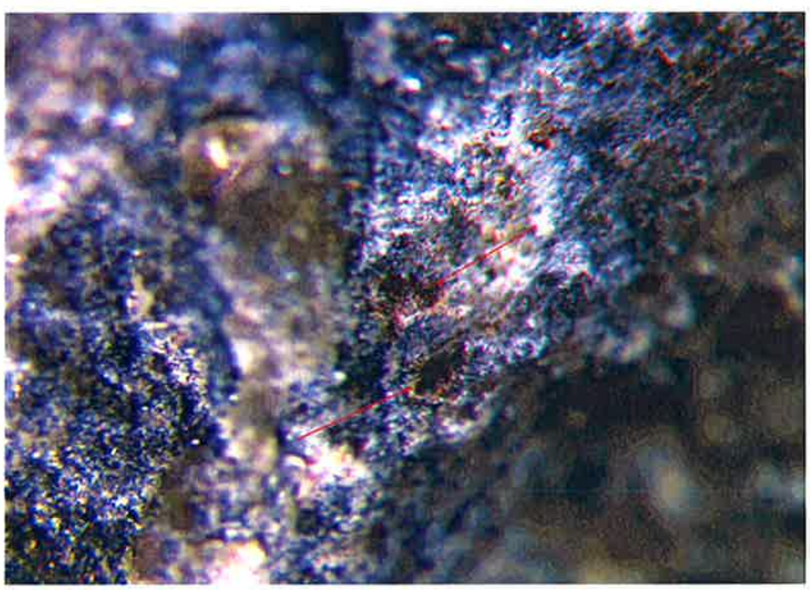


Figure #24: Weathered pyrite pits (red arrows) with halos of iron oxide on the split side.

The "AVM Stone"

In May of 2001, a large, approximately 2500-pound (1135 kg) granite gneiss glacial erratic with an inscription on the top of the stone was discovered in a pile of field-cleared boulders. The stone was found within a few hundred yards of the discovery site of the Kensington Rune Stone, an initially thought to be related to it. The message contains 13 carved characters including the letters "AVM."

Figure #25: The "AVM Stone" inscription was carved on a granite gneiss glacial boulder. Letters in the dark gray, roughly 2 ½" (6.5 cm) wide band of biotite-rich schist are white in color.

The "AVM Stone" was examined in the APS laboratory in August of 2001. Close inspection of the carved characters in the lighter colored, granitic areas revealed conspicuous rust-colored halos around actively oxidizing exposed pyrite crystals. None of these decomposing pyrite crystals were observed on the glacial-aged surfaces of the stone.

Figure #26: A pyrite crystal exhibiting cubic habit and a gold-colored metallic luster under plane polarized and reflected light, in a thin section made from the core sample obtained from the AVM Stone.

The actively oxidizing pyrites within the original carved surfaces of the AVM Stone were in stark contrast to the pyrite pits observed on the KRS. This discrepancy became clear when a group of five individuals came forward in September of 2001 claiming responsibility for carving the inscription in the spring of 1985. Their Rune Stone "hoax" suddenly became an important control sample that exhibited weathering of an inscription in rock comprised of essentially the same minerals as the KRS. Further, both inscriptions were exposed to the same weathering conditions with one important difference. The KRS was found buried in the ground whereas the AVM Stone was exposed to an exterior weathering environment. The rate of weathering in an exterior environment would be expected to be greater and more severe than a below-grade environment. Several additional factors would impact the rate of weathering at the surface that would not be present in the ground. These items include numerous wetting and drying events, multiple cycles of freezing and thawing, ultra-violet light exposure, ventification (wind polishing), and acid attack derived from decomposing plant material, animal feces and lichen. l.c.

I assume you don't see pyrite → Fe oxides. what you see evidence of the process including I assume intermediate steps

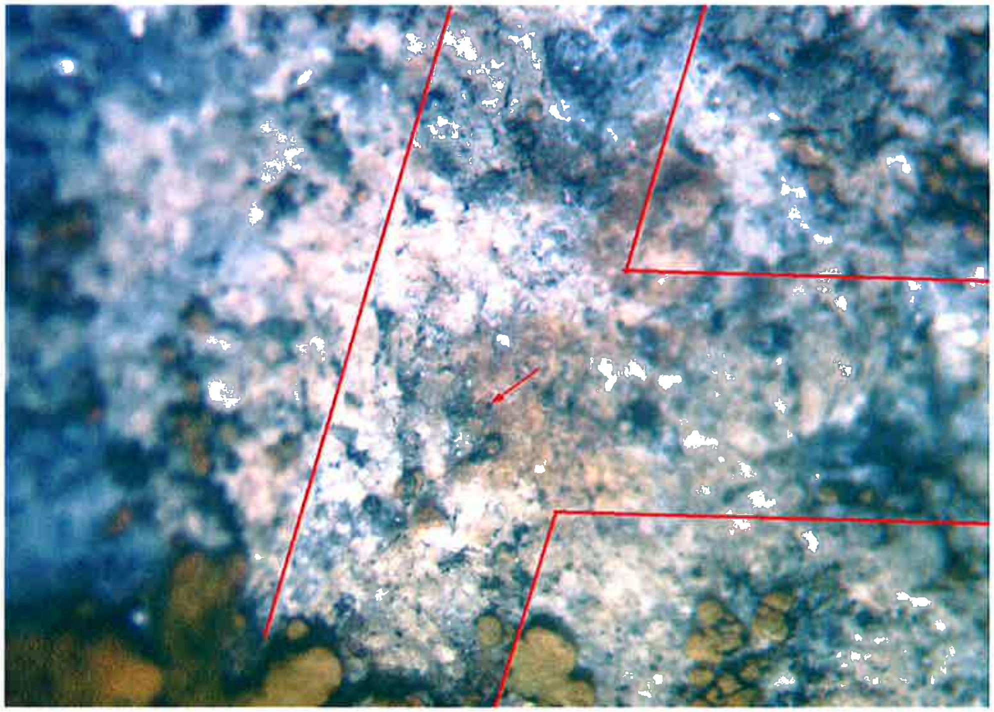
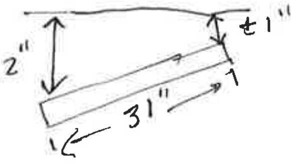


Figure #27: A rust-colored iron oxide stain formed from a decomposing pyrite grain within a carved character (the red lines indicate the first carved letter, an "A", on the stone) in the lighter-colored granitic area of the glacial erratic boulder (20X).

Figure #28: An actively corroding pyrite crystal (red arrow) creates a pronounced halo of iron oxide within a carved character on the AVM Stone (60x).

ok geometry or is there something amiss with 12"



If the below-ground system were wet then it must go faster than the above-ground where there is lots of O2 but dry or at best intermittently wet

It should be noted that the KRS was found in the soil horizon (the stone was reportedly found buried at an angle from within an inch of the surface to roughly 12" at the deepest) of a limey glacial till that has a pH of 7.5, which is on the alkaline side of neutral. This relatively stable environment would tend to slow the rate of pyrite oxidation relative to the above-grade environment. These factors all contribute to a reasonable and conservative comparison of the relative rate of pyrite decomposition between the two inscribed stones. One must also remember that the layout of the inscription on the KRS suggests the stone was likely set upright into the ground. Therefore, the inscription would have been exposed to an unknown period of exterior weathering. Regardless of whether the KRS was buried by humans or natural processes, the pyrite weathering comparison is still valid.

In 2002, the AVM Stone was returned to the farmer on whose property the stone was discovered. It was requested that the stone be left out to continue weathering and periodic observations of the weathering of the stone are ongoing. The most recent examination was performed on April 25th of 2003. Active oxidation of the pyrite grains within the inscription was still occurring. Since the pyrite crystals are still actively corroding within the AVM Stone inscription after 18 years of weathering, the pyrite crystals on the original man-made surfaces of the KRS clearly took longer than 18 years to completely decompose. T. Term

Photo-library of the Inscription

From December 11 through December 13, 2002, a digital photo-library was generated of all 287 characters that comprise the inscription on the Kensington Rune Stone. At least two photos were taken of each character using reflected light at both high and low angles with magnification ranging from 3.75 to 64 times. These images were generated to gain a better understanding of the physical characteristics of the inscription as well as provide a detailed data base that can be used in the future for research, educational and security purposes.

Figure #29: A photograph taken with low-angle reflected light that revealed a previously unknown split at the bottom of this rune-form in line 4. This character is believed to be an intentional combination of two runes called a "bind rune."

Core Sampling

One phase of the analysis involved obtaining a core sample from the KRS. Several test specimens were generated that enabled precise mineral identification and more detailed study of the various weathered surfaces. We selected an area on the glacial back side that included a branching portion of the white lineations and an apparent joint fracture. A water-cooled, diamond-studded coring bit was used to cut a 1 ¼" (32 mm) diameter by 2" (50 mm) long core sample.

Figure #30: The core sample location on the glacial back side of the stone.

Figure #31: A 1 1/4" (32 mm) diameter diamond-studded coring bit is positioned over the backside of KRS.

Figure #32: The 2" (50 mm) long sample after coring.

The top ½" (13 mm) of the core was cut off first. This top portion, or puck, was then cut perpendicular to the top surface and across the white lineation to create a cross-sectional profile. Examination of the polished profile revealed that the white lineation penetrated the rock to a depth of 1.5 mm. The whitened color was produced by chemical leaching of iron and magnesium elements from biotite minerals in the stone. The organic-based origin of the lineations suggests prolonged contact in the ground with tree roots.

lost me! what is evidence for "organic" based origin?

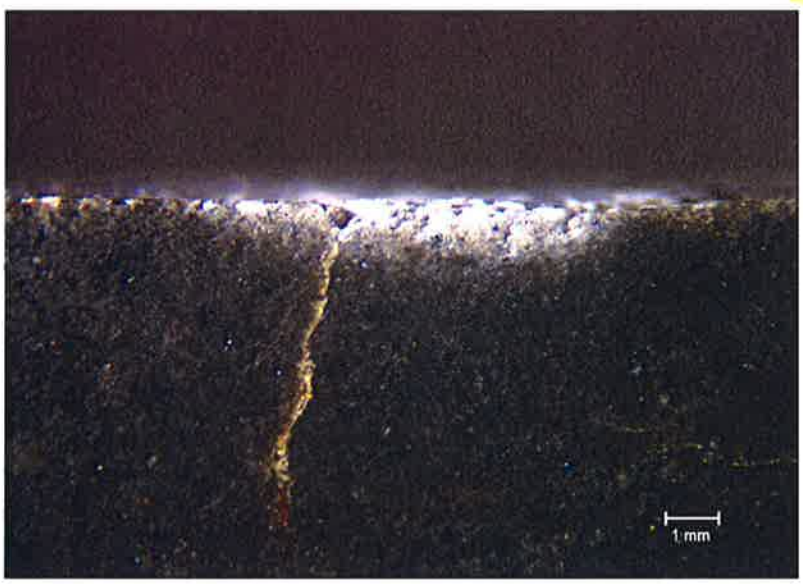


Figure #33: A cut and polished cross-sectional profile of a white lineation on the glacial back side of the stone. A yellowish colored fracture runs sub-vertically from the top surface.

The pattern of the white lineations is similar to the testimony and hand-drawn sketches of the witnesses who saw and described roots that tightly gripped the stone when it was discovered. Olof Ohman, his son Edward, neighbor Nils Flaten, and Kensington residents Roald Bentson and Samuel Olson all described the root as being about 3" (76 mm) wide and flattened to conform to the stone

Figure #34: Olof Ohman's December 9, 1909 letter with the sketch of the tree roots gripping the stone. Ohman labeled the sketch with the inscription side of the stone facing down.

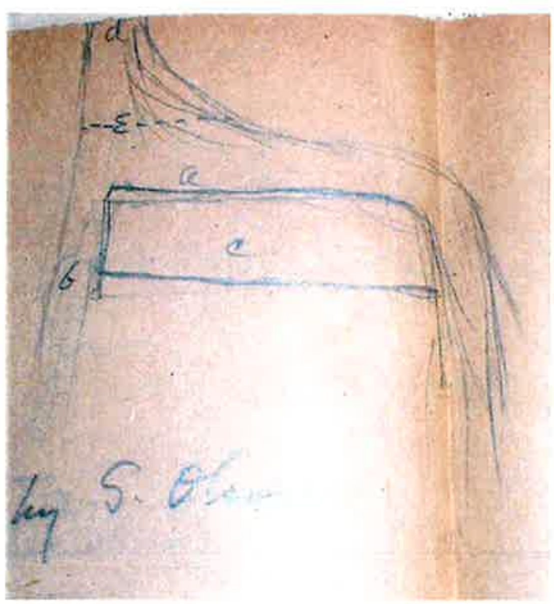


Figure #35: Sam Olson's drawing (March, 1910) of the roots over the back side of the stone. This sketch appears in Newton Winchell's field notebook.

are you sure only is this the explanation for the white veinlets?

Interpretations

1. The white lineations on the back side of the KRS are not geologic in origin and appear to have been formed by the roots of the tree under which the stone was found (See figures 10 and 11). The whitened color of the lineations was produced by chemical leaching of iron and magnesium elements from biotite minerals in the stone (See figure 32). The organic-based origin of the lineations suggests prolonged contact in the ground with tree roots.

2. There is an obvious discrepancy between the much larger size of the flattened root described by the witnesses and the ½" (13 mm) maximum width of the white lineations. It is interpreted that the leaching occurred when the roots where relatively young and smaller in size. The highly active immature ends of the roots seek out nutrients through chemical reactions. Recent research suggests that ectomycorrhizal fungi mobilize essential plant nutrients directly from minerals through the excretion of organic acids (Van Breeman and others, 2001). As the leading ends of the roots grow downward into the ground, the nutrient-seeking phase of that part of the root ends. A bark then grows gradually around the root and its diameter increases with age.

3. The indentations and curved fractures and along the edge of the stone that contains the last three lines of the inscription appear to indicate purposeful impacts (See figures 14 and 15). The stone was apparently shaped or "dressed" prior to the carving of the inscription.

4. The white gypsum coatings observed on the top of the split side of the stone within rune grooves and word separators are likely the remnants of plaster from casts of the KRS that were reportedly made in the 1940's by the Smithsonian Institution in Washington, D.C.

Thin Section Analysis

Thin sections were cut from the core sample to properly identify the constituents of the stone. A glass slide was epoxied to the polished surface of the core at the ½" (13 mm) depth. The core was then cut off and the slice of rock attached to the slide was ground down to a thickness of approximately 25 microns. The section was placed under a polarized light microscope and examined under polarized transmitted light.

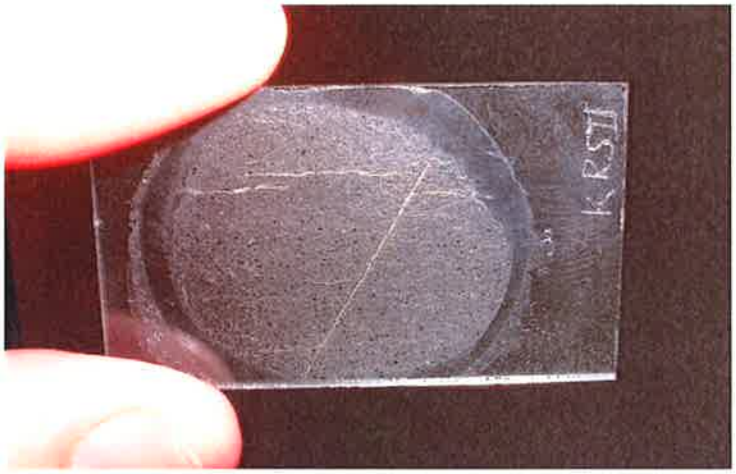


Figure #36: One of the thin sections made by cutting slices from the core sample. The core sample was examined for identification of the constituent minerals.

The mineralogy of the metagreywacke was documented by combining point counts of two thin sections (300 points on each) cut from the core sample and comprised of the following constituents (*personal communication, R. W. Ojakangas, 2003*):

Mineral	Estimated Percentage
1. Muscovite-sericite	22.3
2. Quartz	20.5
3. Felsic volcanic rock fragments	18.0
4. Quartz-feldspar-mica (fine-grained)	14.7
5. Orthoclase feldspar	7.3
6. Chlorite	7.0
7. Biotite	5.5
8. Plagioclase	2.5
9. Leucoxene	1.3
10. Pyrite	0.7
11. Calcite	0.3
12. Hematite-magnetite	0.2
Total	100.0

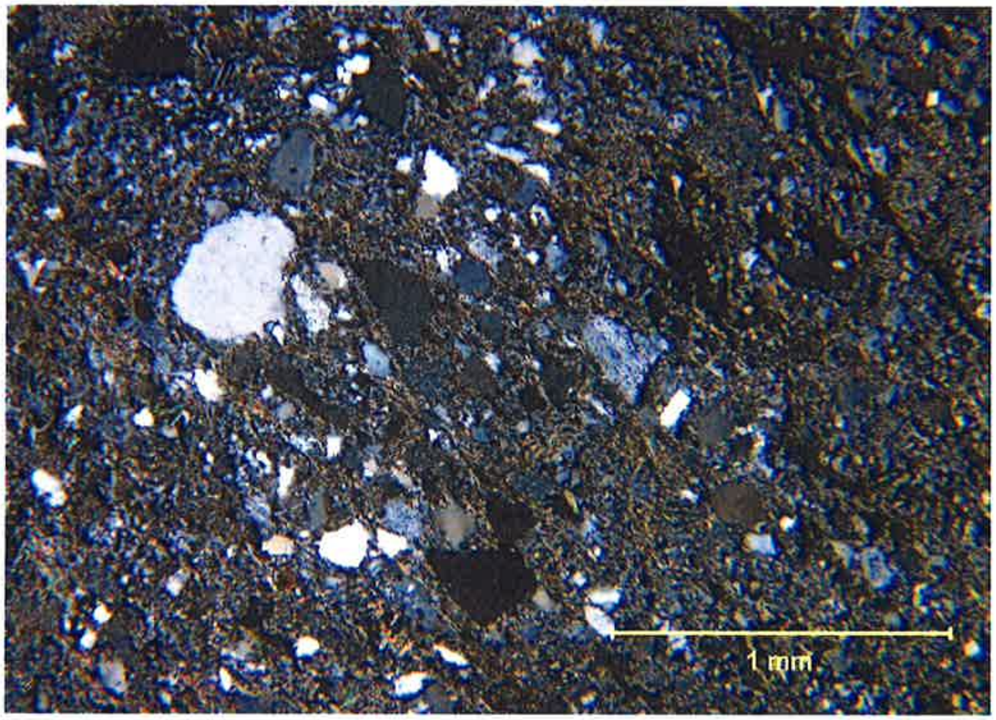


Figure #37: Angular quartz, orthoclase and plagioclase sand grains are visible under cross polarized light.

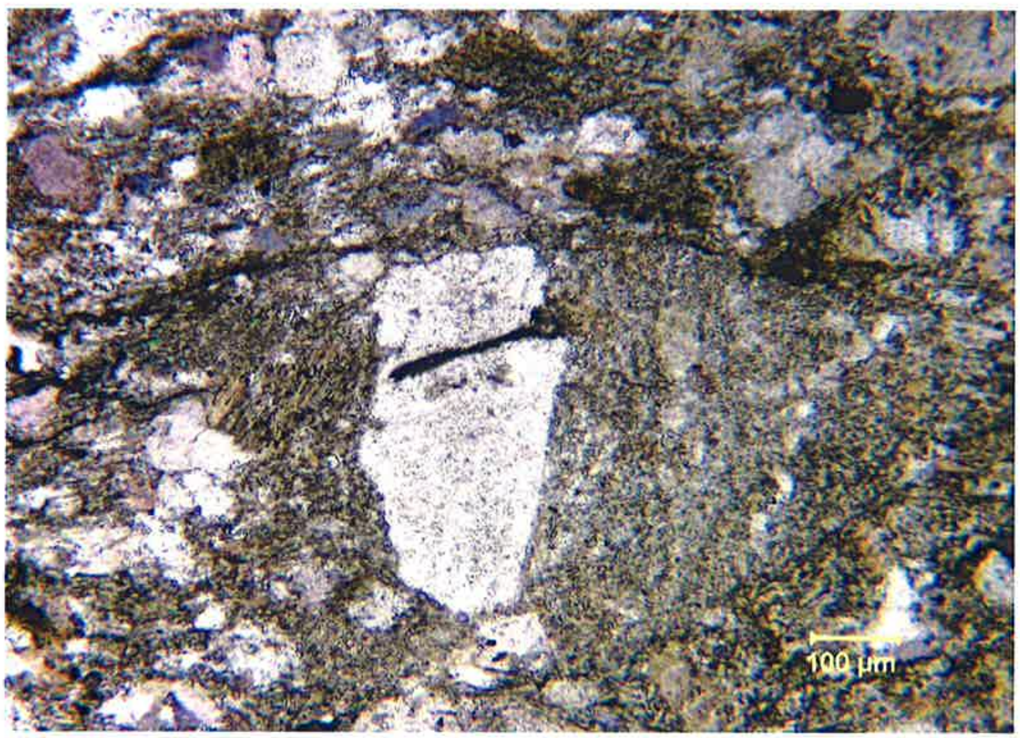


Figure #38: Rock fragments, like this porphyritic felsic volcanic clast under plane polarized light, comprise roughly 18% of the KRS.

The KRS is fine-grained metasedimentary rock called a metagreywacke. The stone exhibits a strong preferred orientation of very fine-grained mica minerals (biotite, muscovite and chlorite). A second, less obvious preferred orientation of micas suggests the stone was subjected to two different metamorphic events. This two-directional foliation of the mica minerals is a unique and diagnostic feature of the KRS metagreywacke.

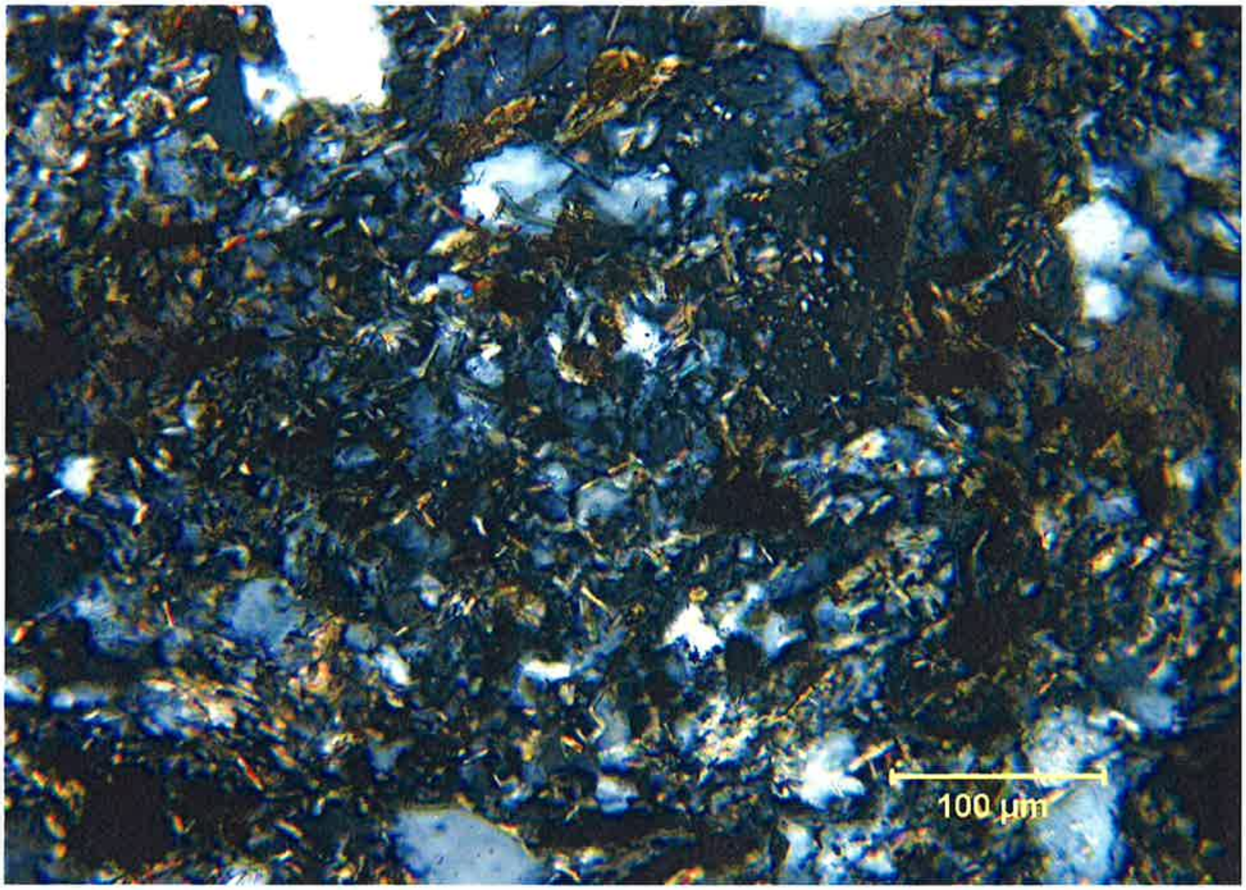


Figure #39: Elongate muscovite mica grains under cross polarized light are aligned in two directions at roughly 90 degrees to each other indicating two metamorphic events that are unique to the KRS metagreywacke.

In the spring of 2003, Dr. Richard Ojakangas, Professor Emeritus of Geology from the University of Minnesota Duluth, examined thin sections of the KRS and compared them with samples of other metagraywackes in an attempt to identify the likely bedrock source. Professor Ojakangas generated a triangle diagram where he plotted the percentages of quartz, feldspar and rock fragments of the KRS and compared it with other metagraywackes. His conclusion was that the source of the metagraywacke upon which the runes were carved probably is the Paleoproterozoic Animikie basin of East-Central Minnesota, 1.85 to 2.1 billion years.

Or did not conclude that the KRS was not Archean and therefore must be Paleoproterozoic ?

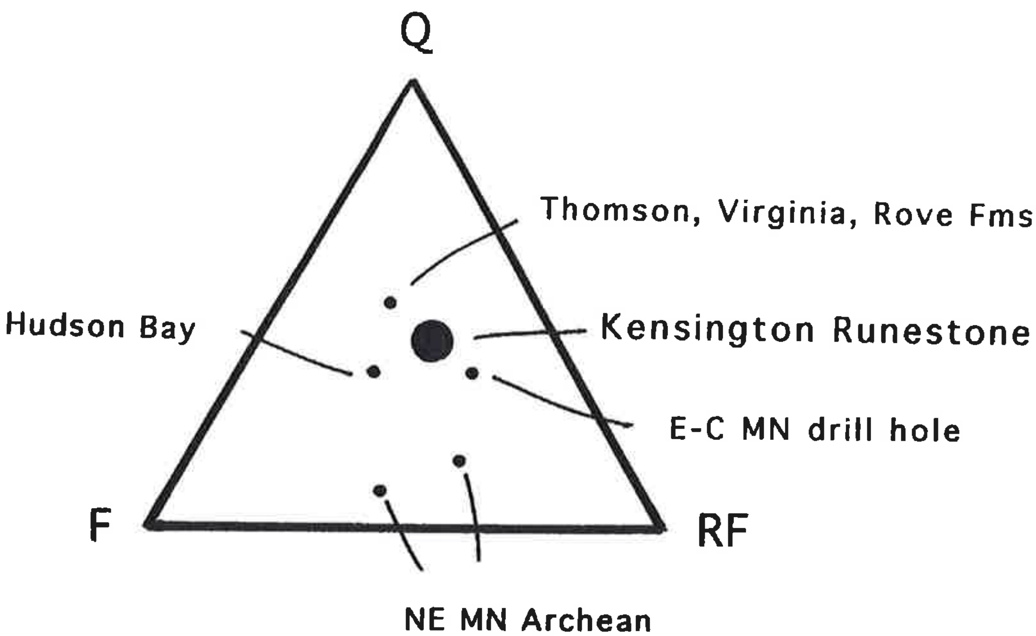


Figure #40: A triangle diagram that plots the relative quantities of feldspar (F), quartz (Q) and rock fragments (RF). The KRS plots close to metagraywackes from the Paleoproterozoic Animikie basin in East-Central Minnesota.

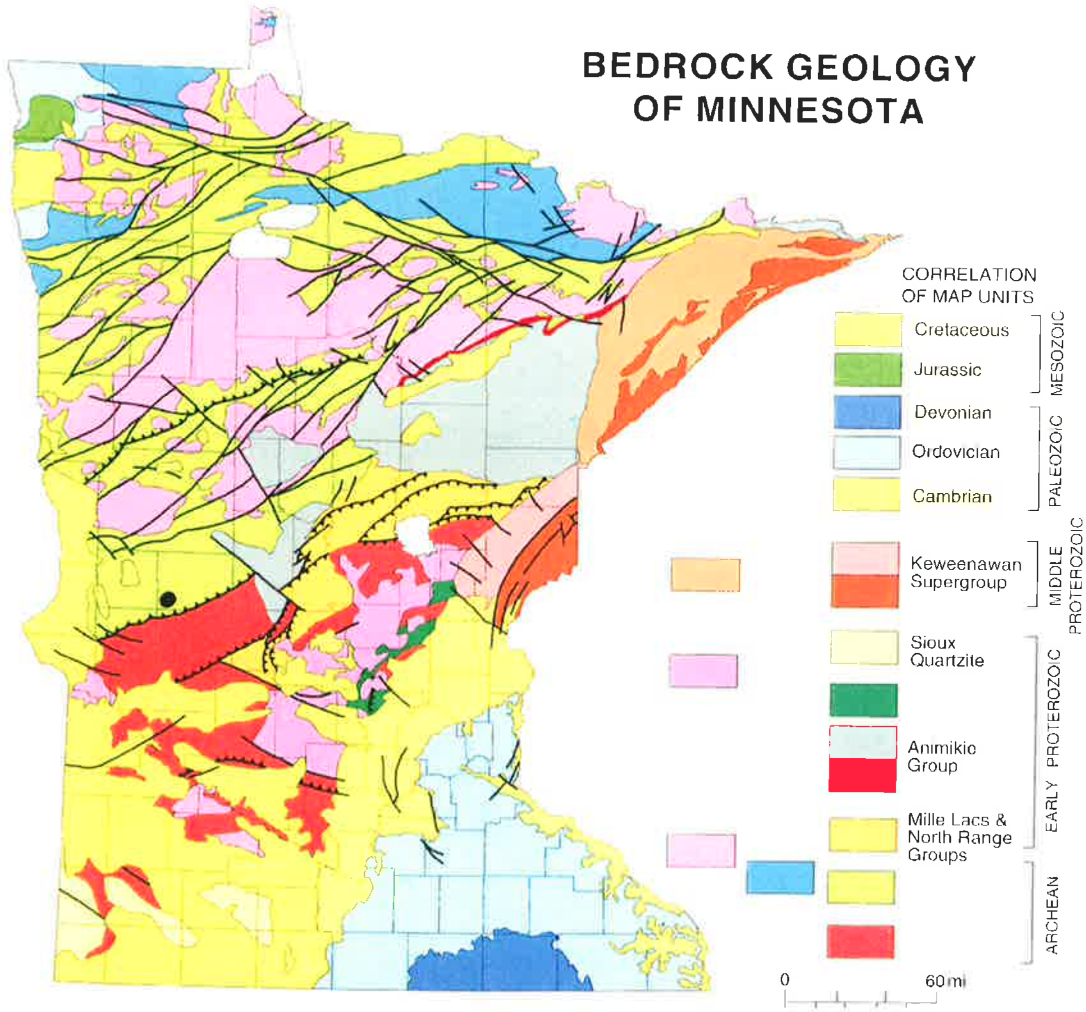
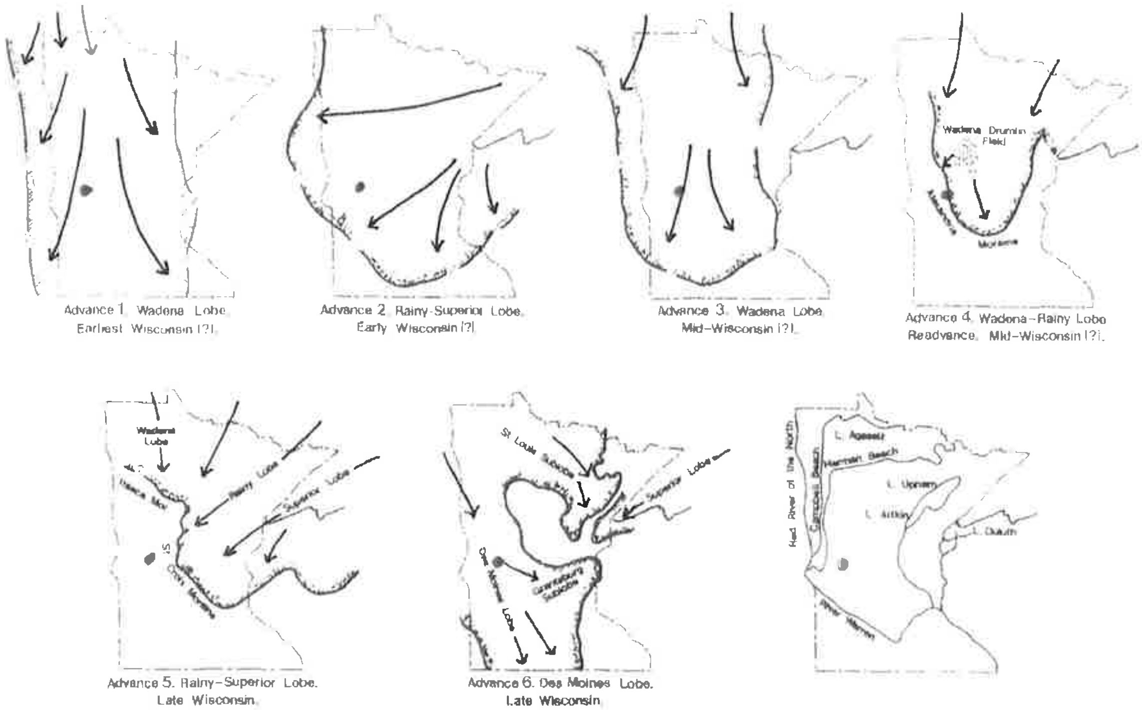


Figure #41: A geologic map of Minnesota shows the Animikie Group rocks, an interpreted likely source of the KRS, located east and northeast of Kensington (black dot). Map by Minnesota Geological Survey, 1997, modified from Morey, G. B., Compiler, 1996.



[illegible] Summary of ice activity during the Wisconsin glaciation as reconstructed from the distribution of glacial sediments and landforms. Dates are approximate. (After Wright [illegible].)

OJAKANGAS & MATSCH, 1982

Figure #42: During the Wisconsin age glacial period, the general trend of the flow of ice was toward the south and southwest. It is quite reasonable for the KRS to have originated from the Animikie basin, which is located generally "up-ice" from Kensington (orange dot).

Split Side Chip Sample

To gain a better understanding of the weathering features of the original inscription, an additional sample was required for analysis. Since the entire split side of the stone was likely created at the same time as the original inscription, this surface has experienced the same amount of weathering. Therefore, a sample taken from anywhere along this surface should yield similar weathering information. A ½" (13 mm) x ¼" (6.5 mm) x 1/8" (3.25 mm) thick chip sample was obtained from the split side of the KRS using a hammer and chisel.

Figure #43: Location of the chip sample obtained from the split side.

Scanning Electron Microscopy

The next phase of the testing program involved reviewing the core and chip samples using scanning electron microscopy (SEM) and energy-dispersive x-ray microanalysis (EDX). The equipment used is located in the Materials Laboratory at Iowa State University in Ames, Iowa. This microscope has low vacuum capabilities and does not require the use of a gold, carbon or nickel coating of the samples. The samples were put directly into the chamber and analyzed. The first surfaces analyzed were the bottom of the core and the back side of the chip where they had been broken off the stone. These freshly fractured surfaces exhibited clean and un-weathered minerals that also represent the original man-made surfaces at the time they were carved.

The top of the core sample was then examined in the areas adjacent to the white lineations. These surfaces represent a glacial aged surface that has experienced at least 12,000 years of weathering. These surfaces exhibit fine-grained, uneven pitting with angular projections of exposed quartz and feldspar grains. Noticeably absent were any of the bladed micas grains that have long since weathered away. This advanced stage of weathering is in sharp contrast to the mica-rich freshly fractured surfaces.

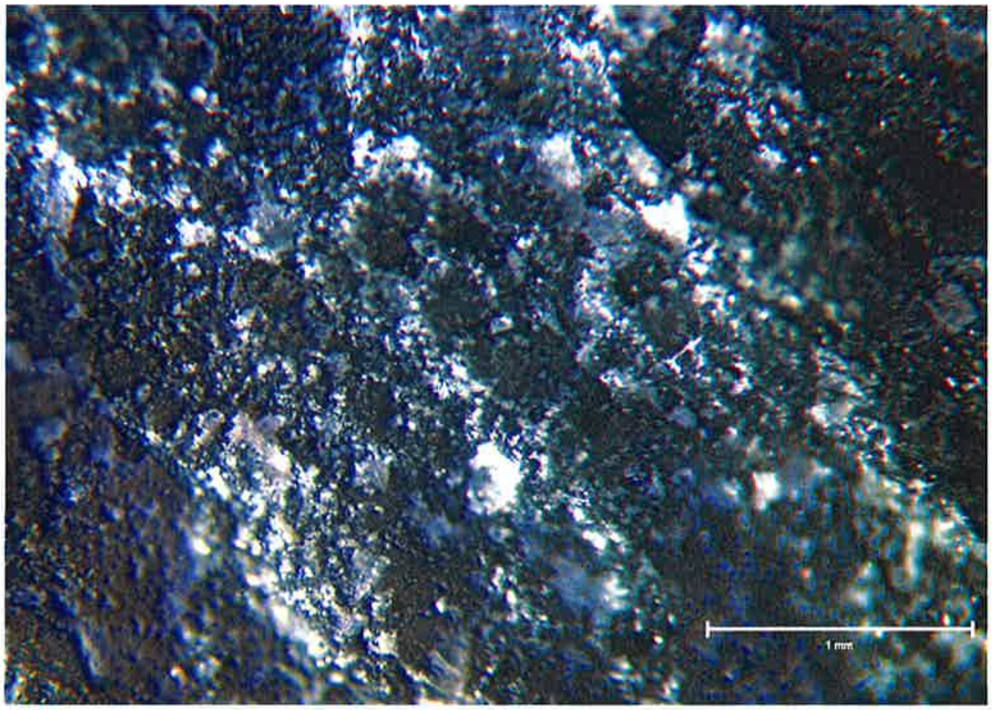


Figure #44: The freshly fractured surface on the bottom of the core sample shows several white clusters of crushed minerals under reflected light.

mica "books" looking down "c"-axis

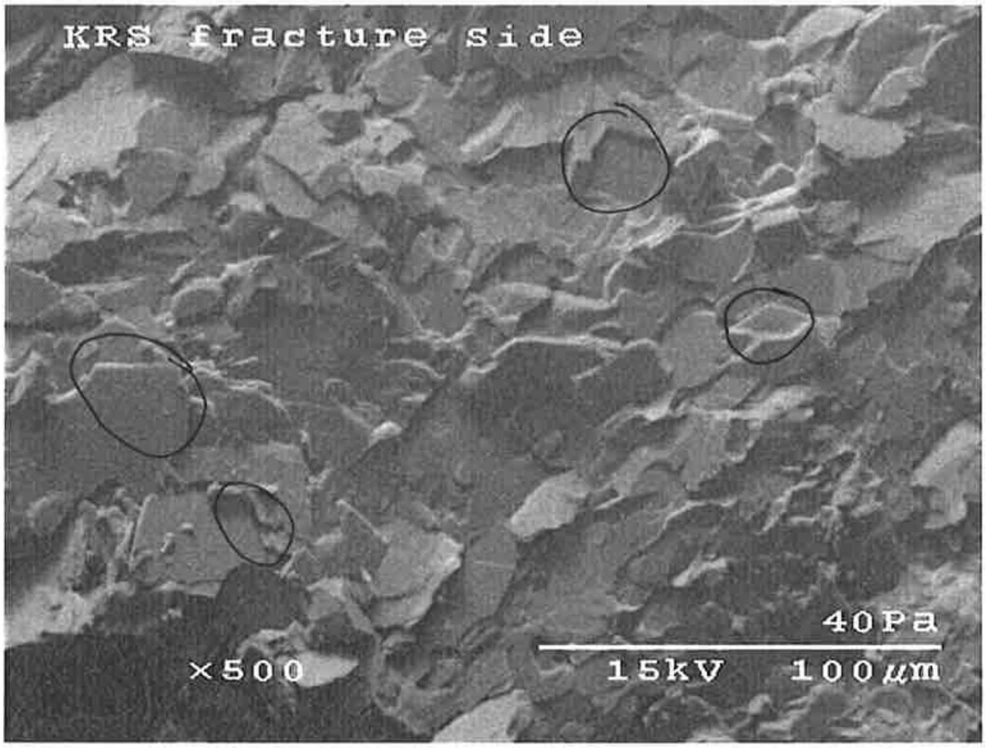


Figure #45: An SEM photograph shows numerous blade-shaped biotite and muscovite mica minerals on the freshly fractured surface on the back side of the chip sample.

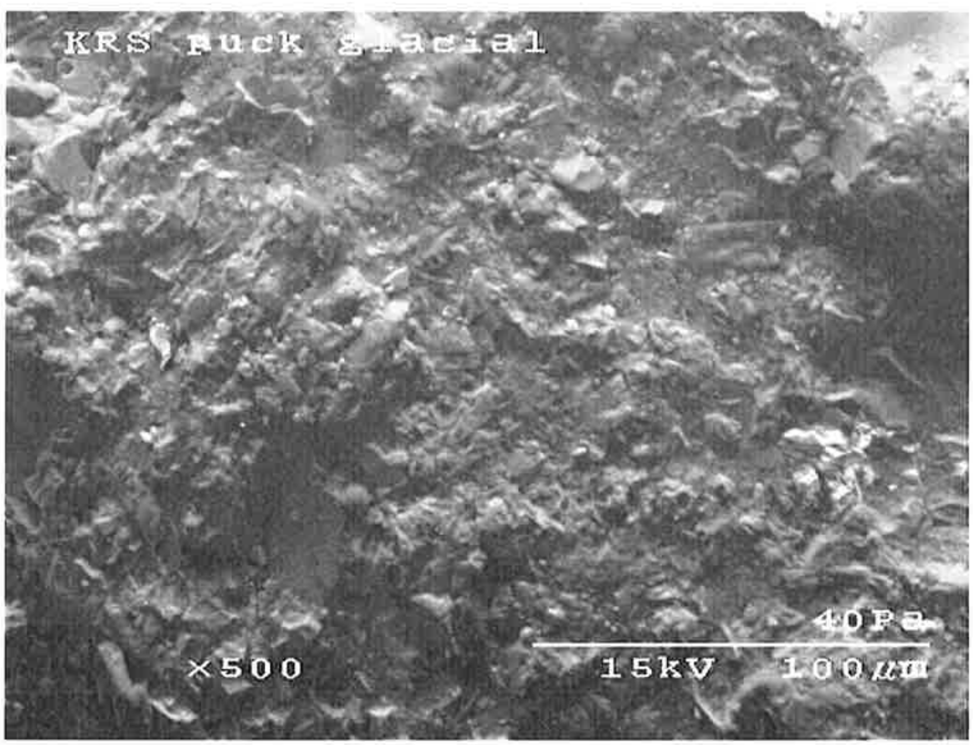


Figure #46: SEM photograph of the glacial top surface of the core that has experienced at least 12,000 years of weathering. Note the absence of the bladed mica minerals.

difference in size - "c" axis books etc.

Lastly, the chip sample was examined with particular attention paid to the state of the mica minerals that were exposed when the split side of the stone was made. The mica minerals were not observed on the surface of the chip, indicating that they had also weathered away completely.

important point that Figs 45-46-47 all have the same orientation relative to the stone

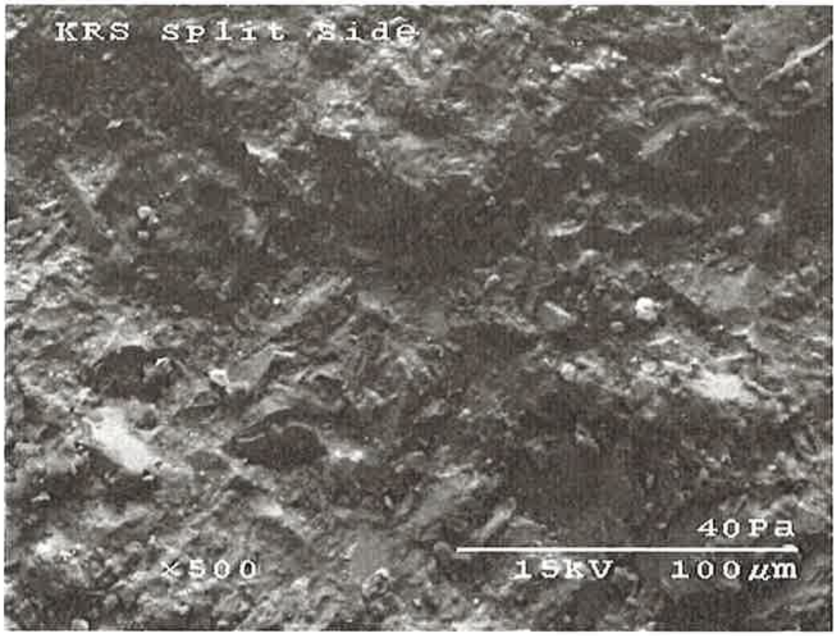


Figure #47: An SEM photograph of the split side of the KRS where the mica minerals have completely weathered away.

The important question is how long did it take for the micas minerals to weather away? One way to try and answer the question is to analyze samples containing micas that have been weathering for a known period of time. The results of such a study would put a time-line on the decomposition of these minerals. One approach is to obtain samples from tombstones of various ages that contain the important mica minerals.

The Tombstone Study

I'm glad!

In March of 2003, 23 chip samples from slate tombstones were collected, with permission, in the Hallowell Cemetery in Hallowell, Maine. The tombstone death dates ranged from 1796 to 1865. This gave a range of 138 to 203 years that the slate tombstones were exposed to roughly similar weathering conditions. The following is an important list of criteria for the testing program that will give the most meaningful data:

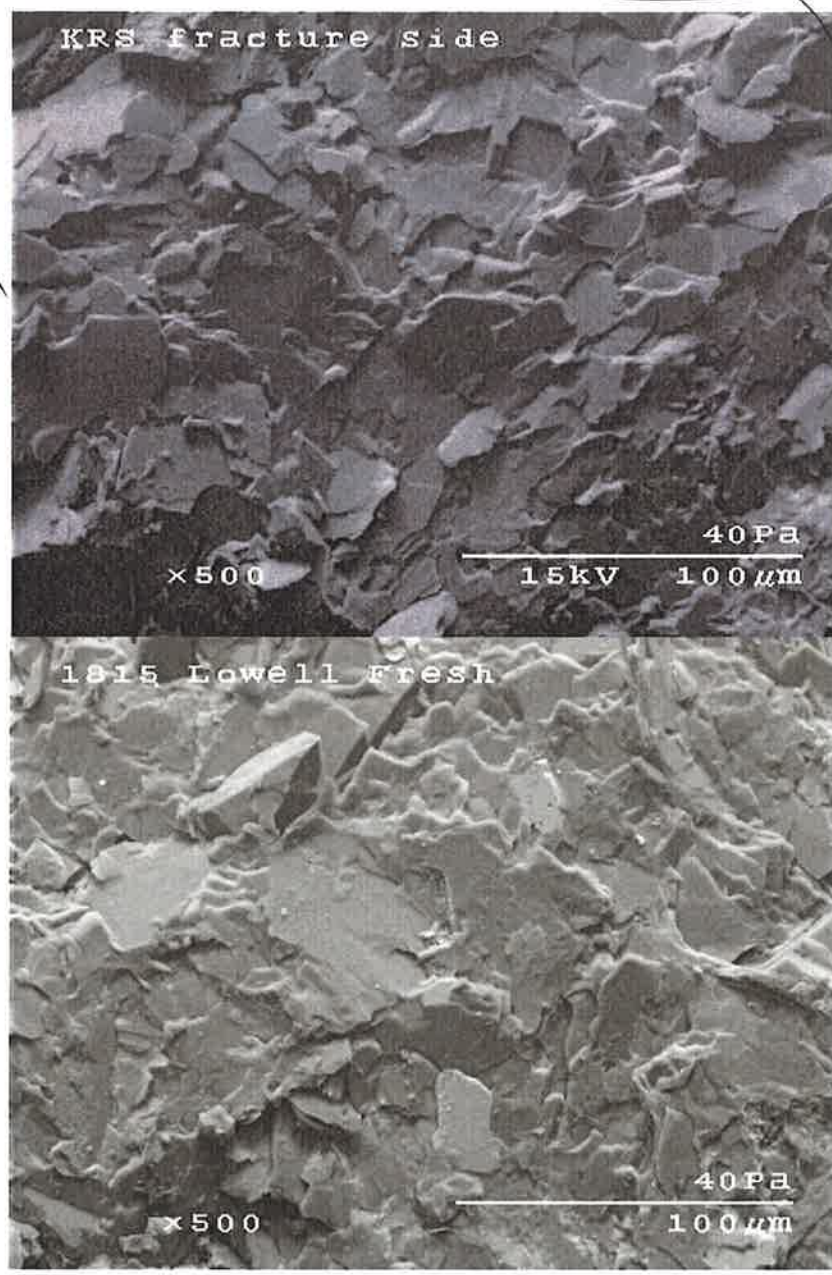
1. In general, if all other conditions are the same, the smaller the size of the mineral, the faster the weathering rate. The micas minerals in the slate tombstones must have the same average grain size as the KRS micas. 3 of the 23 samples obtained had a comparable mica grain size. The samples were identified as follows:

Sample Number	Decedent	Death Date	Years of Surficial Weathering
1	Richard Dummer	1806	197 Years
3	Gorham Dummer	1805	198 Years
22	Abner Lowell	1815	188 Years

1815
188
2003

The average age of weathering of the three samples was 194.3 years.

1806
197
2003



same as Fig 45. slightly different reproduction scales

Its picky but when you get this precise, I assume, or you assume that stone was placed shortly after death. I would simply say 194 years or some such

193 ± 5

Figure #48: SEM images of the KRS micas (biotite, muscovite and chlorite) above and the Lowell tombstone mica (biotite) below. The mineral grain size in the two samples is about the same.

2. The weathering environment where the test samples were obtained must be comparable to the environment where the KRS was found. The climate in Hallowell, Maine is quite similar to the climate ~~in the~~ at Kensington, Minnesota ~~area.~~.

3. The samples should be obtained from both above-and below-grade. Only above-grade samples were collected because the ground was frozen and covered with a foot of snow.

4. The chip samples were examined using both reflected light microscopy and SEM at magnification up to 5000x.

5. The geochemistry of the samples was documented using elemental mapping and X-ray diffraction analysis.

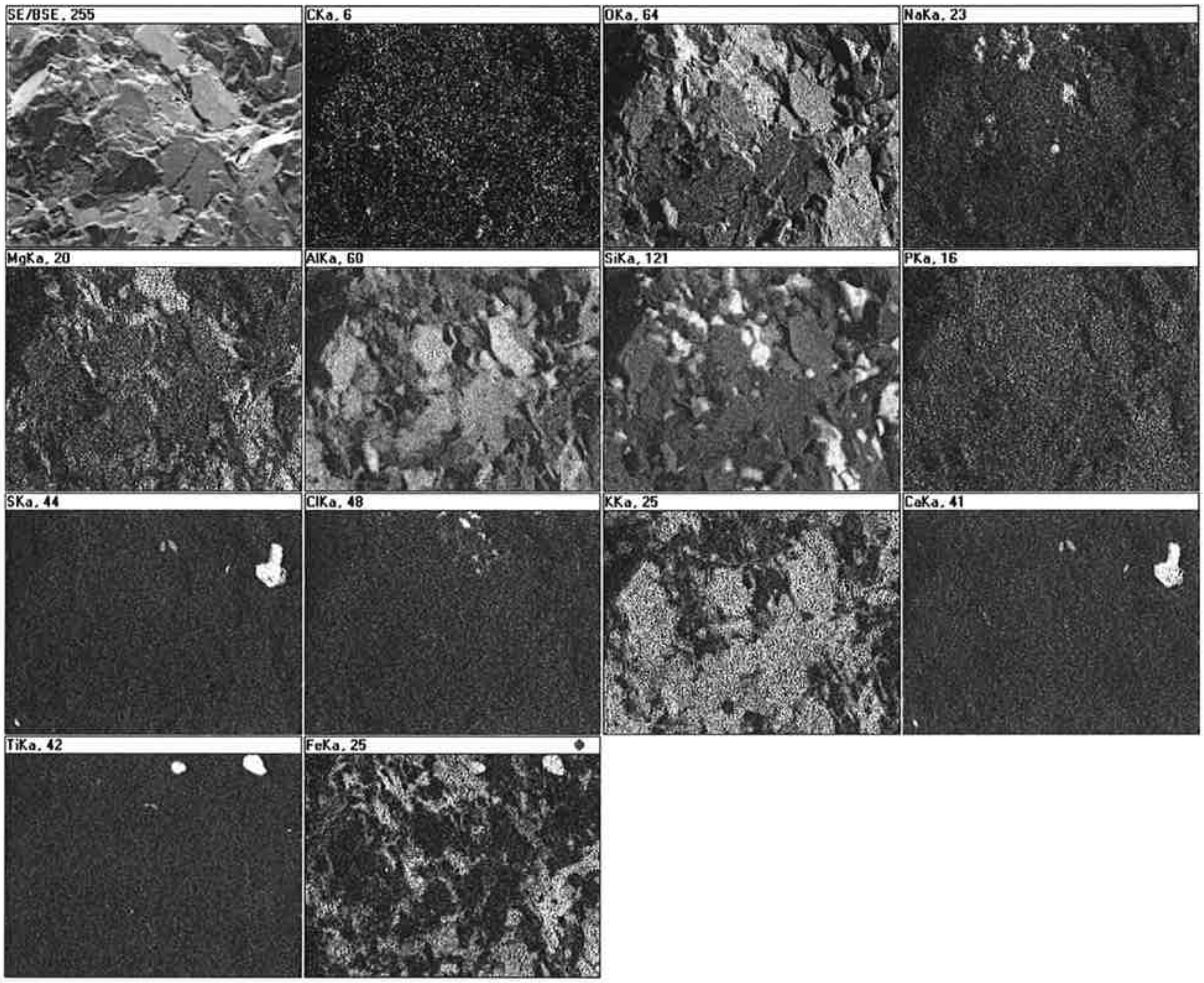
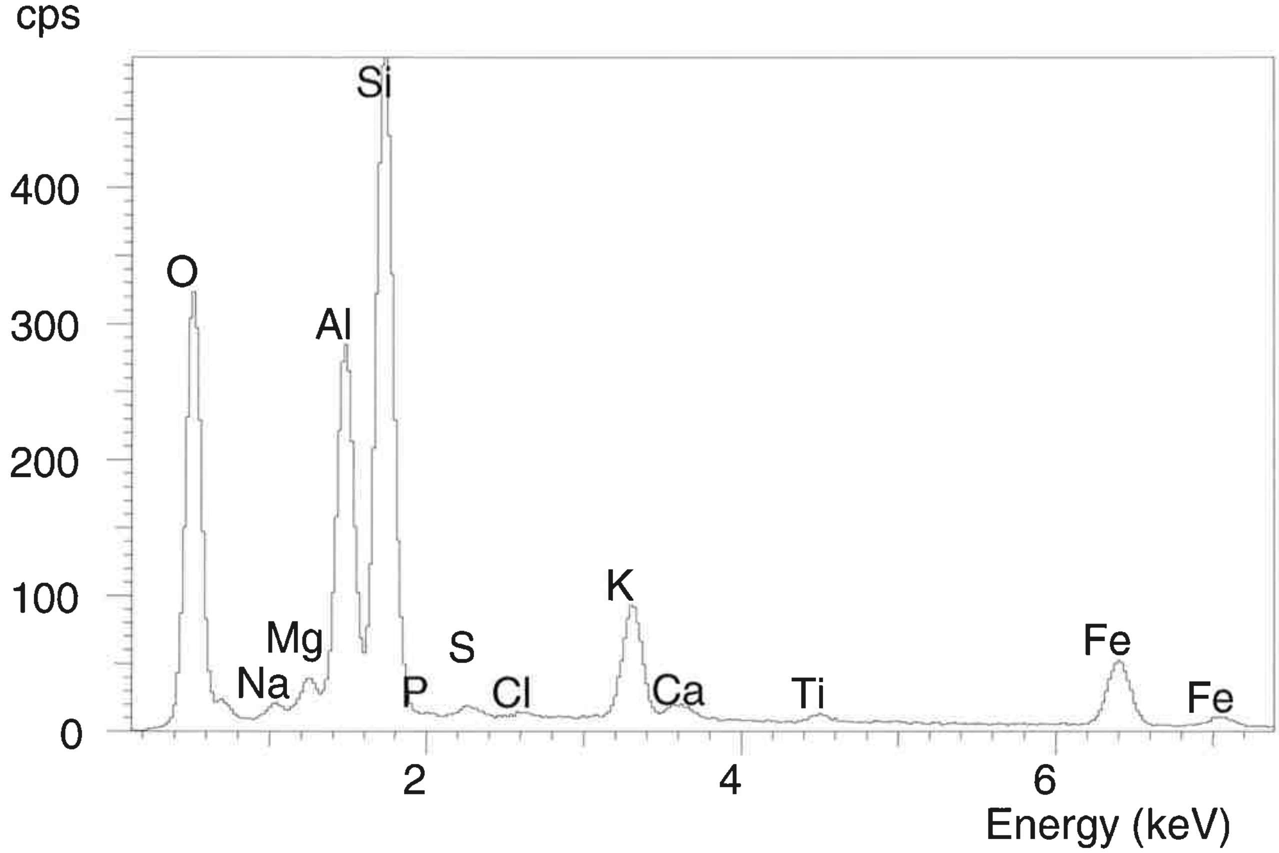


Figure #49: 1815 Lowell Fresh Surface at 500X

An elemental map highlights the selected elements of a freshly fractured surface of a tombstone chip sample. The backscatter image being mapped is in the upper left-hand corner. The relative brightness of areas in each panel is impacted by the relative quantity of a given element as well as its atomic weight. The elements selected for this particular map were carbon (C), oxygen (O), sodium (Na), magnesium (Mg), aluminum (Al), silicon (Si), phosphorous (P), sulfur (S), chlorine (Cl), potassium (K), calcium (Ca), titanium (Ti), and iron (Fe).



1815 Lowell Fresh at 500X

Figure #50: An X-ray diffraction analysis spectra for the mineral biotite, which was obtained from a tombstone chip sample.

Figure #51: The Theresa Stratton tombstone (1802) and the equipment used in sampling. The climate in Hallowell, Maine is comparable to Kensington, Minnesota. Because of the snow and frozen ground, only above-grade samples were obtained.

Figure #52: Tombstone chip samples being loaded into the SEM sample chamber.

In general, the individual letters, numbers and images of the inscriptions looked very sharp and exhibited very little visual weathering overall. However, of the approximately 100 slate tombstones reviewed that ranged from about 150 to 200 years is age (based on the death dates), the weathering features of the slabs overall, consisted of the following:

1. Delamination along cleavage planes aligned sub-parallel to the faces of the tombstones.

2. Roughly parallel, linear fractures at various orientations across the tombstone faces.

3. Exudation of secondary minerals from within the fractures.

Figure #53: White-colored secondary deposits exuding from sub-horizontal fractures traversing the face of a slate tombstone.

4. Intermittent iron oxide staining on exposed surfaces.

Microscopic review of the slate chip samples under reflected light revealed a considerable difference in color between the freshly fractured areas as opposed to the weathered surfaces. The weathered surfaces are dark gray in color and have a somewhat smoother texture.

Figure #54: Sub-parallel fractures and rust-colored iron-oxide deposits on the face side of the Richard Dummer (1806) tombstone.

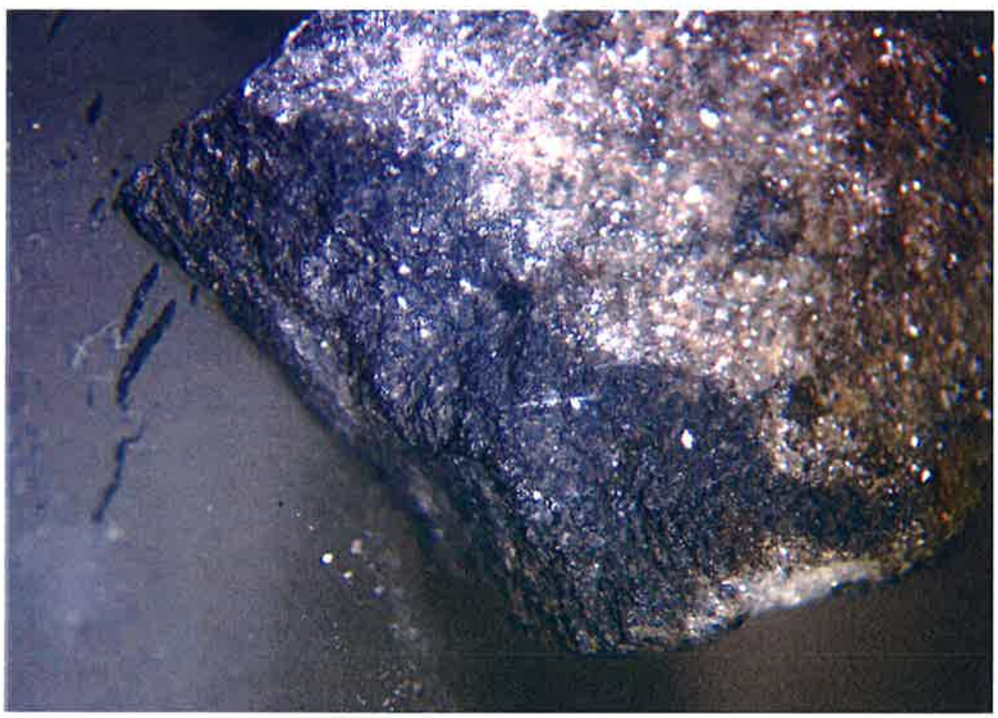


Figure #55: The Abner Lowell (1815) chip sample showing the dark gray weathered area at left, and the light gray freshly fractured area to the right.

The weathered surfaces of the three chip samples when examined in the SEM exhibited several features that were consistent with decomposition of the incipient biotite mica. In general, the biotite grains exhibited both chemical and physical degradation. It appears that before the biotite completely weathers to vermiculite, individual sheets exfoliate off the surface of the stone. In roughly 200 years of weathering biotite minerals exhibited the following characteristics:

1. The edges of multiple sheet clusters or "books" of biotite mica begin to expand and separate. as the mineral hydrates -- I suspect the frayed stuff is hydrobiotite

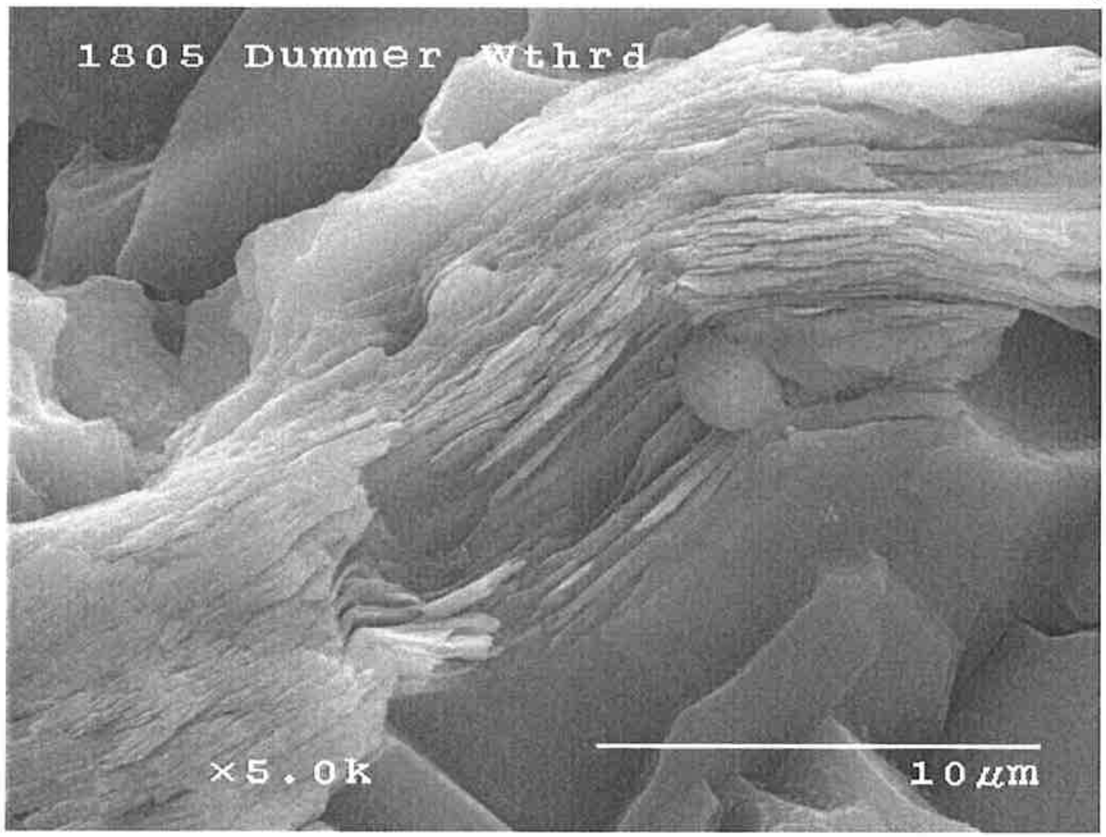


Figure #56: The edges of individual sheets of clustered biotite begin to expand and separate on the weathered surface of a slate tombstone after 200 years.

2. Individual mineral edges become rounded and frayed.

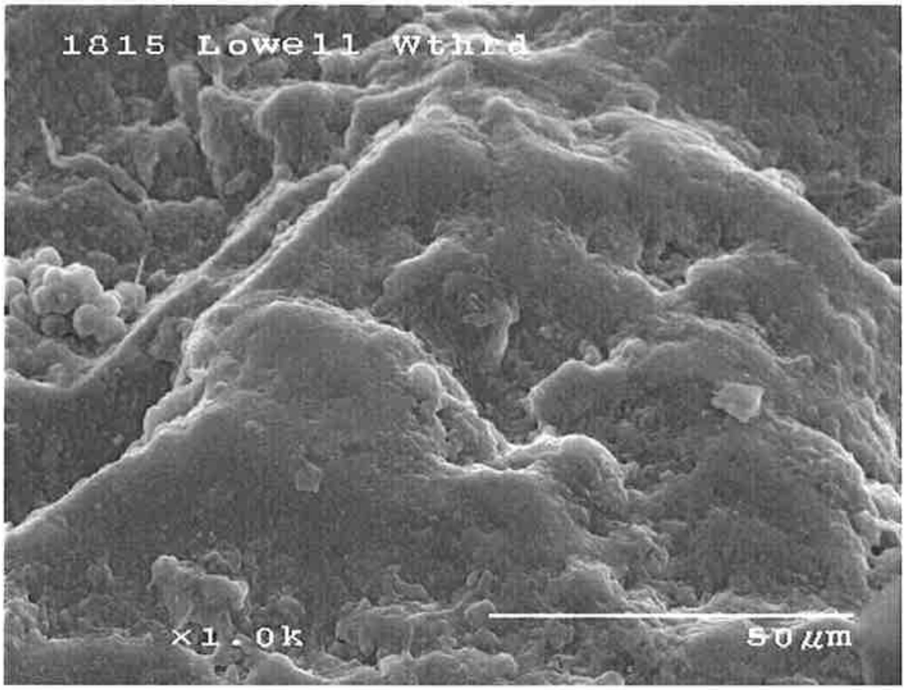


Figure #57: Rounded and frayed edges of biotite mica grains on the weathered surface.

3. Pitting develops on the basal surfaces.

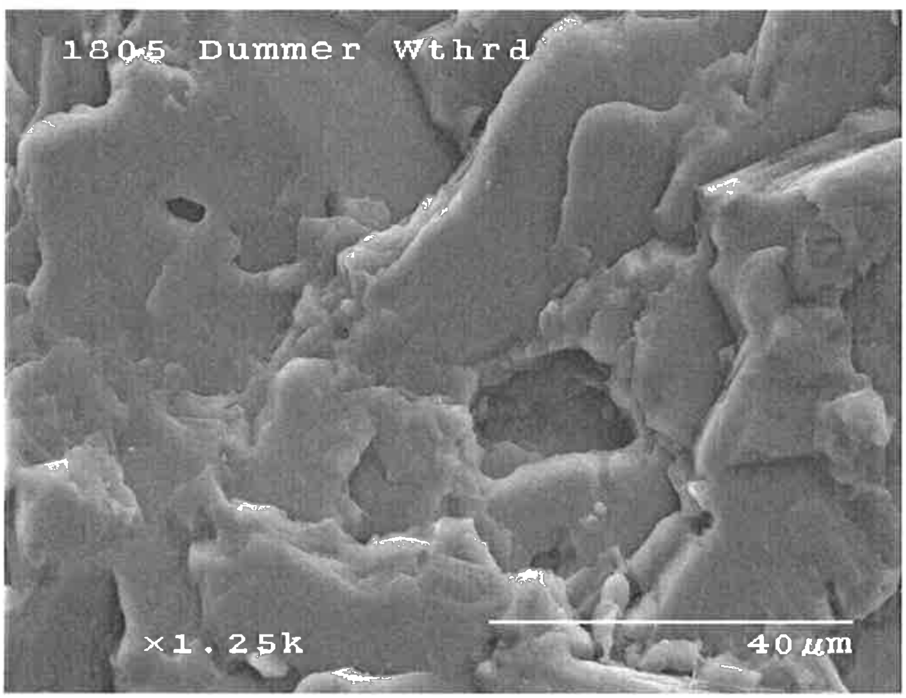


Figure #58: Large-and small-scale pitting was observed on the basal surfaces of weathered biotite grains.

4. Individual sheets of biotite begin to exfoliate off the weathered surface of the slate tombstone.

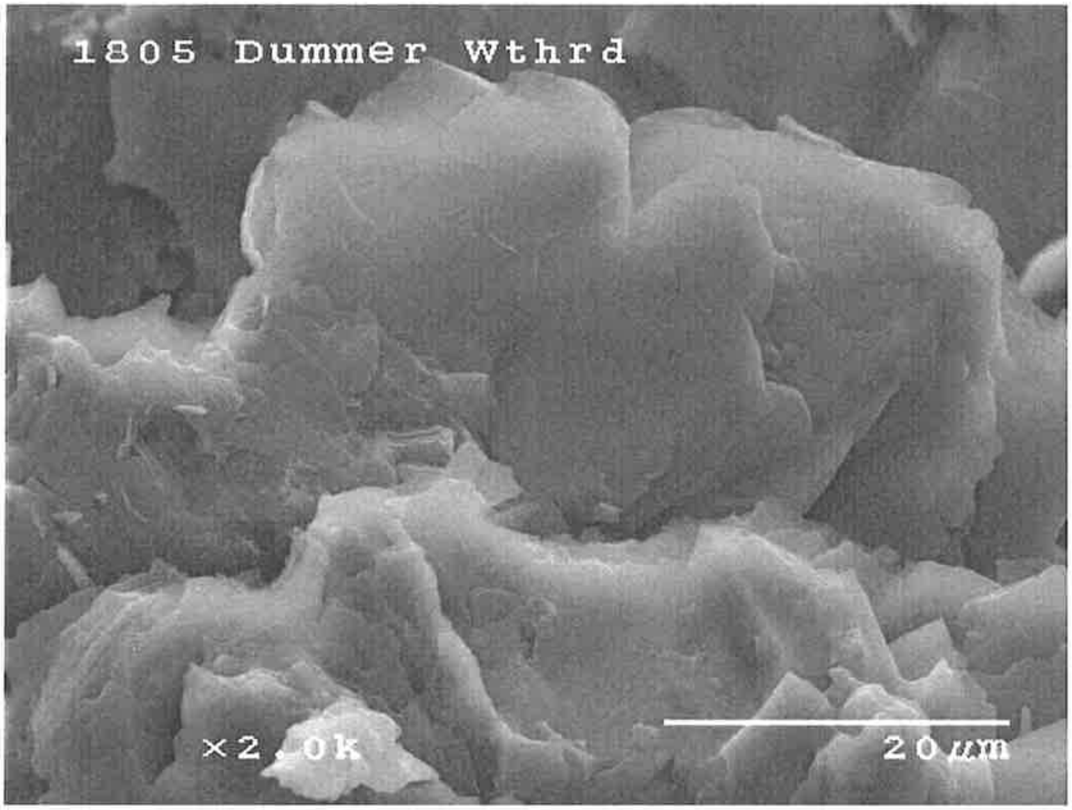


Figure #59: Individual sheets of biotite exfoliate off the weathered surface of the slate tombstone.

5. Acid produced by lichen on the surface of the tombstones accelerates dissolution of biotite grains at an unknown rate. The amount of lichen development on slate tombstones is an important parameter in understanding the rate of weathering.

Another factor of weathering that we need to be mindful of is that the Hallowell Cemetery is located within a few yards of the railroad. Localized acid rain conditions were produced by the exhaust from the sulfur-laden coal of steam engines over a period of 200 years. This would certainly accelerate the weathering of all of the tombstones in the cemetery. Ironically, the slate tombstones are closest to the railroad. Even though we observed exfoliation of some biotite grains after 200 years of weathering, the vast majority of the minerals were still intact.

Interpretation

When we compare the tombstone data with the weathering of the original man-made surfaces on the KRS, a statement about the relative age of the inscription is possible. Based on the results of this initial round of tombstone sample testing, the weathering features of the original man-made surfaces (this includes the runes, flaked areas, the "Oh Shoot" area and the entire split side) on the Kensington Rune Stone took longer than 200 years to develop.

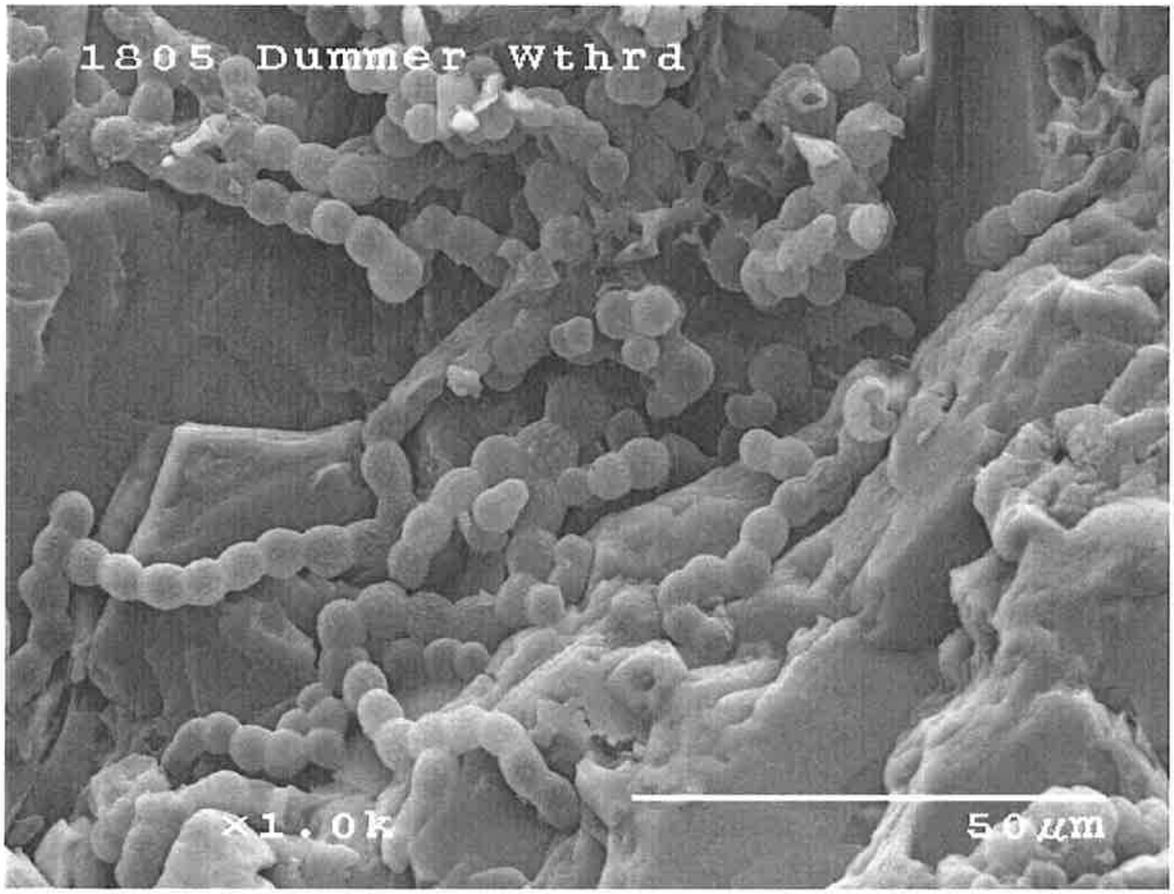


Figure #60: Tiny worm-like beads of lichen partially cover the surface of a slate tombstone. Acid produced by the lichen accelerates the weathering rate of biotite mica.

It should be noted that although the dissolution of sheet silicates, including biotite, have been studied for decades, there are numerous new research opportunities. It is hoped that this ongoing tombstone research will add to the understanding of the weathering characteristics of not only micas, but other minerals as well.

Conclusions

Based on our observations, test results, research and past experience, the following conclusions are appropriate:

1. The KRS is a tabular-shaped, dark gray, metagraywacke glacial erratic boulder of Archean age (roughly 2.7 billion before present). The back side of the stone exhibits very pronounced, roughly parallel, glacial striations.

2. Several curved fractures along one edge of the stone were produced by purposeful man-made impact. The previously larger-sized stone was shaped, or “dressed,” prior to the inscription being carved.

3. Approximately 95% of the runic inscription was cleaned out with a nail shortly after its discovery. This "retooling" removed weathering features from the bottom of the carved grooves and crushed the constituent minerals, which turned these surfaces white. This "fresh" appearance of the inscription has led to confusion and mis-interpretation of the relative age of the inscription. Several runic characters in the last three lines of the inscription on the side of the stone were not retooled and exhibit original weathering features.

4. We observed white coatings of gypsum (CaSO4-2 H2O) on several characters on the stone, which are likely remnants of the plaster casts. The Minnesota Historical Society reportedly made several plaster casts of the stone in the 1940's.

5. The glacial back side of the KRS exhibits two, approximately ½" (13 mm) wide, white, undulating and branching lineations. The white lineations were produced when iron and magnesium were leached from minerals in the stone by young tree roots. The pattern of the lineations closely matches the description and sketchs by witnesses (Olof Ohman and Sam Olson), that roots tightly gripped the KRS when it was discovered.

6. Based on comparison with the still actively oxidizing pyrite crystals within the AVM Stone inscription carved in 1985, the completely oxidized pyrite pits observed in the original KRS inscription took longer than 18 years of weathering to develop.

7. Based on comparison of weathering characteristics of the chip samples obtained from slate tombstones, the biotite mica that was exposed at the time of the original inscription on the KRS took longer than 200 years to completely weather away.

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