Field Investigation of the Geology and Possible Pisolitic Bauxite Occurrence at Menemsha Hills Reservation, Martha's Vineyard, Massachusetts

Compiled by Stephen B. Mabee and Peter Panish

Prepared for The Trustees of Reservations

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Additional copies of this report and all accompanying documentation are available upon request by contacting the Office of the Massachusetts State Geologist.

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Authors wish to thank Byron Stone of the USGS for his assistance in interpreting the surficial geology during a field visit in December 2007. We also acknowledge the assistance of Greg Whitmore who helped with logistics, lodging and transportation to and from the field. We thank Steve Nathan and Mark Leckie of the University of Massachusetts who examined samples for microfossils.

Cover: Close up view of ferricrete layer. Picture taken along the beach at Menemsha Hills Reservation on July 30, 2007.

Executive Summary

The Office of the Massachusetts State Geologist was asked by The Trustees of Reservations to make an assessment of an unusual deposit of what appears to be pisolitic bauxite or iron hardpan exposed on the beach at Menemsha Hills Reservation in Chilmark, Massachusetts. The formation occurs as thin 10-20 cm wide lenses extending from 0.5 to 6 meters in length. They are found most commonly along a 200 to 250 meter section of the shore in the intertidal zone. The intact lenses trend northeast at about 25° to 35° and dip at 61° to 75°. The material occurs in a variety of forms. These include hematite and clay rich botyoidal (grape-like) surfaces, as iron hardpan cementing together gravel and pebble-sized stones, and as 1-2 cm wide pisolites (concentrically layered round structures).

Bauxite is typically found in tropical climates and is the primary source of aluminum ore. Kaye (1967) documented the occurrence of pisolitic bauxite fragments in glacial drift on Martha's Vineyard. He postulated that the fragments were carried to the island by the glaciers from some unknown source area on the mainland. The purpose of this work is to determine if this new occurrence of apparently intact material is indeed pisolitic bauxite or something else.

Scanning electron microsope and energy dispersive spectral analysis (SEM-EDS) was conducted on a sample of the pisolitic material. Analyses were carried out on the materials that make up the interior and rims of the pisolites, the matrix and the cement that bridges individual pisolites.

Results suggest that the material is comprised predominantly of silica, iron, aluminum, oxygen and minor amounts of potassium, magnesium and sodium. These data combined with the SEM images suggest that the materials are likely comprised of the minerals hematite, goethite, detrital quartz, muscovite and biotite, and various clay minerals such as kaolinite.

Based on these results, the material does not appear to be bauxite. The deposit is not concentrated enough in aluminum to be considered bauxite ore. There are too many other constituents in the material. Therefore, we suggest that the term pisolitic ferricrete be used instead to describe these deposits. The likely mode of formation is secondary precipitation of iron oxides due to a change in redox conditions as groundwater percolated through the bedding planes in the sediment. Proximity to organic matter may also have played a role in controlling the solubility of the iron in the groundwater.

The age of the ferricrete formation is unknown. However, field relationships suggest that the iron cementation is post-Pleistocene in age and may actually be occurring today.

Contents

Appendix

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INTRODUCTION

The Office of the Massachusetts State Geologist was asked by The Trustees of Reservations to make an assessment of an unusual deposit of what appeared to be pisolitic bauxite or iron hardpan exposed on the beach at Menemsha Hills Reservation in Chilmark, Massachusetts. This field report summarizes the results of that assessment.

Background and Previous Work

Kaye (1967) published a paper in Science documenting four occurrences of pisolitic bauxite in Pleistocene drift on Martha's Vineyard. Three samples were found in Pleistocene deposits in the cliffs at Gay Head and one was found in till deposits in the interior part of the island. In hand specimen these samples exhibited elliptical to spheroidal morphologies with some of the spheres (pisolites) attaining diameters up to 20 cm. None of the samples were considered to be in place but rather were transported by glaciers from some distant source area to the north. It is postulated that these materials were derived from some unknown Cretaceous-age coastal plain deposit on the mainland and may represent the northernmost known occurrence of bauxite in North America (Kaye, 1967).

Bauxite is comprised almost entirely of aluminum oxide/hydroxide. It is the primary source of aluminum ore in the world. It generally forms in subtropical to tropical environments. It is found in laterite soils. These are soils that have undergone considerable weathering where most of the constituent elements have been leached from the soil leaving behind a residuum concentrated in aluminum oxide/hydroxides. The primary minerals associated with bauxite are diaspore, gibbsite, boehmite, some kaolinite and various iron oxides.

Many bauxites have an oolitic or pisolitic structure. These are concentrically layered rounded structures that can be several centimeters in diameter (Figure 1). Large spheres (>a cm across) are called pisolites and those that are much smaller than a centimeter in diameter are referred to as oolites.

On February 2, 2007, the Trustees of Reservations contacted the Office of the Massachusetts State Geologist and asked us to examine samples collected from the beach at Menemsha Hills Reservation to determine the origin of the material. The material observed at Menemsha Hills differed from that reported by Kaye (1967) in that the deposit at Menemsha Hills was found to be in place and undisturbed. In fact, a lens of iron-rich material 6 meters long and 10 to 20 cm in

Figure 1. Example of pisolitic bauxite from Arkansas.
(http://www.newarkcampus.org/professional/osu/faculty/jstjohn/Common%20rocks/Bauxite.htm)

width was exposed along the beach in the intertidal zone (Figure 2)

The Trustees of Reservations collected a representative sample of the material, which our office retrieved for review in April 2007. This was followed by two more excursions to the island to examine the deposits in the field. Dr. Peter Panish and Dr. Stephen Mabee, State Geologist, visited the site on July 30, 2007. A second field visit was made on December 10 and 11, 2007 by the State Geologist and Dr. Byron Stone from the U.S. Geological Survey.

The purpose of these trips was three fold.

1. To examine the geologic setting within which the deposits are found;
2. To document the occurrence of the deposits and collect samples; and,
3. To perform scanning electron microscope analysis on selected samples to determine the general composition of the material.

The results of this work are provided below.

Figure 2. Intact lens of iron-bearing material approximately 10-20 cm wide.

Location of Study Area

Menemsha Hills Reservation is located on the north shore of Martha's Vineyard off of North Road in Chilmark. The entrance to the Reservation is located between Tabor House Road and Menemsha Cross Road. It is a 211-acre preserve with frontage on Vineyard Sound. The study area examined includes the beach and the cliff exposures along the shore. The area of investigation extends from just northeast of Roaring Brook (passed the old brickworks) southwest toward the beach access trail (Figure 3).

GEOLOGIC SETTING

General Geology

The geology of Martha's Vineyard is well studied and has been documented thoroughly by others (Hitchcock, 1841; Shaler, 1890; Woodworth and Wigglesworth, 1934; Kaye, 1964a, 1964b, 1972, 1980, 1983; Oldale and Barlow, 1986; Oldale, 1976, 1980, 1982, 2001). The reader is referred to these sources for a detailed discussion of the geology of the island. All that will be said here is that the northwest and northeast sides of the island form the terminal moraines for the last great continental glaciation that reached its maximum extent in New England about 21,000 years ago. The rest of the island consists of a vast outwash plain of sand and gravel that extends from the terminal moraine southward. Figure 4 shows a generalized geologic map of Martha's Vineyard. This map only shows the distribution of the materials found at the surface.

Although the general geologic history of the island is well known, the number of glaciations and the exact age of the unconsolidated deposits associated with these glaciations continue to be debated (Oldale, 2001). These issues will not be resolved until irrefutable evidence or material that can be dated by laboratory methods is found.

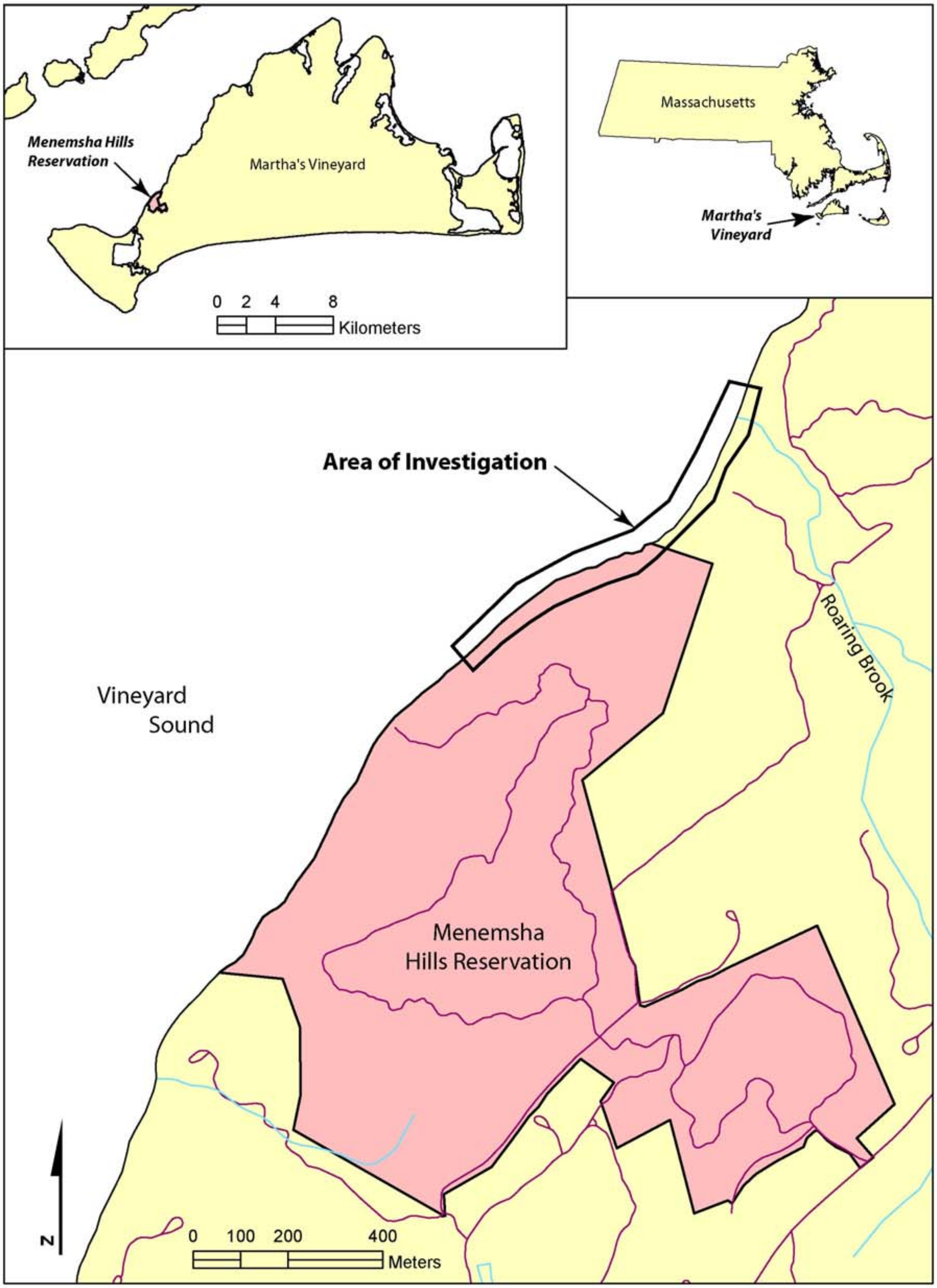


Figure 3. Map showing the location of the area investigated in this report.

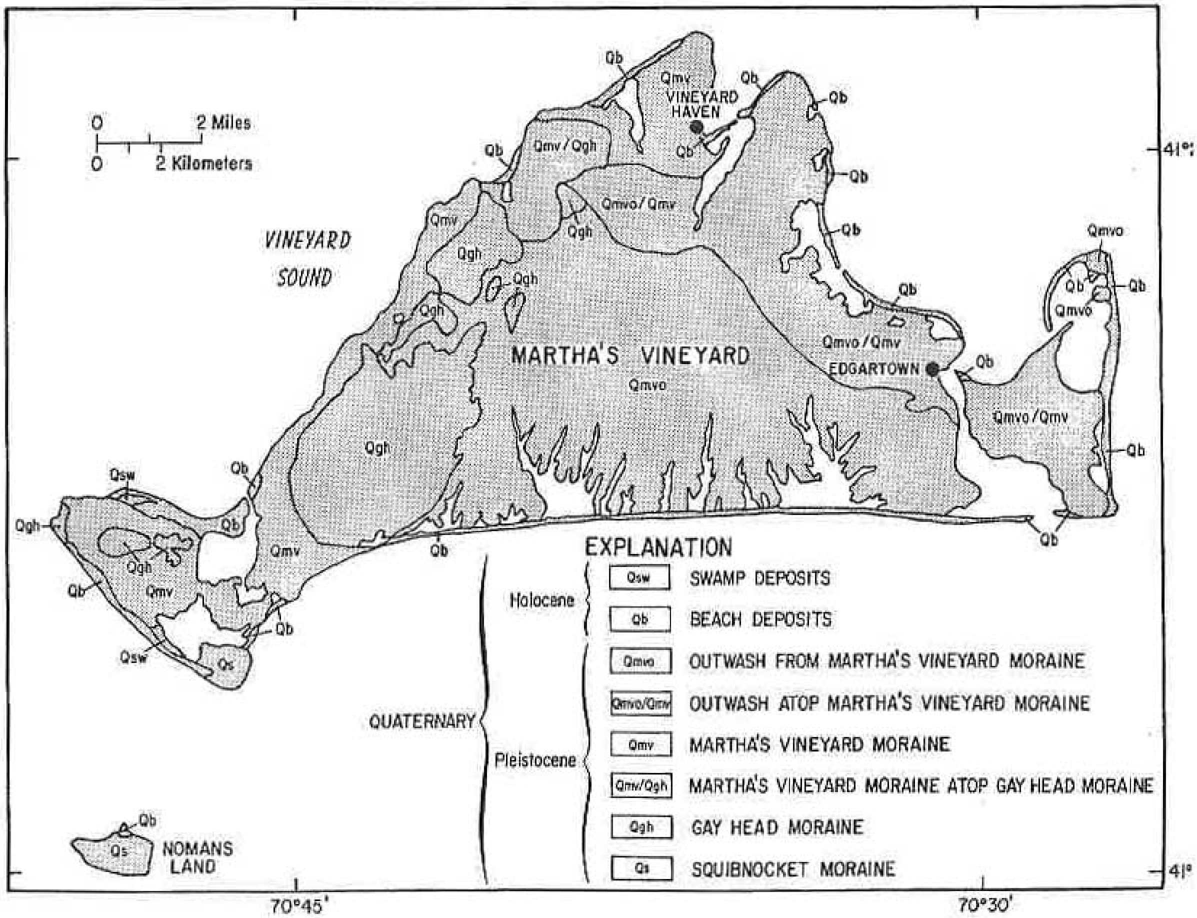


Figure 4. Surficial geologic map of Martha's Vineyard (from Kaye, 1972).

Geology of Menemsha Hills Reservation

The geology at Menemsha Hills Reservation and Gay Head at the southwestern end of the island is complex. What we do know from the literature is that Cretaceous and Tertiary age coastal plain deposits were shoved up from low lying areas in a series of imbricated thrust sheets by the advancing Pleistocene glaciers (Figure 5). Evidence of these thrust sheets is preserved in the cliffs at Gay Head and at least one thrust sheet can be observed in the cliffs at Menemsha Hills Reservation. The thrust fault at Menemsha Hills Reservation dips at approximately 30 degrees to the north (Figure 6). The presumed mechanism for peeling off successive layers of coastal plain deposits is that the colder climate during the ice age froze the sediments allowing them to be displaced in a block-like fashion. Eventually the glaciers overran the thrusted sheets depositing a thin veneer of sandy, bouldery glacial till on top of the coastal plain deposits (Figure 5). Thus, the till deposits rest unconformably on top of the coastal plain deposits.

An examination of the cliffs at Menemsha Hills was undertaken on December 10, 2007 to better understand the vertical arrangement of the various unconsolidated units and to provide a field context for the iron bearing (bauxite) formations observed at the site. Four sites were examined in detail in the cliffs beginning approximately 750 feet northeast of the steps at the access road

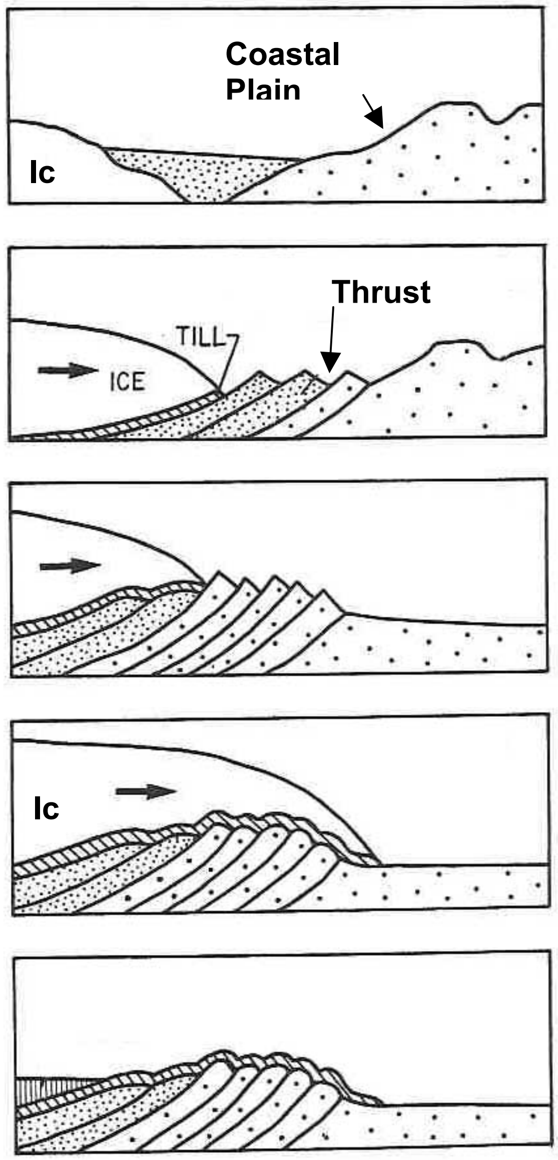


Figure 5. Schematic cross section showing how the advancing glacier produces thrust faulting of sediments ahead of the glacier. The ice eventually overrides the imbricated thrust slices (modified from Oldale, 2001).

by Roaring Brook to a point approximately 950 feet northeast of the beach access trail on Menemsha Hills Reservation property. Figure 7 shows the location of the observation points. Detailed descriptions of each site are provided in Appendix A along with pictures.

Based on these observations the following general stratigraphy was noted and is described from oldest to youngest.

1. Variegated clay – This is the oldest unit observed at the site. It consists of multiple layers of multicolored silty clay. Clays are white, tan, red and brown in color. The age is unknown but thought to be upper Cretaceous based on similar descriptions noted in the cliffs at Gay Head (Kaye, 1983). These units are exposed mostly in the western end of the site beginning just northeast of site 121007-4 (Figure 7) and extending southwest. Glimpses of these units are observed along the base of the cliff. The clays contain iron concretions and are lignitic.

2. White kaolinitic silty sand – This unit lies above the variegated clay and is a non-plastic almost pure white quartzitic silty fine sand. It is exposed at the base of the section near the top of the cliff at site 121007-4 and at the bottom of the cliff by the large flat boulder on the beach at the promontory (Figure 7). Its thickness is unknown but is likely several meters thick.

3. Dark gray to tan clay – This unit rests on top of the white silty sand. The nature of the contact with the silty sand is unknown. The clay unit is observed to be 0.2 to several meters thick. The upper part of the clay is lignitic. Dr. Steve Nathan, a micropaleontologist at the University of Massachusetts, examined the clay for microfossils. No foraminifera were found in the sample. The sample also lacked diatoms, ostracods, sponge spicules, sea urchin spines, bivalve shells, worm casts/tubes or fecal pellets. Dr. Mark Leckie, another micropaleontologist at the University of Massachusetts, confirmed the lack of microfossils. The sample did show substantial glauconite suggesting a marine origin. Mark Leckie

thought it might be a marine transgression sequence. Bits of fossilized plant material were also observed. Mark Leckie thought the fragments could be Cenozoic in age.

4. Pebbly coarse sand – This unit we believe lies above the clay as noted by the stratigraphic relationships at Site 121007-1 (Figure 7)(Appendix A). This unit is a clean, white (brown where oxidized and weathered), trough crossbedded pebbly coarse sand. It is thought to be a Pleistocene delta that perhaps formed in a proglacial lake prior to ice advance over the island. The unit is estimated to be 10 meters to greater than 13 meters thick.

5. Till – Lying unconformably on top of the pebbly coarse sand is a cobble boulder gravel to pebbly sandy clayey till. A gravel boulder line often marks the base of the till. This unit is most likely the source of the large boulders found along the cliff face and on the beach. The observed thickness of the till is 0.5 to 2 meters. It may be thicker in other locations. A buried soil (paleosol) was developed on top of the till and is observed at Site 121007-4. There is a buried A and B horizon observable at site 121007-4 (see Appendix A).

6. Eolian deposit – Resting unconformably above the till are Holocene age eolian (windblown) sands that in the central part of the Reservation have formed a substantial dune on top of the cliff. The observed thickness of the eolian deposits ranges from 0.5 m to greater than 4 m.

Southward-directed thrust faulting has disrupted this stratigraphic sequence. At sites 121007-2 and 121007-3 (Figure 7), the gray clay has been thrust over the pebbly coarse sand. The top of the clay, which is marked by a lignitic layer, is in direct contact with the till at site 121007-2. The till also has entrained blocks of clay. These blocks appear to be rotated and deformed suggesting that they were picked up and then disturbed by the overriding glacier. The lower contact between the clay and the sand is abrupt, less than 1 cm wide. We interpret this to be the fault surface.

The evidence for faulting is more convincing at site 121007-3 (Figures 6 and 7). Here the fault plane can be observed in cross section. The fault cuts the bedding in the sand at an angle forming an angular unconformity. The fault plane itself forms a 0.5-1 cm oxidized brown surface followed by 12 cm of tan homogeneous clay and silt, another oxidized layer followed by unweathered gray clay (Figure 6).

The effect of the thrust faulting is that it brings older stratigraphic units into higher relief. As such the units exposed in the cliff face become progressively older as one walks from the beach steps at Roaring Brook to the southwest. This is often referred to as going down section. Because the faulting has tilted the units, the deposits become progressively older in a southwest direction along the beach. Figure 8 provides a conceptual cross section of the stratigraphic relationships of the units in the cliff.

Today, the cliffs are eroding due to storm waves and sea level change. The gray clay unit having been thrust over the coarse sand often slumps down the face of the cliff as the sand upon which it sits is undercut by wave action. Some of the slump blocks are relatively large and have slid all the way to the beach. The random arrangement of some slump blocks has created intermittent

Figure 6. Exposure of thrust fault: A) Lower crossbedded sand is truncated by an upper tan to gray clay. Clay has ridden up and over the sand. B) Close up view of fault plane marked by the 0.5 to 1 cm wide oxidized zone.

springs on the cliff face and caused ponding of water in a few places. This ponding has created wetlands that now support phragmites.

Occurrence of Iron-bearing Formations

Most of the pisolitic iron-bearing material found at the Reservation occurs in a limited area. Although float (out of place pieces of the rock) is found commonly, the intact sections appear to be concentrated in the area between sites 073007-1 and 073007-3 (Figure 7). The area extends

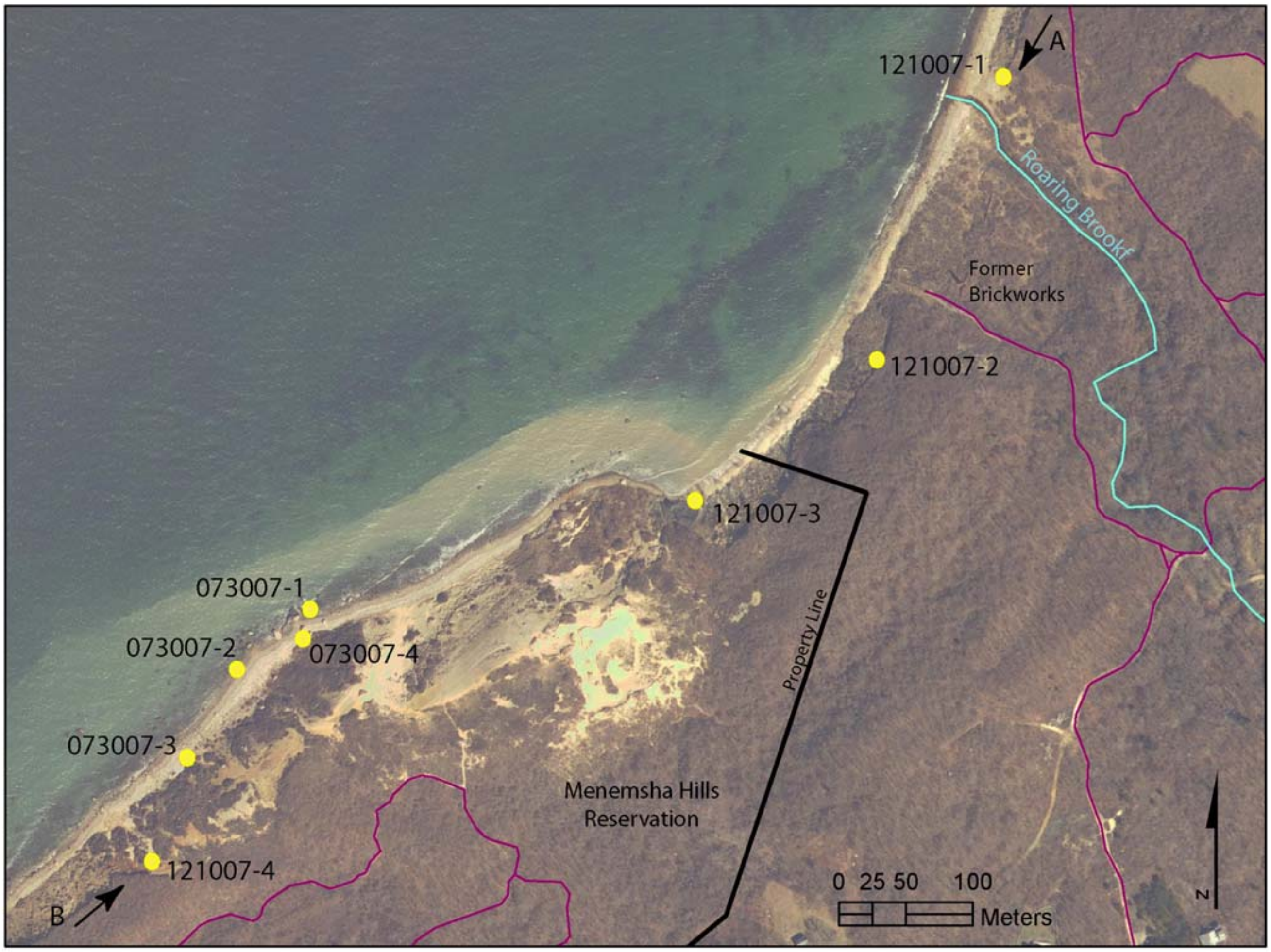


Figure 7. Map showing the location of sample stations and observation points referred to in the report. Individual sites are identified by the date in mmddyy format followed by the station number. The arrows marked by the letters A and B indicate the location of the schematic profile shown in Figure 8.

distance of about 200 to 250 meters (Figure 7). Intact lenses of the rock were observed at three locations. The largest lens is 10-20 cm wide and about 6 meters in length (Site 073007-1) (Figure 2). The smaller intact samples are approximately a meter or less in length and also 10-20 cm wide (Figure 9). The lenses or isolated pods trend north 25° to 35° east and dip 61° to 75° to the southeast and northwest.

The physical characteristics of the iron-bearing material is variable. In some locations the iron is acting as a cement and is clearly bonding larger fragments of pebbles and gravel together (Figure 10). Some surfaces are smooth with a botryoidal appearance (Figure 11). Others have a pisolitic structure (Figure 12).

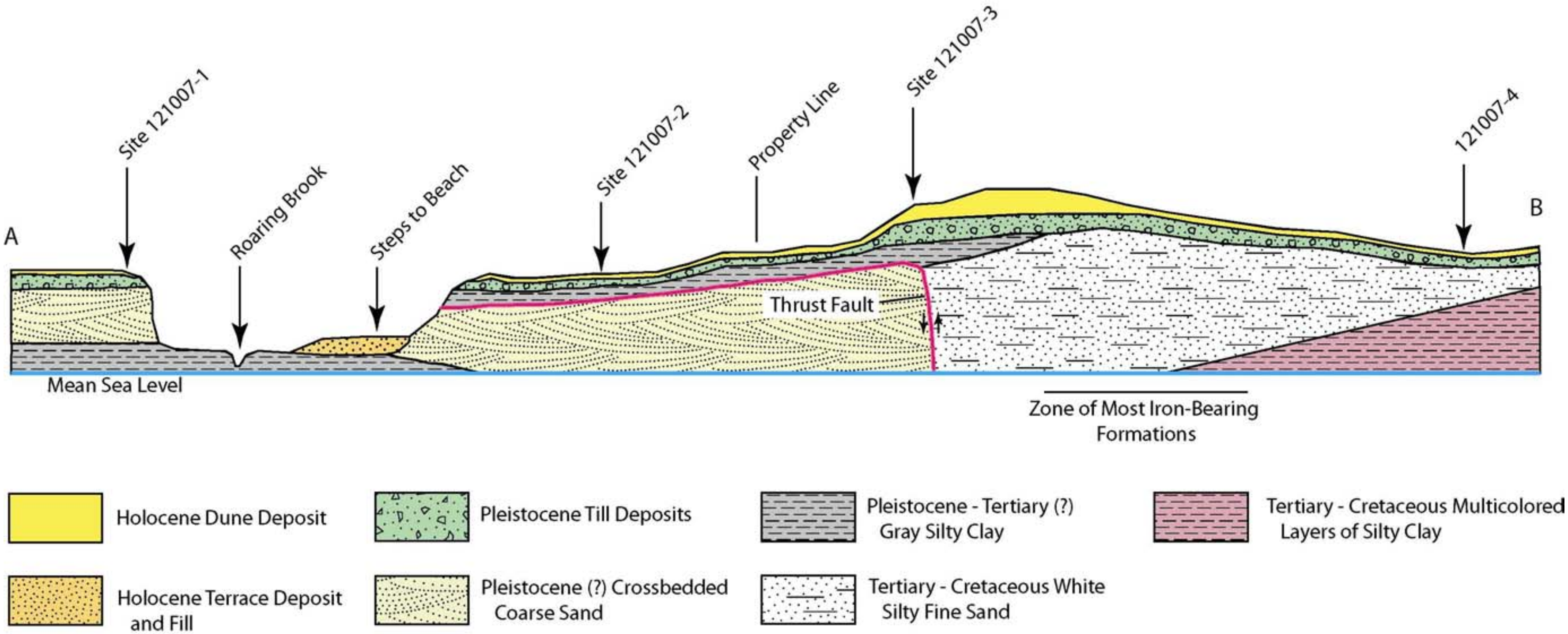


Figure 8. Schematic cross section AB showing a possible interpretation of the geology in the area of investigation. View is from Vineyard Sound looking toward shore. Cross section is not to scale. The red line shows the trace of the thrust fault as viewed from the water. Fault is projecting out of the cross section toward the reader and dips towards the water. This interpretation is conceptual and based on limited observations. Subject to change.

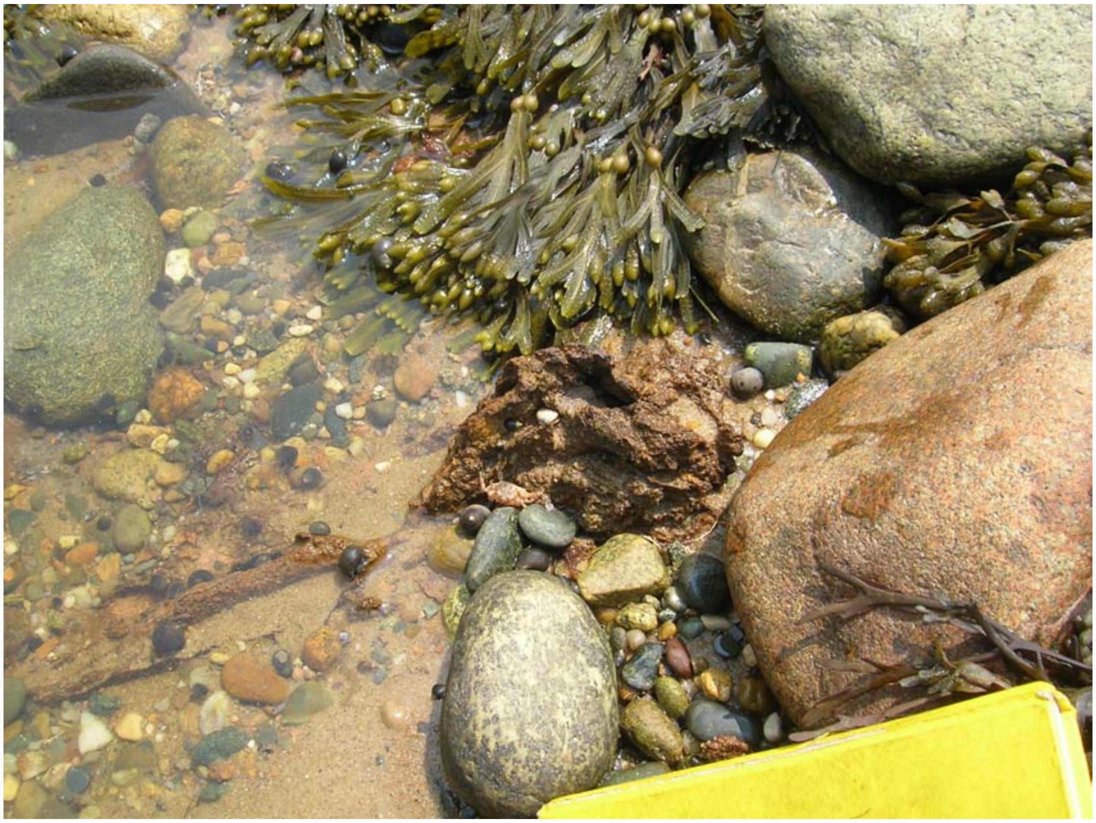


Figure 9. Small lens of iron-rich rock near Site 073007-1. Lens strikes 035° (northeast) and dips 72° to the southeast. Field notebook for scale.

Figure 10. Example of iron-cemented gravel and pebbles at Site 073007-2. Formation is intact and strikes 205° (southwest), dipping 61° to the northwest.

Figure 11. Sample of iron-rich material showing the characteristic botryoidal (grape-like) texture (see lower part of sample at 6 o'clock). Sample was collected by the Trustees of Reservations and was the sample analyzed with the scanning electron microscope. Ruler for scale.

Figure 12. Example of iron-rich rock showing pisolitic texture. Spherical pisolites are 1 to 1.5 cm in diameter.

The age of the iron-bearing formation is difficult to assess. The lenses are clearly steeply dipping suggesting that perhaps they were formed first along bedding planes and then tilted during faulting. This would suggest a pre-Pleistocene age for the material. On the other hand, field relations suggest that formation of the iron-bearing rock may be a more recent phenomenon. Gravel and pebbles that are thought to be associated with Pleistocene-age or younger deposits are entrained by the iron cement (Figure 13). This suggests a Pleistocene or younger age for the material.

LABORATORY METHODS

Four centimeter-sized samples were broken off a sample of pisolitic iron rich rock provided by the Trustees of Reservations in April 2007 and analyzed using the Zeiss EVO 50 scanning electron microscope with a Bruker energy dispersive X-ray analytical system (SEM-EDS). This machine is housed in the Department of Geosciences at the University of Massachusetts at Amherst. In preparation, the four samples were mounted on a glass slide, placed in the vacuum chamber of a sputter-coater, and sputter-coated under vacuum with a gold-palladium alloy. This coating is necessary to increase the electrical conductivity of the sample surface. The samples were transferred to the sample chamber of the SEM, which was then evacuated. The SEM works

Figure 13. Picture showing iron-rich cement adhering to a granite cobble. Granite cobbles are generally associated with materials transported by the glaciers and is therefore considered to be Pleistocene in age. Accordingly, cementation of rock by iron oxide precipitation is thought to be a post-Pleistocene event and may still be ongoing.

by scanning an electron beam across the sample. In reaction, the sample emits secondary electrons, and also X-rays with energies characteristic of the elements in the sample. The secondary electrons are used to image the sample. The EDS measures the intensity of the X-rays over a range of energies (in this case from <1 to 10 kV). This information is then displayed in graphical form as energy spectra with X-ray peaks. The amplitudes of these peaks are proportional, in part, to the concentration of the elements in the sample. The mode in which the EDS was used in this study did not allow for a precise determination of the concentration of each detected element. Instead a qualitative estimate was made. The EDS computer identified and labeled each peak with the appropriate element symbol.

In all EDS spectra of this report, the gold (Au) and palladium (Pd) peaks are from the metal sputter-coat and not the sample. In some cases the spectra in this report cannot be used by themselves to uniquely identify the minerals, but by adding visual inspection and SEM imaging to get color, size and form of mineral grains, the mineral choices can be narrowed down.

RESULTS

The hand specimen from which the four small SEM samples were taken has a reddish-brown botryoidal surface in which sand grains are imbedded (Figure 11). Quartz, muscovite and biotite were identified using a hand lens, but other light and dark grains are also present. Once the specimen was cut open more features were seen. The botryoidal surface is a 1-15 millimeter thick rind surrounding a more open interior consisting of 1-5 millimeter-wide pisolites and irregular vugs between the pisolites all bound together by a reddish-brown matrix similar to the rind. The pisolite rims are also of this same material. Sand grains similar to those in the rind are also imbedded in the matrix and pisolite rims. A fine gray powder fills many of the pisolites and interstitial spaces. In small patches, especially toward the rind, the powder is yellow-brown or reddish-brown.

All this material was examined using the SEM. Figure 14 shows the samples and the points analyzed by the EDS system. The reddish-brown matrix and pisolite rims are iron oxide, probably mostly hematite (Fe_2O_3) based on the big iron peaks (Figures 15, 16, and 17b). EDS confirmed detrital muscovite in the matrix (Figure 17), detrital quartz and muscovite in the rims (Figures 17 and 18) and detrital biotite in the walls of the vugs (Figures 19 and 20). As expected aluminum (Al), silicon (Si), and potassium (K) X-ray peaks are prominent in the muscovite (formula=$KAl_2AlSi_3O_{10}(OH)_2$) spectra. Those peaks together with iron (Fe) peaks are present in biotite (formula=$KFe_3AlSi_3O_{10}(OH)_2$). These grains are considered detrital because of their anhedral shapes, large size relative to the matrix, and occurrence in the surrounding sediment layers. In addition, secondary silica was found both as very fine-grained material and euhedral grains (Figures 21) in the walls of the vugs. The EDS spectra of the secondary silica and quartz (SiO_2) show prominent silicon (Si) peaks and little else (Figures 18, 20 and 21). The gray powder material filling some pisolites and vugs is platy (SEM image, Figure 22) and has EDS spectra with prominent oxygen, aluminum, and silicon peaks (Figures 21 and 22) with or without a small iron peak and no potassium peak. All these features are consistent with one or more clay minerals, such as kaolinite ($Al_2Si_2O_5(OH)_4$).

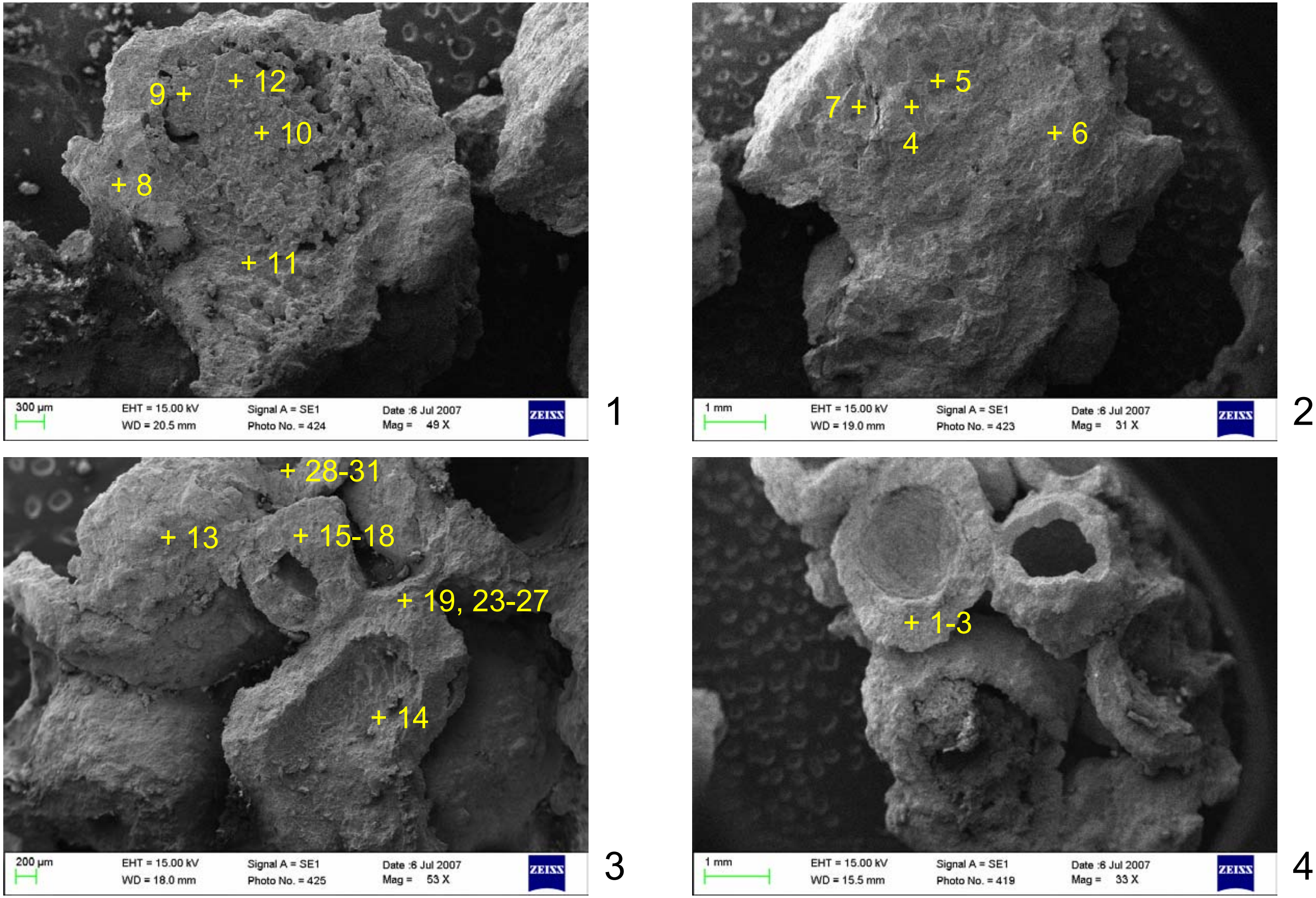
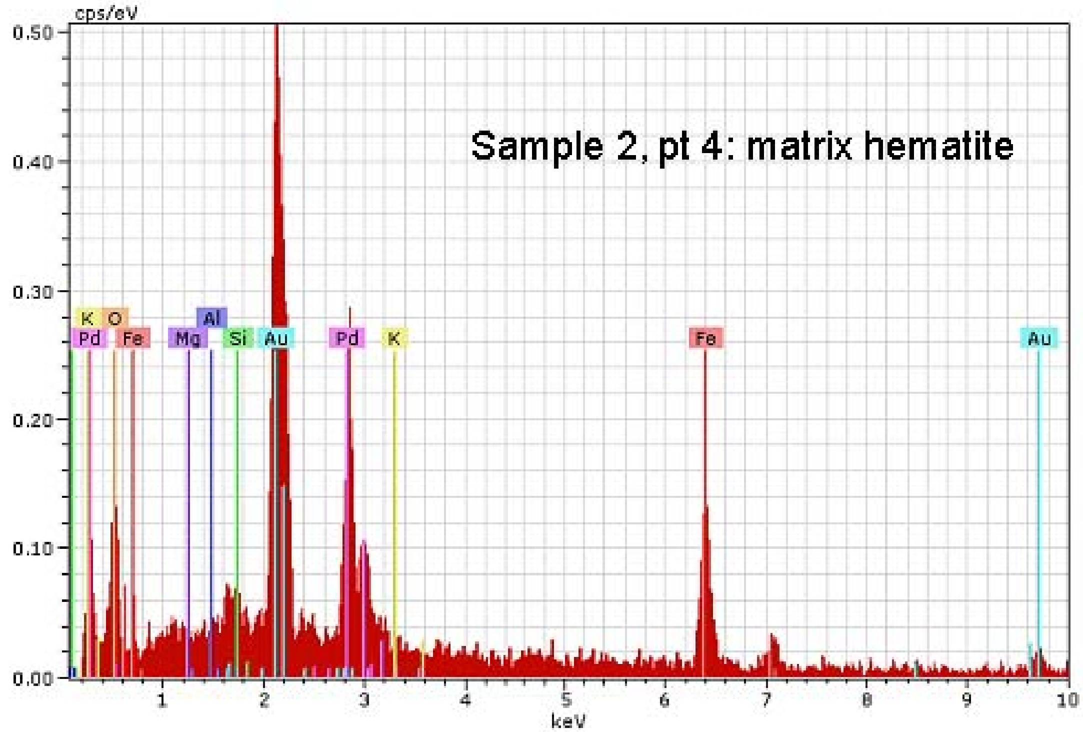


Figure 14: SEM images of the four analyzed samples. Sample 1 is an individual pisolite with rim and filled interior. Sample 2 is the matrix between pisolites. Sample 3 is a cluster of several broken and whole pisolites, intervening voids, and adhering matrix. Sample 4 is another cluster of broken pisolites and intervening voids. Some interiors are empty and some are partly filled. Numbered crosses are analysis points.



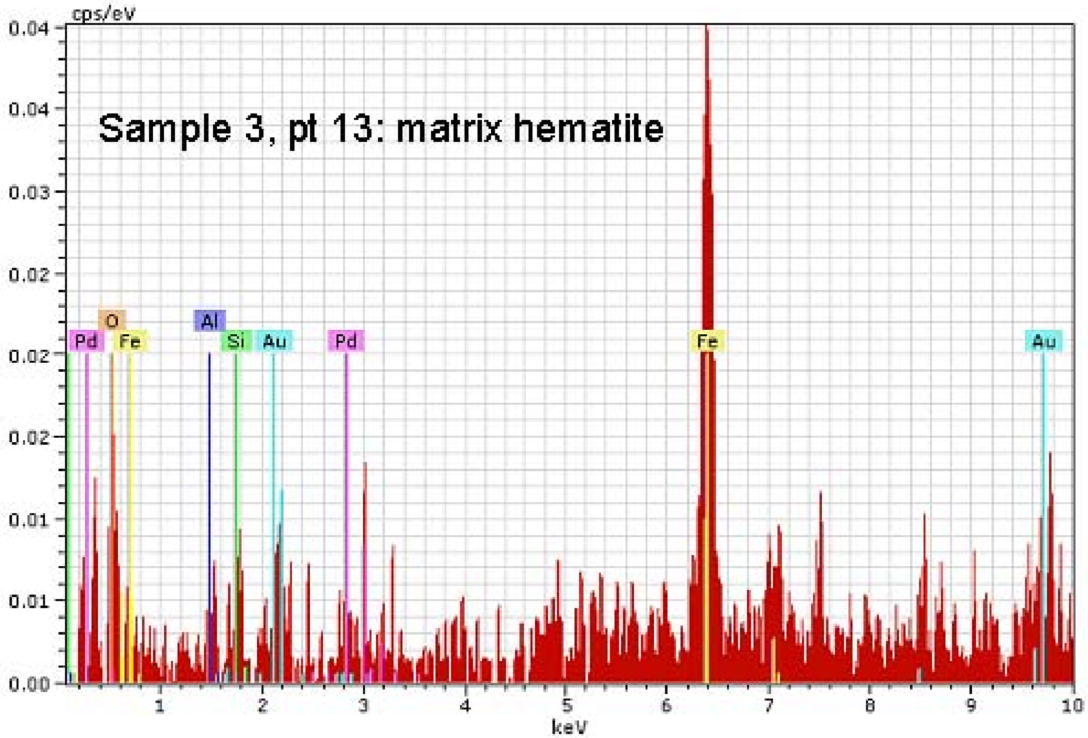
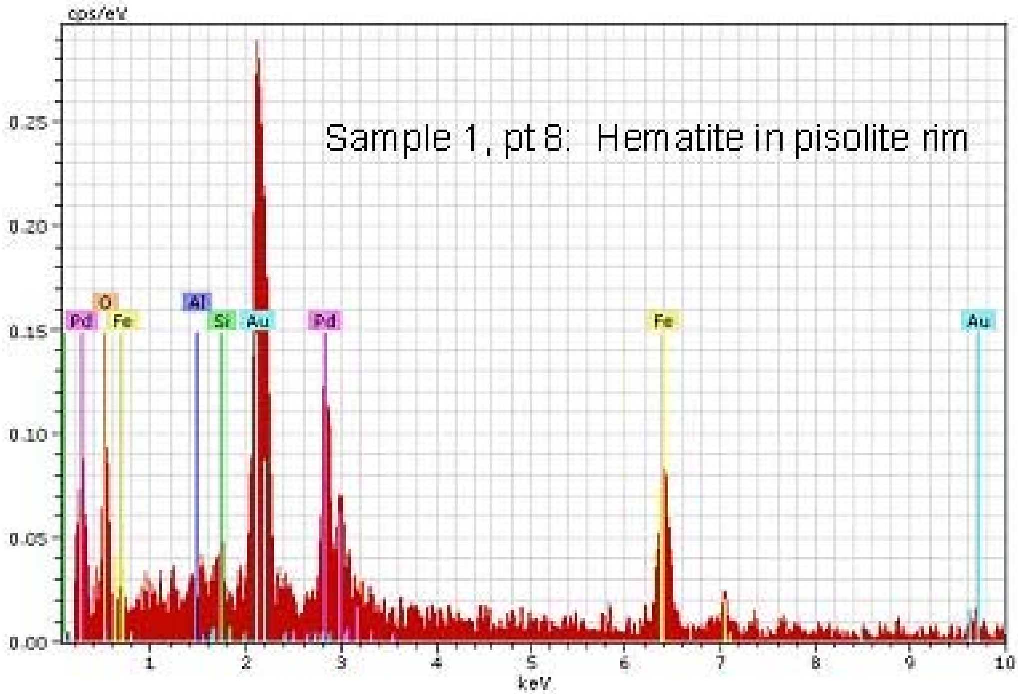


Figure 15: Matrix hematite (or goethite) based on the prominent iron (Fe) and oxygen (O) peaks. Small amounts of aluminum (Al) and silicon (Si) are due to minor amounts of other phases. Gold (Au) and palladium (Pd) are from the metallic coat sputtered onto the samples.



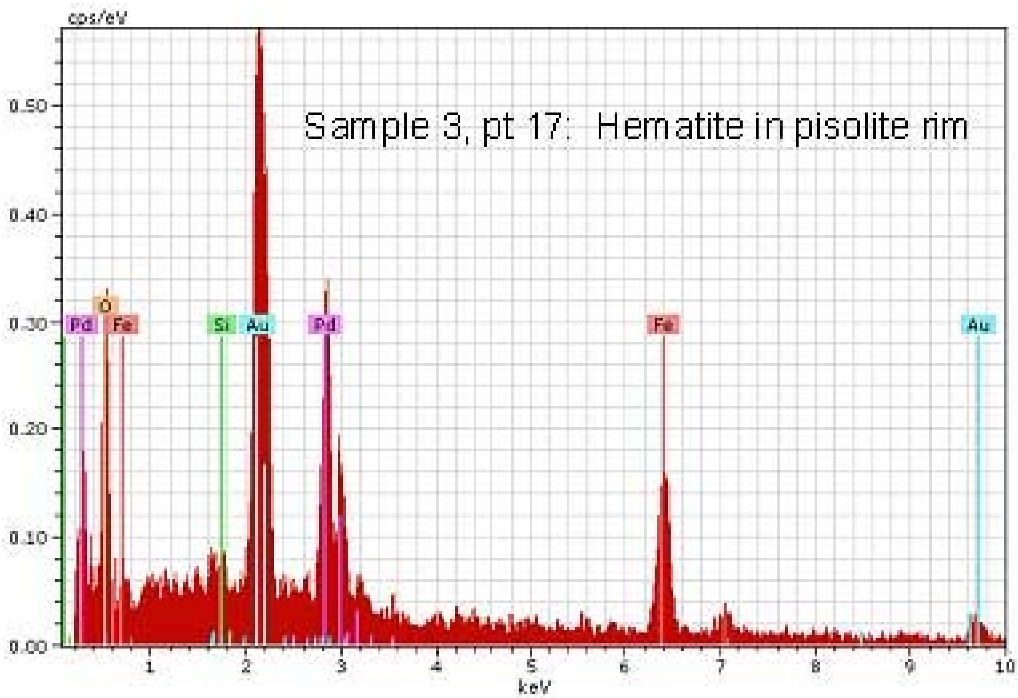


Figure 16: Hematite (or goethite) in pisolite rims based on prominent iron (Fe) and oxygen (O) peaks. Small amounts of aluminum (Al) and silicon (Si) are due to minor amounts of other phases. Gold (Au) and palladium (Pd) peaks are from the metallic coat sputtered onto the samples.

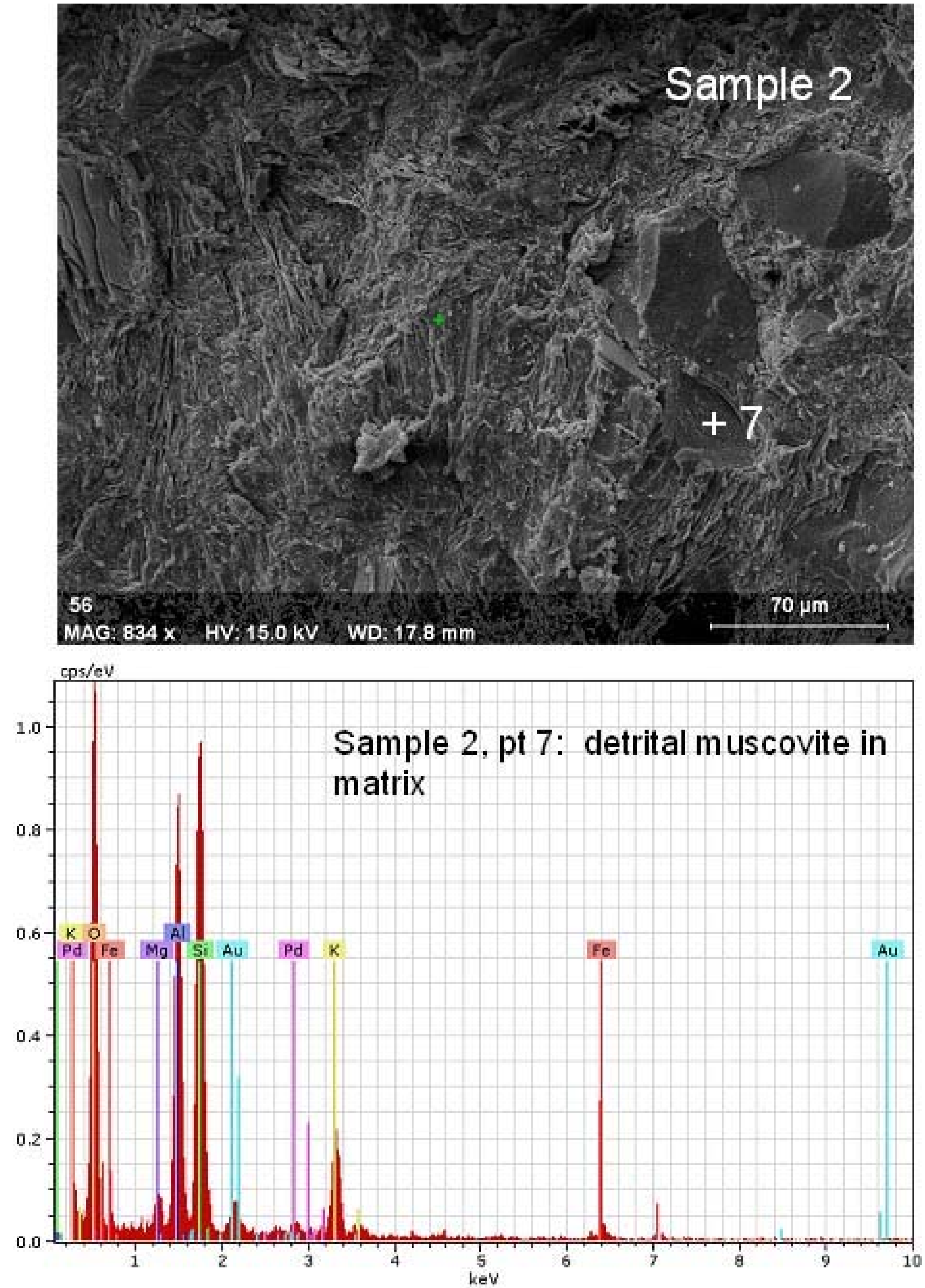


Figure 17: Sample 2, point 7. SEM image and EDS spectrum of detrital muscovite found in matrix. The peaks should only be used to qualitatively estimate the elemental abundances. Oxygen (O), aluminum (Al), Silicon (Si) and potassium (K) are relatively abundant, magnesium (Mg) and iron (Fe) are not. The gold (Au) and palladium (Pd) peaks are from the Au-Pd coating sputtered onto the sample.

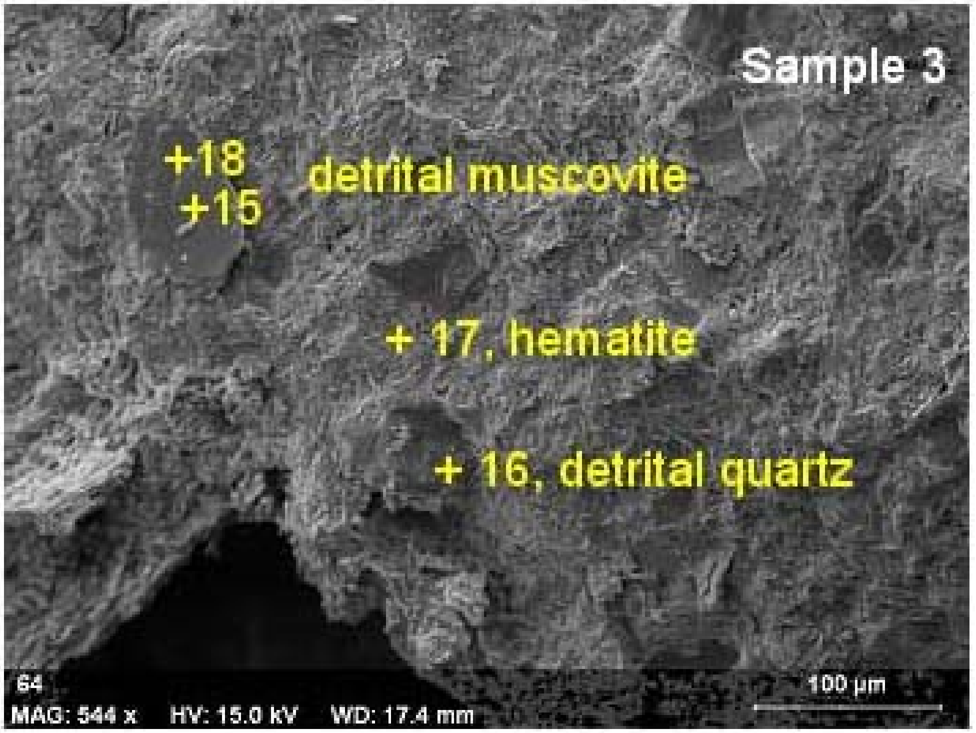


Figure 17a: SEM Close-up of a pisolite rim from sample 3 showing detrital muscovite and quartz within the fine-grained hematite.

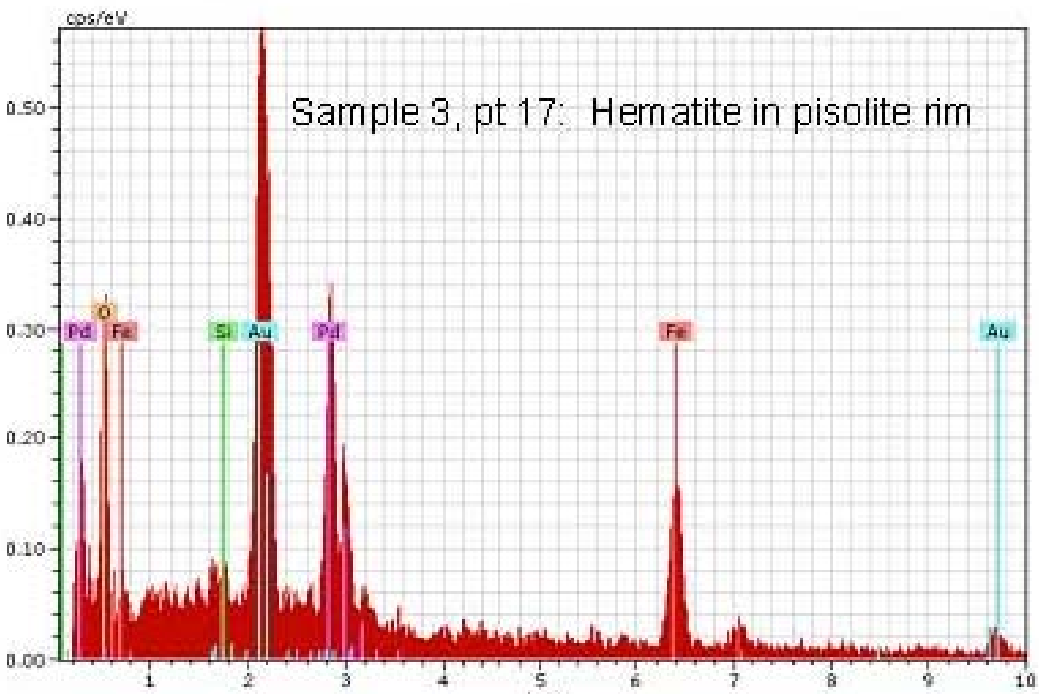


Figure 17b: EDS spectrum of rim hematite showing the iron (Fe) and oxygen (O) peaks. Gold (Au) and palladium (Pd) peaks are from the sputter-coat.

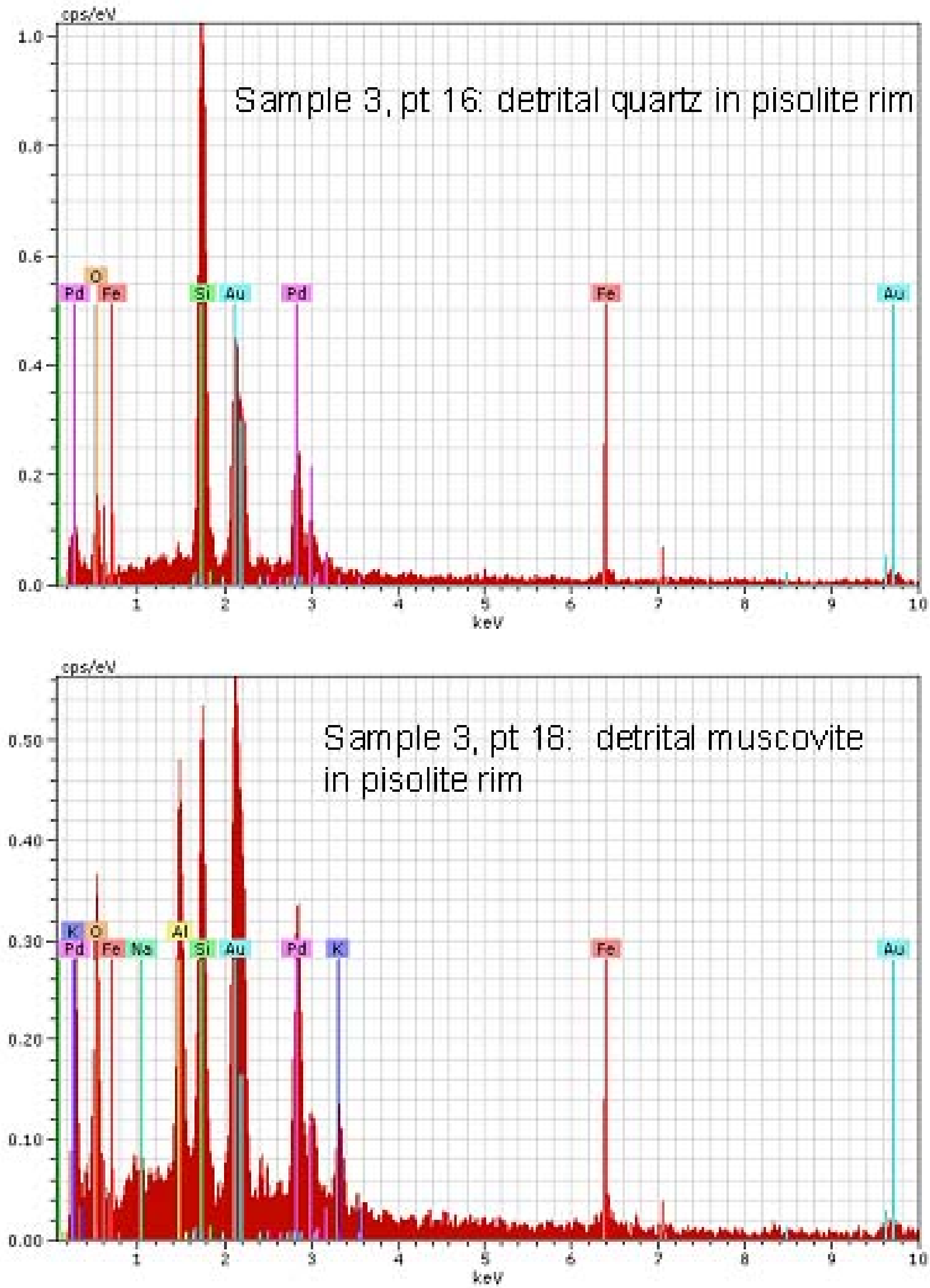
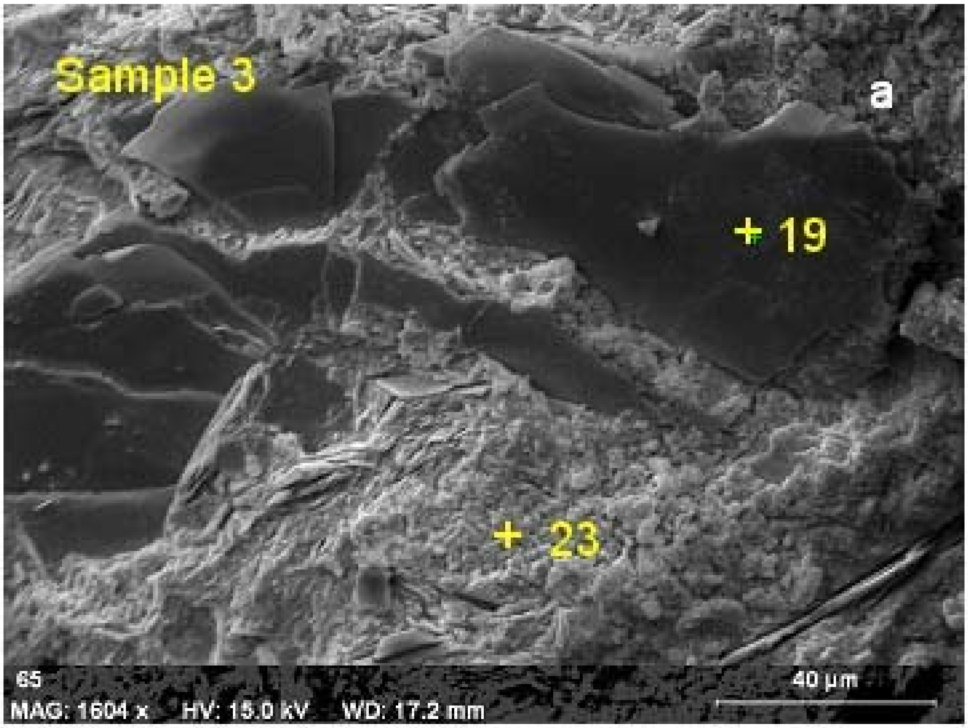


Figure 18: EDS spectra of detrital quartz and muscovite in a pisolite rim from Sample 3. Note the prominent silicon (Si) peak for quartz and the potassium (K) peak for muscovite. SEM image in previous figure.



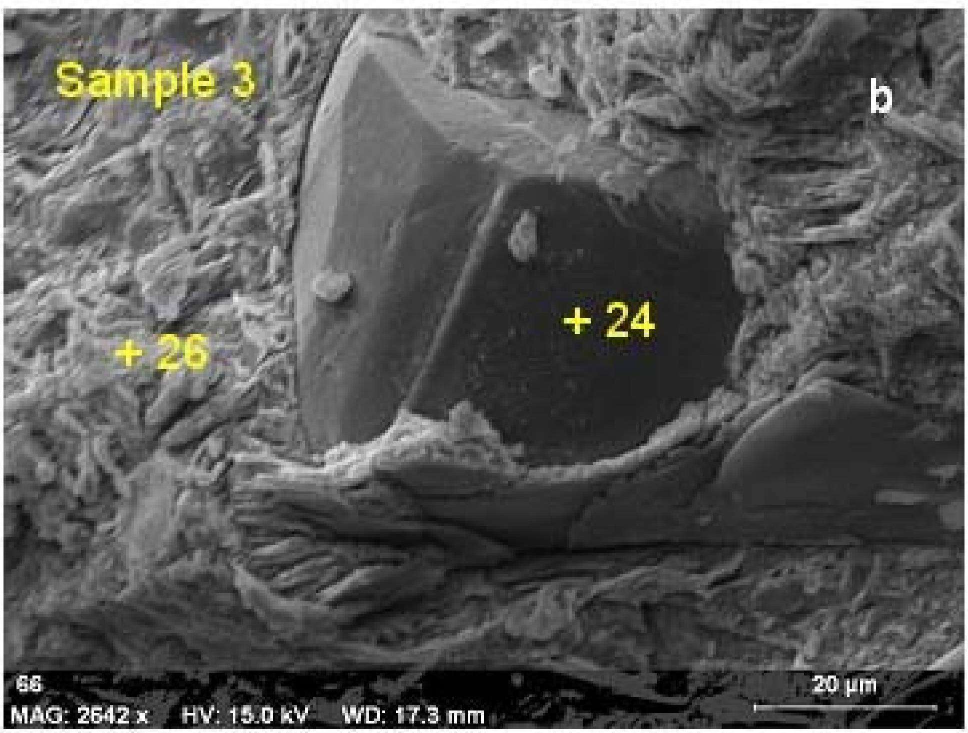
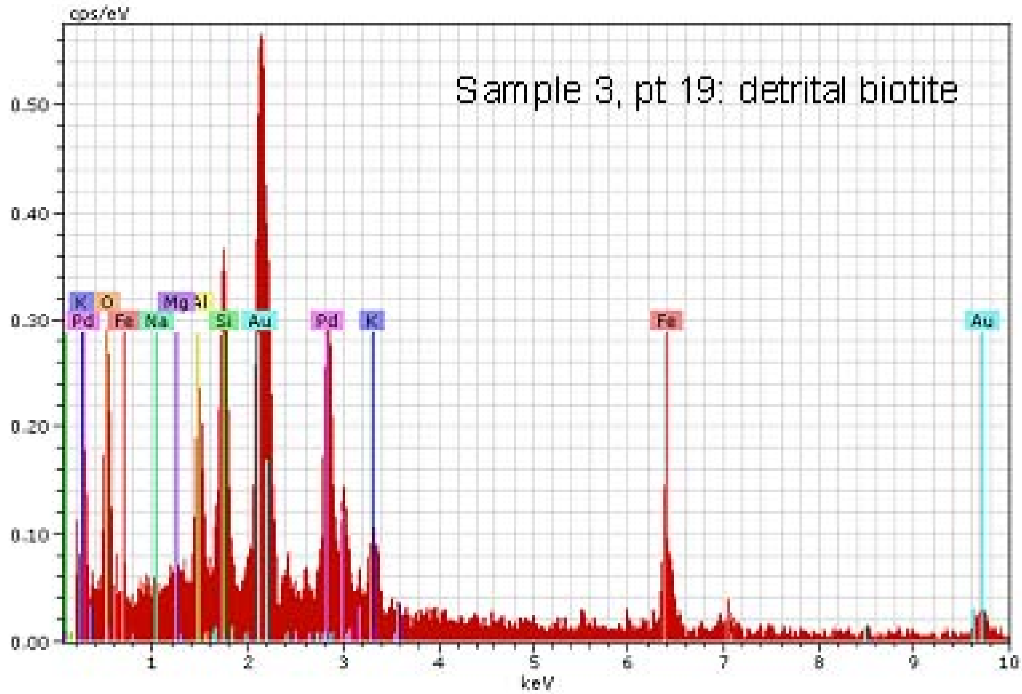


Figure 19: a. Detrital biotite (pt 19) and a very fine-grained secondary silica (pt 23) along the wall of a vug between pisolites. b. A euhedral silica grain (pt 24) and clay along the wall of the same vug.



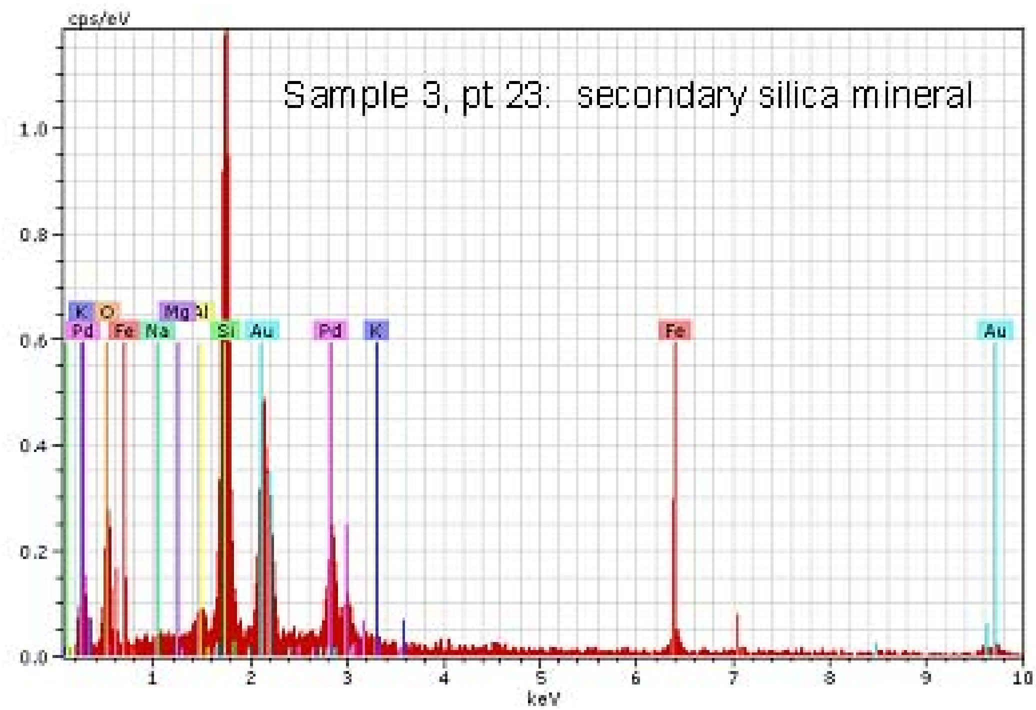


Figure 20: EDS spectra of what is interpreted as detrital biotite and secondary silica in the wall of a vug between pisolites. SEM image in the previous figure.

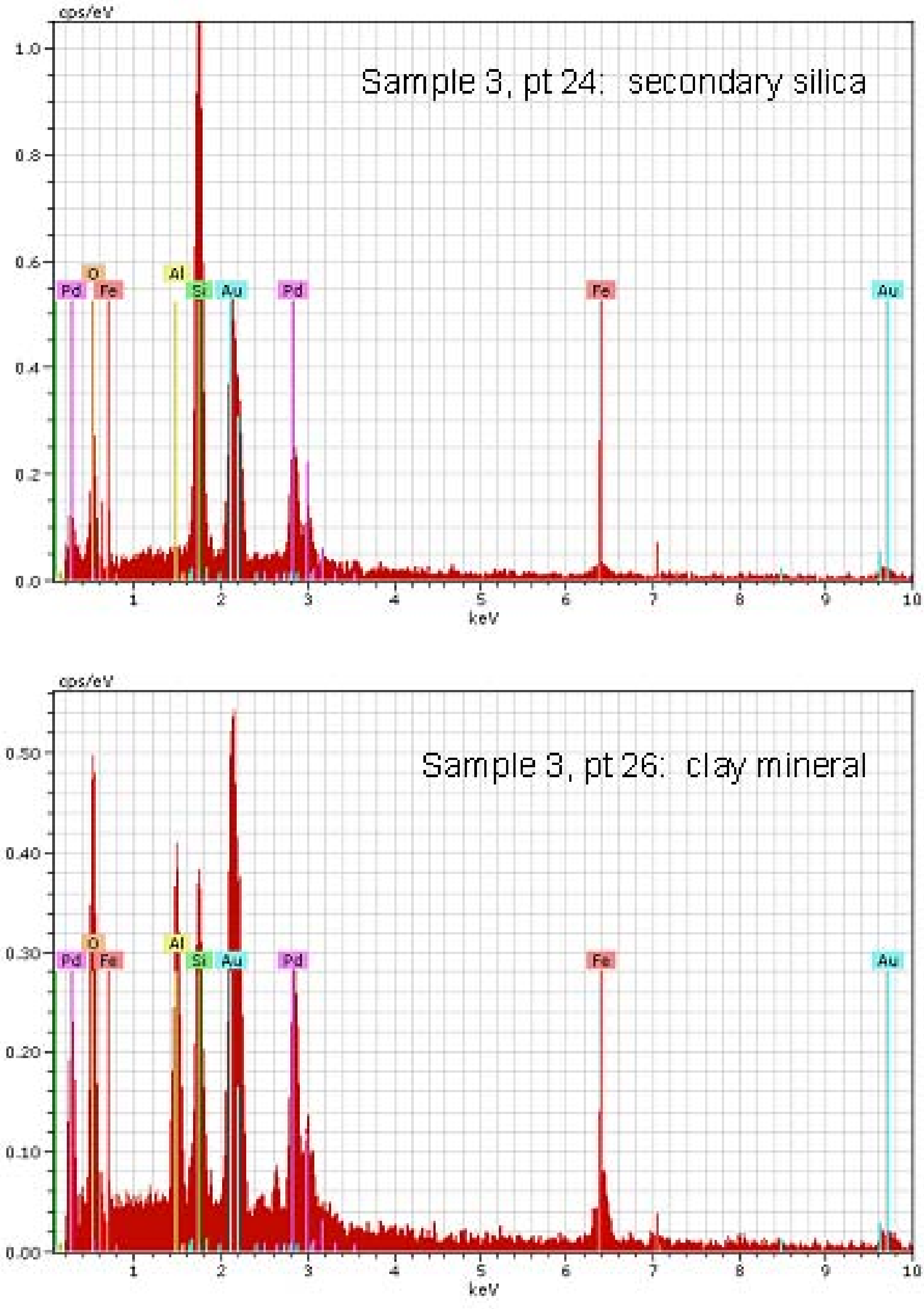
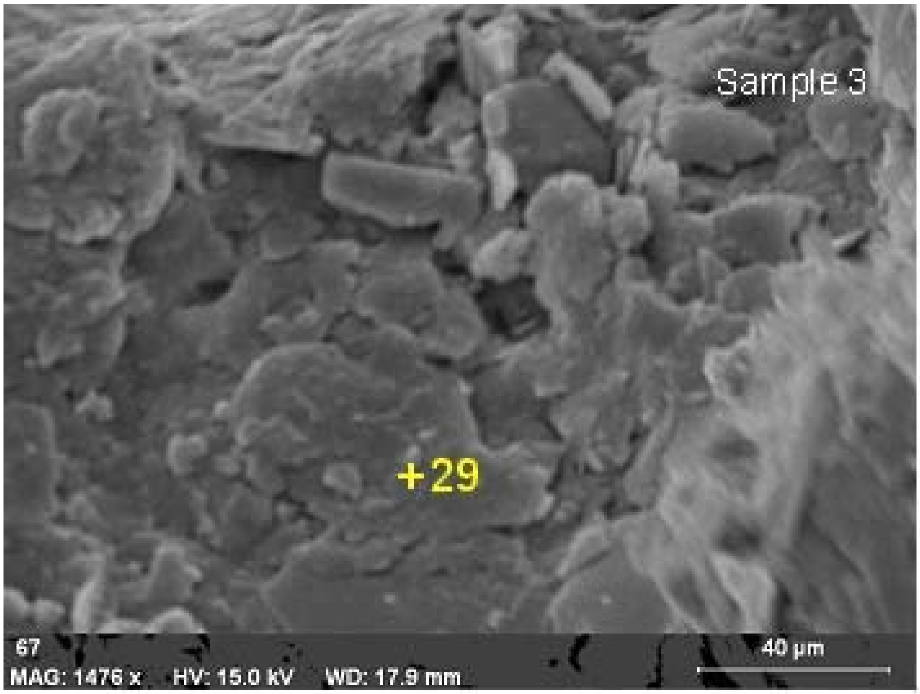


Figure 21: EDS spectra of a euhedral secondary silica mineral and clay mineral (kaolinite?) along the wall of a vug between pisolites. SEM image of these grains is in figure 19.



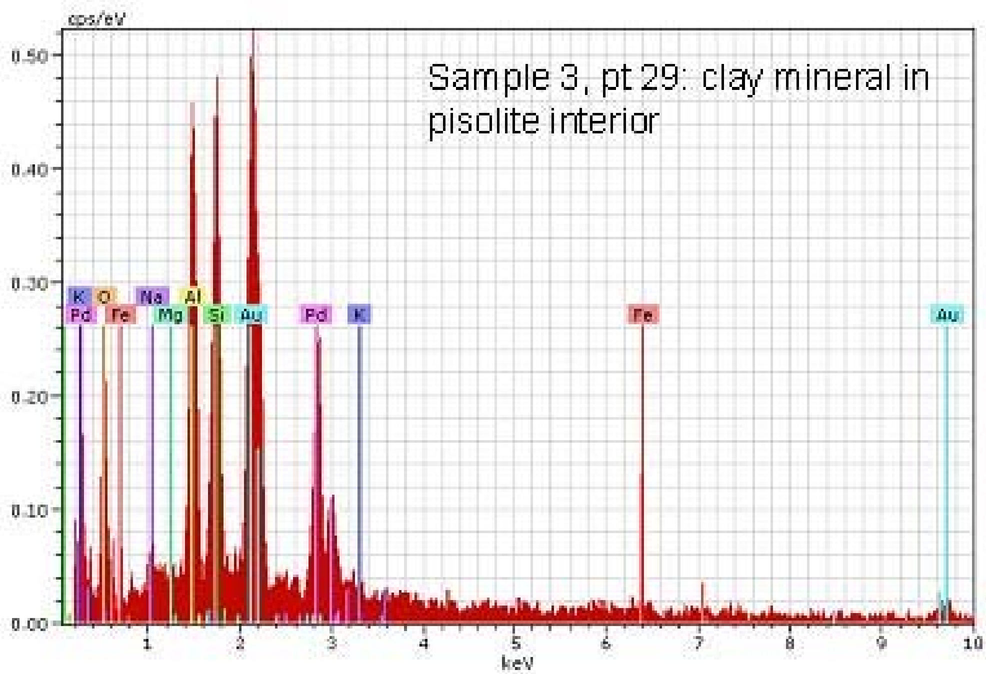


Figure 22: SEM image of platy mineral lining the interior cavity of a pisolite in sample 2. EDS spectrum shows prominent silicon (Si), aluminum (Al) and oxygen (O) peaks, but no significant potassium (K) peak. Gold (Au) and palladium (Pd) peaks are from the sputter-coat.

CONCLUSIONS

At the beginning of this study a question was raised about whether any of the material could be termed bauxite. The answer based on the SEM-EDS work is no. Bauxite mostly consists of aluminum hydroxide minerals such as gibbsite ($AlO(OH)_3$). No EDS spectra showed only oxygen and aluminum peaks. Everything is either a silicate or iron oxide. Given the textural and compositional characteristics of the material, its layer-like geometry and apparent concordant distribution within other sediment layers, this formation could be termed a pisolitic ferricrete.

The mode of formation is unknown. However, it is likely that the deposit is the result of progressive upward precipitation of iron oxide due to a change in redox conditions as groundwater percolated through the bedding planes in the sediment. It is also interesting to note that most of the visible intact lenses of the ferricrete occur near the base of the white, non-plastic silty fine sand deposit near the contact with the underlying variegated clay (Figure 8). Accordingly, the location of the ferricrete may be related to groundwater discharge at or near this impermeable boundary. Reducing waters percolating through the silty fine sand leaches out the iron and then is discharged at the interface. Because the discharge point is an oxidizing environment, the iron in solution precipitates out. The age of the ferricrete formation is unknown. However, field relationships suggest that the iron cementation is post-Pleistocene in age and may actually be occurring today.

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Appendix A

Sediment Descriptions
(refer to Figure 7 for locations)

Site 121007-1

Location: At top of bluff, 15 m NE of Roaring Brook, cliff 12 to 15 m high
GPS: 41.37832° N; 70.74523°W

0 – 0.6 m	Very fine sand; eolian material
0.6 – 2.1 m	Cobbly, bouldery gravel, base marked by boulder gravel line; till
>2.1 m	Crossbedded coarse sand
	Exposure of tan to gray clay at bottom of cliff in bed of Roaring Brook.

Site 121007-2

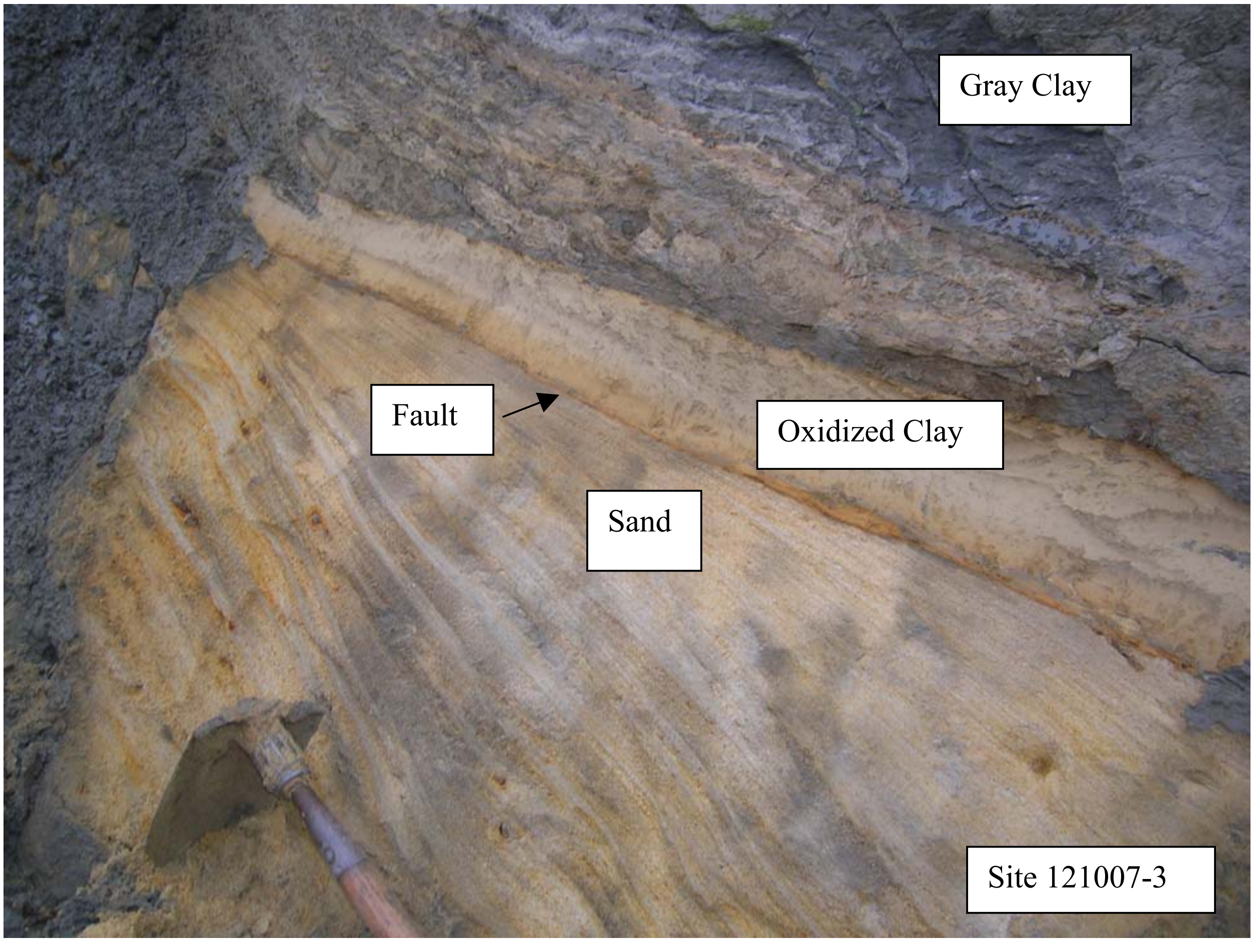
Location: First bluff SW of access steps to beach
GPS: 41.37612°; 70.74523°W

0 – 1.25 m	Very fine sand; eolian material
1.25 – 2.25 m	Pebbly, sandy clayey till with scattered cobbles; till Contains large blocks of gray silty clay that are rotated and deformed
2.25 – 4.25 m	Gray silty clay; top of clay is very lignitic; contact with sand below is very abrupt, 1 cm.
>4.25 m	Pebbly, very coarse sand with trough cross bedding; comprises remainder of bluff

Site 121007-3

Location: Bluff exposure just inside Reservation property at SW end of sandy beach area
GPS: 41.37535°N; 70.74683°W

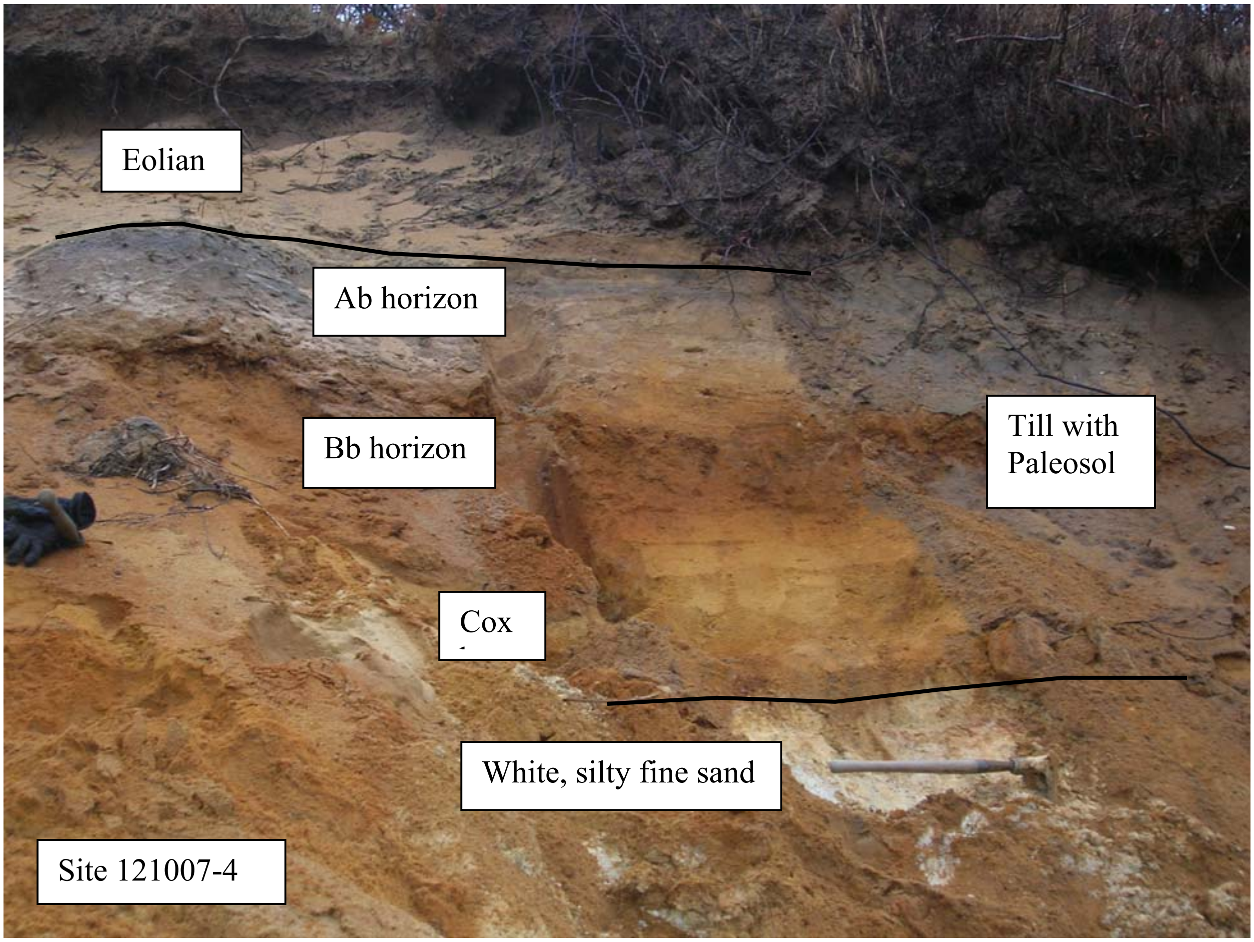
Fault contact – crossbedded pebbly very coarse sand is cut by gray clay. Contact consists of 1-2 mm rusty colored shear zone, 12 cm of tan homogeneous silty clay; 10-12 cm of brown sheared silty clay followed by undisturbed gray silty clay (see photograph below).



Site 121007-4

Location: Approximately 600 m from property line on beach, near the top of the bluff.
GPS: 41.37300°N; 70.75156°W

0 – 3 m	Very fine to medium sand; eolian material
3 – 4 m	Buried soil horizon formed on till, Ab and Bb horizons
4 – 4.6 m	Till, very thin veneer
>4.6 m	White, non-plastic, kaolinitic silty fine to medium sand
	(See photograph below)


Eolian
Ab horizon
Bb horizon
Till with
Paleosol
Cox
White, silty fine sand
Site 121007-4

Site 073007-1

Approximately 350 m from property line on beach, in the intertidal zone, in situ layer of iron-bearing material, 035° strike, 72° dip SE (see photography below).

Site 073007-2

Approximately 75 m SW of Site 073007-1, in situ layer of iron-bearing material, 205° strike, 61° NW (see photograph below).

Site 073007-3

At base of cliff by big boulder used by transients as a shelter. Contact between white non-plastic silty fine sand and underlying multicolored clay (brown). Clay is lignitic and iron hardpan and concretions forming at interface (see photograph below).