Systems: Tectonic & Hydrologic – Field Study Observations & Interpretations

by

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I. Introduction

This course demonstrates how tectonic and hydrologic systems have shaped our landscapes of today. Based on my field study observations and interpretations, this course attempts to recreate the petrogenesis of The Cobbles outcrop over the last 600 million years.

Petrogenesis is the branch of study under petrology that covers a rocks origin and its past. The Cobbles outcrop is part of the Cheshire quartzite formation. Formation names include two key pieces of information: location and principal rock unit. Cheshire quartzite, describes its location in Cheshire, MA; and describes its dominant rock unit – quartzite.

Showing The Cobbles current elevation of 1800ft, the following is a partial view of a recent topographic map (7.5-Minute Series, Cheshire Quadrangle, Massachusetts, Berkshire County, USGS, 2015) which was used to help in this field study.

Figure 1.1: Topographic Map – The Cobbles

Also note that the name, "The Cobbles", is a misnomer. An actual cobble refers to a standard clastic sediment the size of about 256 millimeters (10.1 inches) in diameter, which is larger than a pebble but smaller than a boulder. All three of which are categorized as gravel; where from largest to smallest of the clastic sediments are: gravel>sand>mud. However, The Cobbles outcrop (under study) is massive, measuring in feet about 67x19x30 (LxWxH), and is therefore not a sediment.

II. Observations

A. Introduction

The main goal of my field visits was to collect objective evidence from observations to assist in the interpretations. I performed reconnaissance in the summer of 2018 that peaked interest and identified accessibility to study the outcrop. Subsequent visits were necessary to complete the field study. The following table summarizes my field visits and dates to The Cobbles outcrop on the Appalachian Trail. All photographs can be correlated with its location in the Outcrop Photograph Reference Map as indicated by section. Finally, the majority of my field study notes from the three field visits were consolidated and summarized into one Field Study Notes section.

Table 1.1: The Cobbles Field Visits

Field Visit Number	Date	Main Objective
#1–2018	6/3/2018	Reconnaissance: photos and rock samples taken
#2–2019	5/27/2019	Complete short list - see section
#3–2019	6/8/2019	Complete short list - see section

B. Field Study, Visit #1–2018

The scope of this first field study visit was limited to the following objectives:

1. Perform reconnaissance: to see if a field study was feasible and of interest to me, to be a challenge to determine its petrogenesis; and to maximize the amount of geology learning
2. Take photographs
3. Collect rock samples

Field Materials:

- Smart Phone Camera
- Small Backpack

The following two photographs are of the same vertical section from upper to lower. Observe the bedding profile is in a vertical, upright position, and evidence of scour respectively.

Figure 2.1: (Photo) Upper Section: 4A–4B

Figure 2.2: (Photo) Lower Section: 4–4A

The following figure identifies the location where a sandstone rock sample was collected and its remaining piece. This finding represents an unconformity that is a nonconformity.

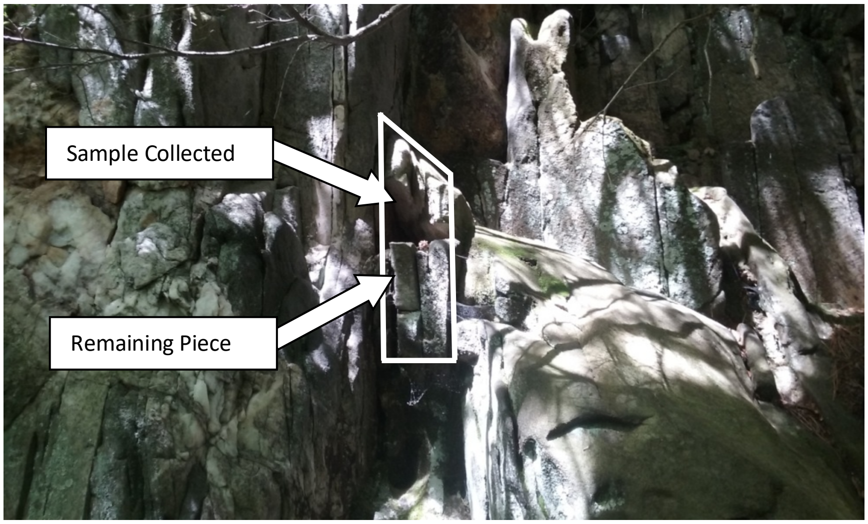

Figure 2.3: (Photo) Sandstone Nonconformity

My reconnaissance concluded that:

- Yes - the field study is feasible, outcrop is accessible to study
- Yes - the field study is interesting to me; should be challenging and maximize learning

With these results, I proceeded with my field study.

C. Field Study, Visit #2–2019 (May)

The scope of my second field study visit was limited to the following objectives:

1. Focus on 3 points of interest, each end and one near middle of outcrop
2. Measure and sketch on graph paper, with scale of each square ≈ 1ft
3. Take two pictures at each of the 3 points, one direct horizontal, and one vertical to top
4. Get additional rock samples that I don't have from previous visit (e.g. all quartzite)

Field Materials:

- Tape Measure: 16ft
- Magnifier for Rock Unit Identification: Carson MicroBrite Plus 60x-120x Power LED Lighted Pocket Microscope (MM-300)
- Smart Phone Camera
- Clipboard
- Graph Paper

- Two Pens
- Headlamp
- Small Backpack

From this visit, the following map of the face of the outcrop was created. The points of three locations studied are marked 1-3 and were photographed. Also added to provide value was Section 4 as marked and the sandstone nonconformity – both were identified during my first field study visit; with the sandstone nonconformity located more accurately during my third field study visit.

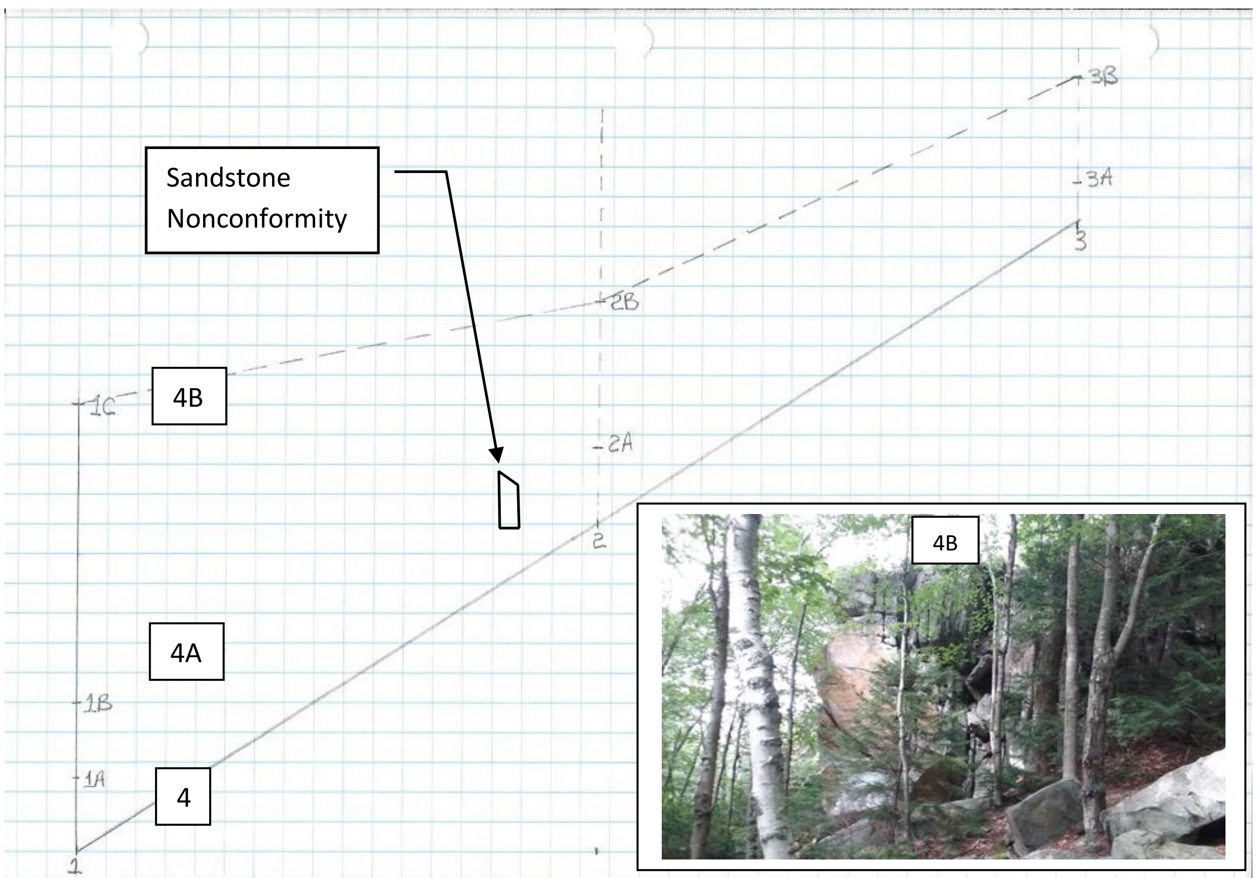

Figure 2.4: Outcrop Photograph Reference Map
scale: each block ≈ $2ft^2$

Actual angle of slope (1-3) may be steeper than shown, about 45°. I slightly decreased the slope and changed scale from 1ft to approximately 2ft per square in order to fit entire face of outcrop on one sheet. The photo inset at bottom right is of the lower half (1-2), with location 4B included to provide point of reference.

Regarding the following figure, the lower deformation joint base is about 10ft above grade, and the base of this joint to top of vertical was estimated to be about 20ft. Common to many outcrops, joints are tension fractures that occur at low pressure.

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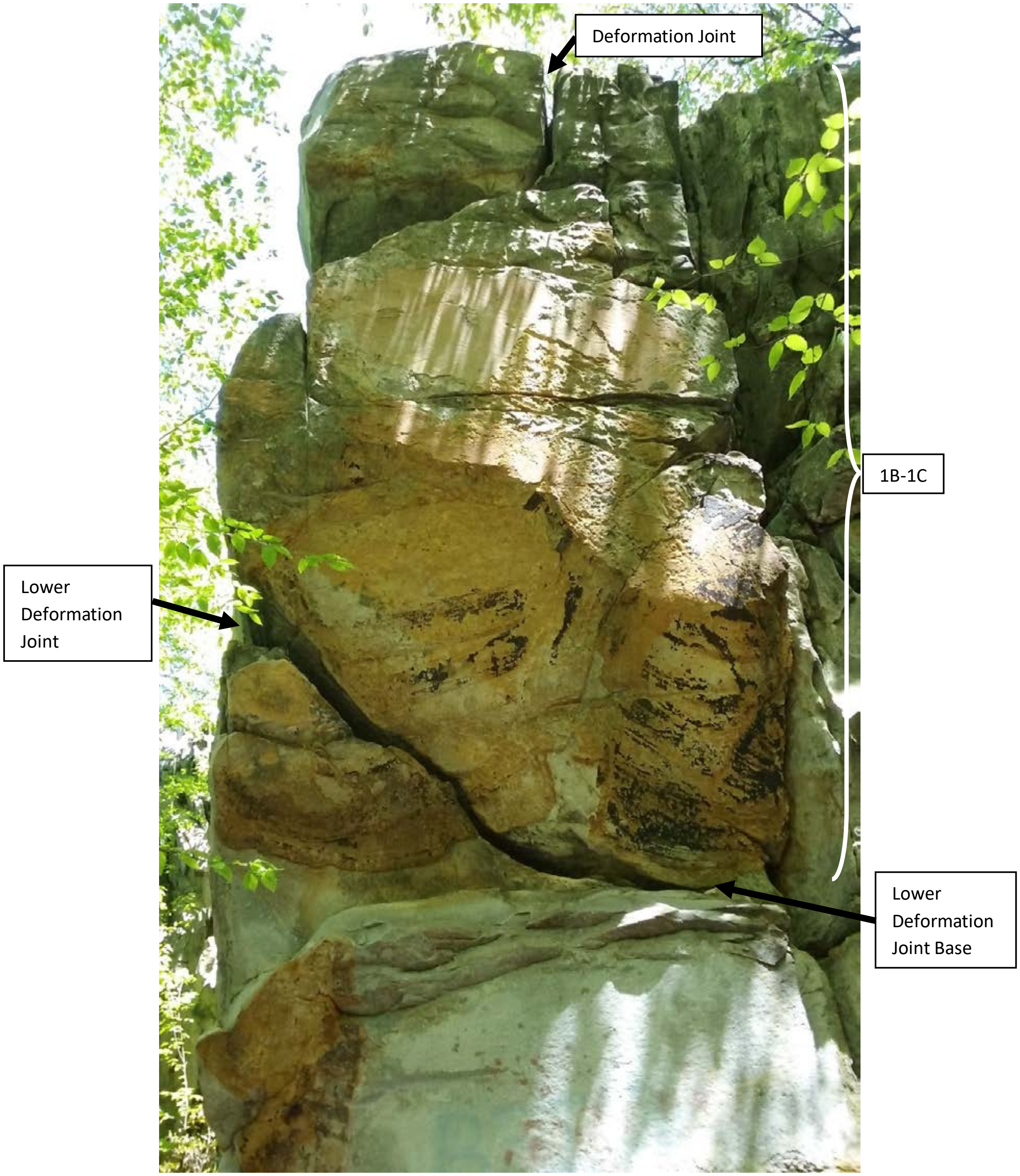

Figure 2.5: (Photo) Upper Section: 1B–1C

Field notes for this section 1 location are:

- 5ft from grade to outermost curved section
- Lower deformation joint base identified at top of this photo is about 10ft above grade, and can be used as a correlation to continue study of the upper section in the previous photo
- Rock unit identified is quartzite
- Evidence of scour at the base of the rock

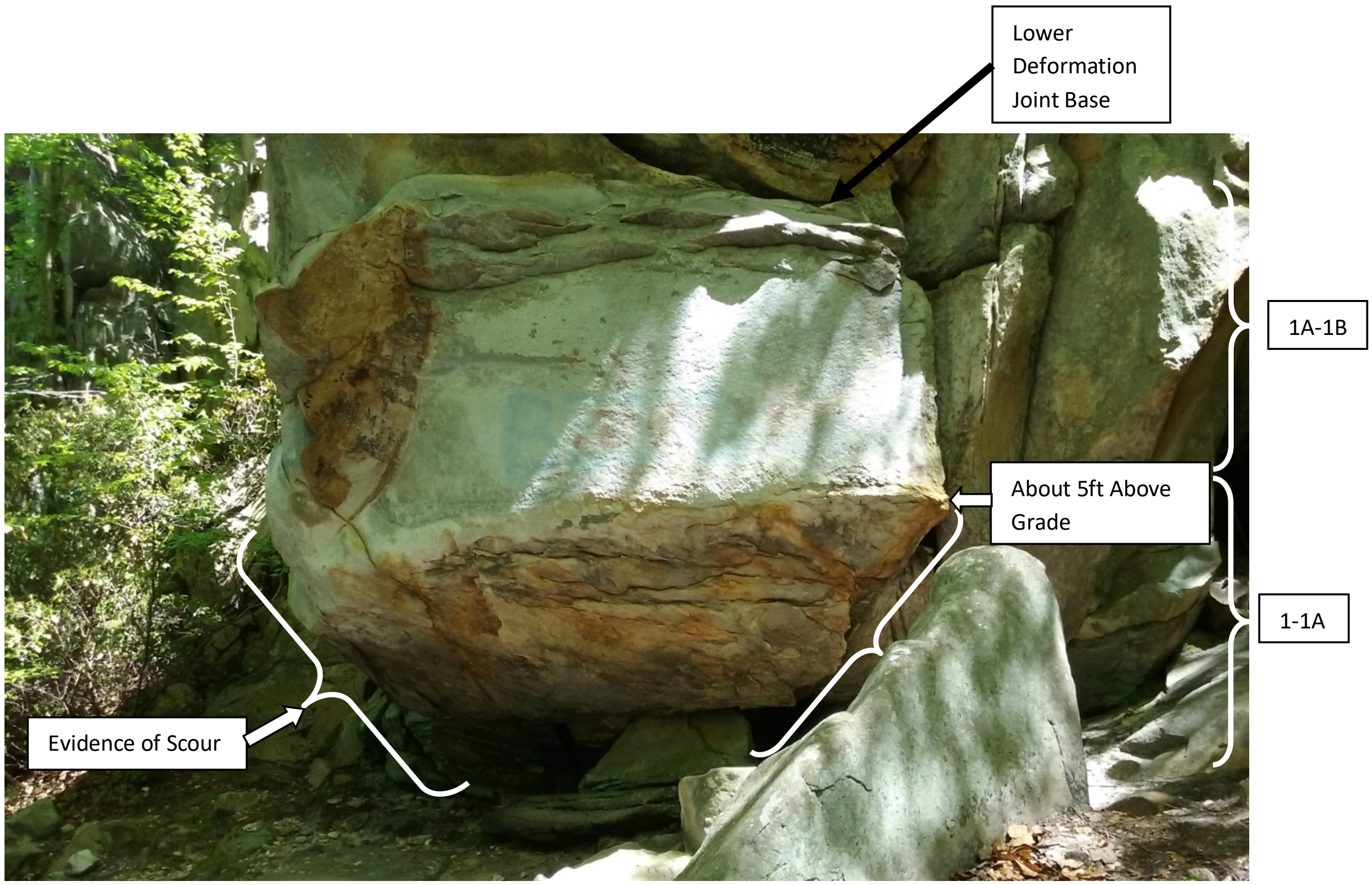

Figure 2.6: (Photo) Lower Section: 1–1B

The lower right tree branch is marked for correlation between this upper section photo and its corresponding lower section photo in next figure. Although this tree is an obvious obstruction to the outcrop in this photo, it was useful as a good mark to measure and as an anchor for safety.

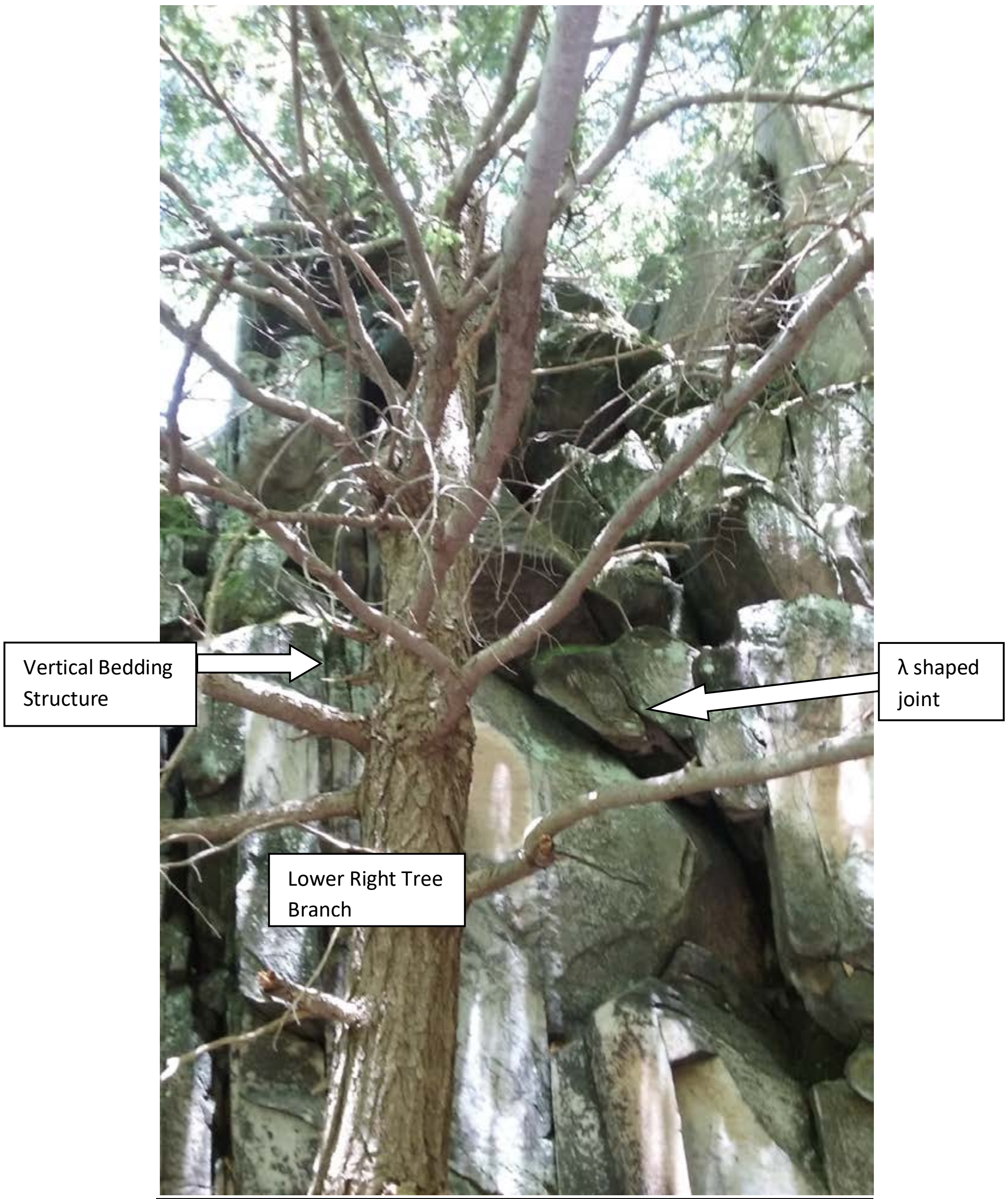

Figure 2.7: (Photo) Upper Section: 2A–2B

Field notes for this section 2 location are:

- Lambda (λ) shaped joint in rock is about 5ft above grade (upper section)
- From lambda joint, extends an estimated 10ft to top of vertical (upper section)
- Vertical bedding structure (both upper and lower sections)
- Rock unit identified is quartzite

The lower right tree branch is marked for correlation between this lower section photo and its corresponding upper section photo in previous figure.

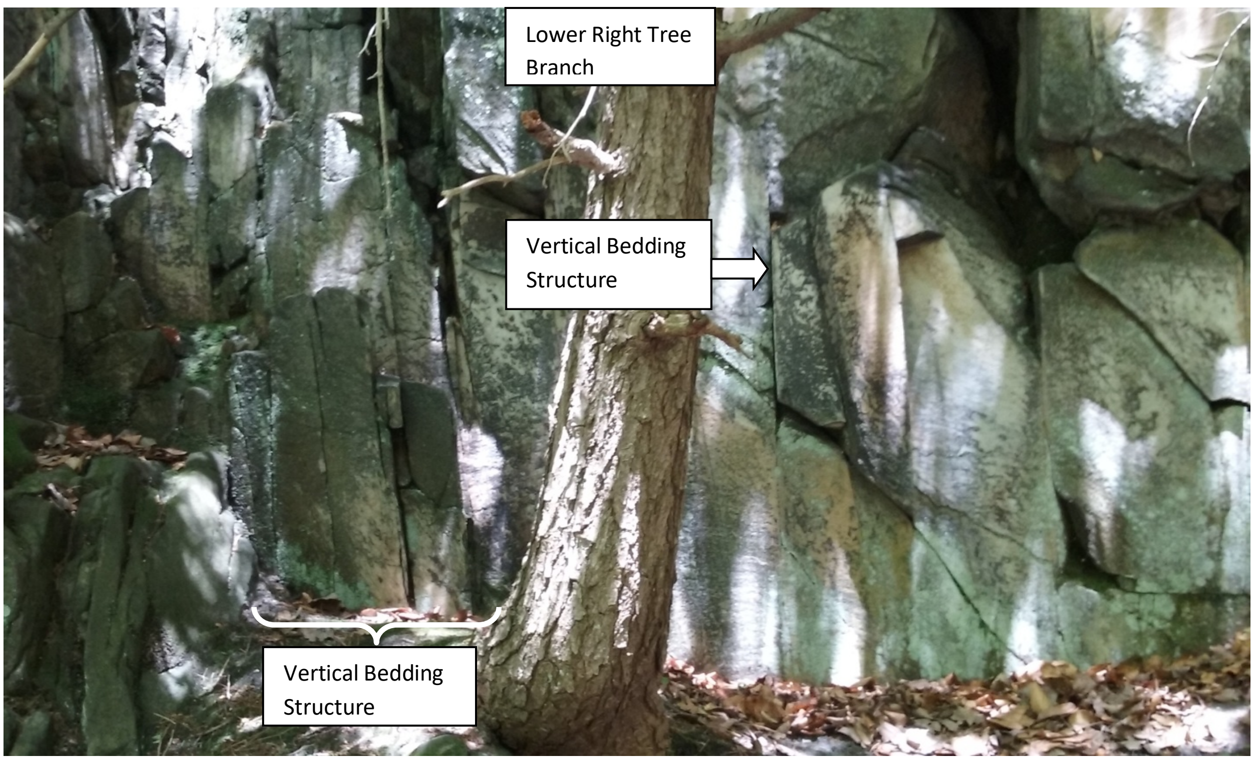

Figure 2.8: (Photo) Lower Section: 2–2A

Field notes for the following section 3 location are:

- Rock unit identified is quartzite
- Multiple deformation joints
- Wide deformation joint is about 3ft above grade, which then extends another 7-8ft to top of vertical

Two pictures were not required to show the entire, shorter, upper section of the outcrop as seen in the following photo. Tree to right of photo (out of view) was used as a good mark to measure and reference.

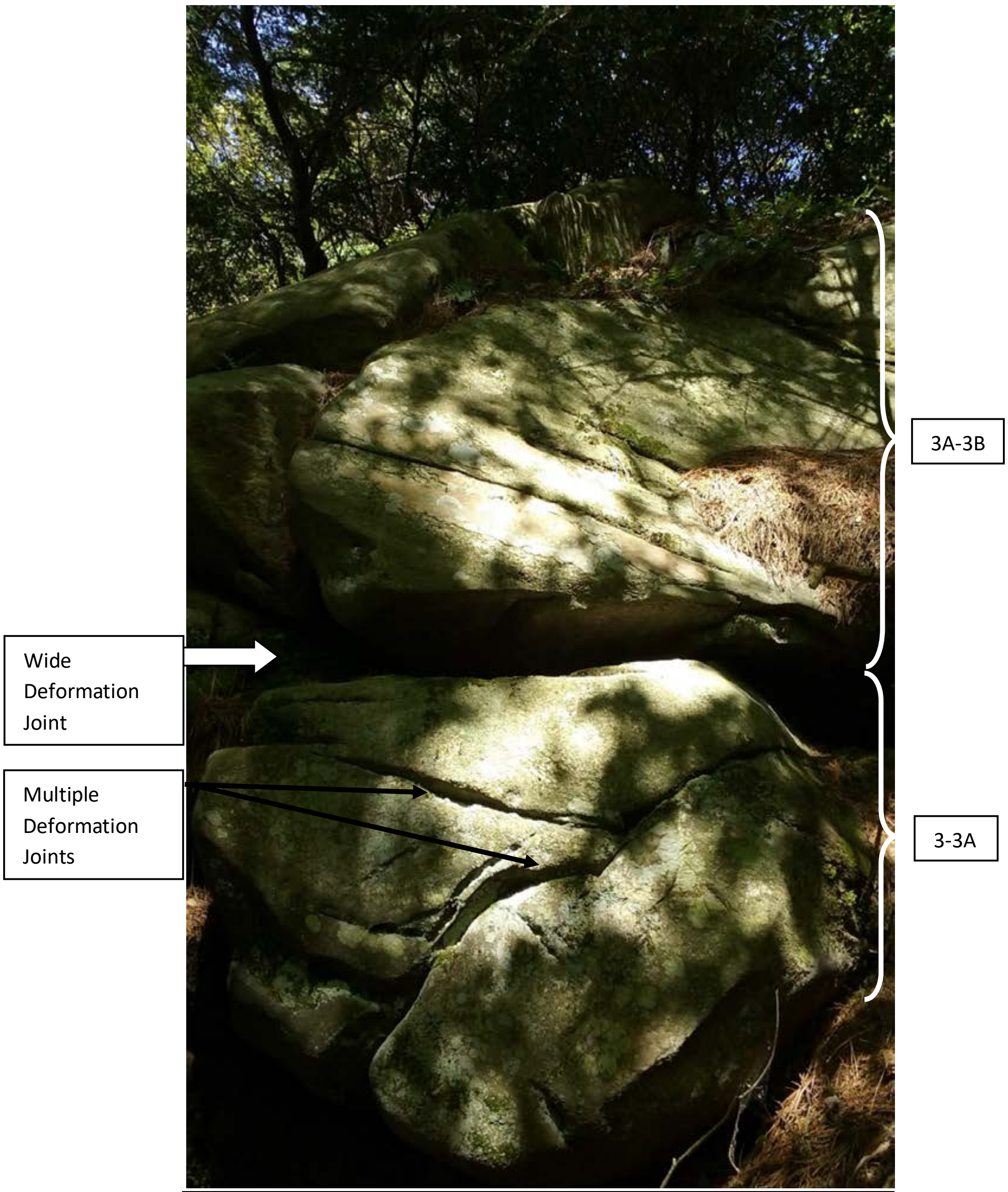

Figure 2.9: (Photo) Full Section: 3– 3B

D. Field Study, Visit #3–2019 (June)

For this visit, I again reviewed Compton's recommended field study to ensure I captured everything that I needed and added numbers for correlation (see Appendix A). The scope of my third and final field study visit was limited to the following objectives:

1. Perform reconnaissance: Check feasibility of mapping entire horizontal along grade - if safe? If not, how many points can I do safely?
2. For #5, measure thickness, (depth), at leftmost location 1.
3. For #6, Identify rock at location 4, second location from left, adjacent to location 1 on the Outcrop Photograph Reference Map.
4. For #7, Get location on map profile for the sedimentary rock sample (contact). Identify rock units adjacent to the sandstone.
5. For #11, if sandstone to quartzite, is contact sharp or gradual?
6. For #11, attempt to locate chert nonconformity on outcrop body, bring binoculars.

Field Materials:

- Tape Measure: 16ft
- Magnifier for Rock Unit Identification: Carson MicroBrite Plus 60x-120x Power LED Lighted Pocket Microscope (MM-300)
- Smart Phone Camera
- Clipboard
- Graph Paper - copy of profile map
- Two Pens
- Headlamp
- Small Backpack
- Binoculars

Regarding my reconnaissance objective, field study results determined that this was feasible and safe. My original plan was to map in 16 sections in subsequent visits, identify rocks, measure vertical bedding widths, then extrapolate vertically based on photographs. However, I decided not to pursue this effort because I believe this would not have provided enough value added for the purpose of this course. The remaining objective results from this field study visit are captured in the following section.

E. Field Study Notes

The field notes as described in "Geology in the Field", by Robert R. Compton, see Appendix A, were used as a guideline to observe and study the outcrop in the field (1-13) – which represents the *objective* data collected as a result of my field study visits. The final number 14, "Interpretation of the unit", will be presented in the next section – Interpretations.

1. Stratigraphic Name of Unit: Cheshire Quartzite, The Cobbles outcrop.
2. Location: Cheshire, MA, at 73° 8′ 30″ West Longitude and 42° 33′ 00″ North Latitude, Elevation 1800ft.
3. Nature of the terrain: Near peak of mountain, forested, high relief (i.e. elevation changes).
4. Overall shape or structure of the rock unit in this area: Planar.
5. Thickness of the unit. Thickness at leftmost location 1 measured about 19ft depth from the face to the face of another structure expected to be of the same unit that likely continues down slope of the mountain another 100ft.
6. Principal rock = quartzite, as identified at all marked locations 1, 2, 3, and 4 on the reference map. Collected one rock sample during Visit #2 - quartzite found at location 1. No samples observed at locations 2 and 3 probably due to slope, where rocks would be susceptible to gravity and be transported down to location 1 where there is a limited plateau before the slope continues downhill. There are many quartzite rock samples in this plateau.
7. Unusual rocks – collected four rock samples during Visit #1:
    - Chert + Quartzite (2), contact rocks: One was found at base of location 1. The other one of these samples was found on the trail to the outcrop; which may or may not be part of this outcrop, could be from a nearby outcrop. For the purposes of this course - assumed to be part of this outcrop and transported downhill by gravity and/or water.
    - Sandstone (1): Photographed and marked the location where the sedimentary rock sample was taken. The rock unit directly above the sandstone sample collected is also sandstone; therefore, it is likely part of the same rock unit. All surrounding rock appeared to be quartzite. Using the tree base at location 2 for reference, measured horizontal distance of about 5ft down slope and about 6ft 2in high above grade. With this information, I was able to mark the location on the Outcrop Photograph Reference Map as Sandstone Nonconformity.
    - Chert + Sandstone (1), a contact rock: Found at base of location 1.

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The following figure is a photo of the rock samples collected during the field visits, where 4 of the 5 (a-d) represent unusual rocks, as nonconformities. These four samples were collected during my first field study visit. The 5th (e), collected during my second field study visit, represents a sample of the principal rock. The description of each follows.

a. *top-left: sandstone (collected off the outcrop at location marked Sandstone Nonconformity on the Outcrop Photograph Reference Map)*
b. *top-middle: chert on sandstone (found at outcrop base)*
c. *top-right: chert on quartzite (found on trail about 1/2 mile down slope below outcrop)*
d. *bottom-left: chert on quartzite (found at outcrop base)*
e. *bottom-right: quartzite (found at outcrop base)*

Figure 2.10: (Photo) Outcrop Samples - The Nonconformities

8. Primary structures in the unit: tabular vertical bedding
9. Fossils. There was no evidence of fossils found. Likely since quartzite, fossils would have been destroyed by the transformation from the parent sedimentary rock into the metamorphosed quartzite rock.
10. Description of rocks, most abundant kind first. Not used.

Although objective field notes include rock color, I am not. By experience in rock identification in 2018, I included color first and often misidentified rocks. Since color is primarily due to the mineralogy present, it is not required for rock identification. Therefore, I am not considering rock color for the purposes of this course.

11. Contacts (fig. 2.10).
    A. Sandstone nonconformity: The contact was sharp for the sandstone to quartzite which is expected for an unconformity.
        - The sandstone deposit represents an unconformity.
        - The contact can be located in the field using the Outcrop Photograph Reference Map.
    B. Unable to locate a chert contact in outcrop body. Binoculars view too close in most cases, therefore, could not get an in focus view. Terrain too steep and wooded to move out farther from outcrop in order to get a clearer view using binoculars.
    C. Scour: Observed at base of rock unit at location 1-1A and 4-4A was evidence of scour. See section photographs and the Outcrop Photograph Reference Map.
12. Characteristic secondary features: quartzite rock structure appears to be highly deformed, with many joints. Sediments appear to have filled some vertical gaps in the quartzite, subsequently turning into sandstone rock.
13. Characteristics for distinguishing this unit from all others in the area: Largest outcrop closest to The Cobbles peak overlook view.

III. Interpretations

A. Introduction

As discussed in the previous section, a field study typically concludes with an interpretation of the outcrop. The final number 14, "Interpretation of the unit" in the field notes as described by Geology in the Field, by Robert R. Compton, see Appendix A, was used as a guideline to help interpret the *objective* data collected; which includes the following:

- Geologic environment or conditions under which the unit was originally deposited or crystallized
- Specific processes contributing to its origin
- Genetic relations to associated rocks
- Later modifications within the rock at grain-scale, as cementation, compaction, autometamorphism, and recrystallization
- Tectonic and other structural modifications
- Geologic age of the unit or age relations to other rock units

Based on my field study observations and other research that I performed, to include the work cited, this section represents my interpretations of the petrogenesis of The Cobbles outcrop.

Firstly, my petrogenesis interpretation began with identification of the principal rock unit during my field study observations as quartzite, a metamorphic rock. This identification is also supported by Norman Herz while working at the USGS [Ref.1 and Ref.2] with the following excerpt:

> *"The Cheshire quartzite of Early Cambrian age...The major part of the formation is a relatively pure white or light gray massive quartzite containing about 99 percent quartz. This massive facies is very resistant and underlies some of the highest hills in the southeast part of the quadrangle, including The Cobbles in the town of Cheshire..."*

Secondly, also found during my field study observations, the sedimentary rock nonconformity on The Cobbles quartzite outcrop is very significant. This finding alone, describes the following four major geological events that must have occurred in sequence [Christiansen & Hamblin]:

1) creation of ancient rock
2) metamorphism
3) uplift and erosion
4) deposition of younger sedimentary rock

Finally, as discussed thoughout the following subsections, changes from geological events generally can take tens of millions of years.

B. Major Event Sequences

1. Ancient Sedimentary Sandstone Strata Formation

600 - 530 million years ago (mya), the area was under a warm, shallow ocean [Appendix B – Mount Greylock]. This is also supported by Brookfield as follows:

> "*Epicontinental (epeiric) seas, are extensive shallow seas that covered vast areas of continents at particular times in earth history. The Middle Ordovician seas of North America stretched, almost unbroken by land, across the entire continent.*"

During this time (and most likely prior), sediments were laid down horizontally on the sea floor in a marine environment. This created layers of sediments, mechanically weathered debris, which accumulated on the shallow ocean sea floor over millions of years. These layers of sediments formed the most common of sedimentary rock structures, beds, subsequently cementing into the clastic sedimentary rock sandstone. These sandstone bedding structures represents the parent sedimentary rock facies, lateral (i.e. side to side), of the Cheshire quartzite. This is also supported by Christiansen & Hamblin referring to metamorphic rock formations of the Appalachian Mountains:

> *"The parents were deposited as horizontal beds of sediment about 600 million years ago."*

Following this long period (≈530 mya) towards the middle of the Cambrian, the final geologic environment was an epicontinental sea; with The Cobbles part of the sea bed as layers of the sedimentary rock, sandstone.

2. Subduction & Metamorphism to Quartzite

<u>Between 530 to 500 mya</u>, located in the forearc of an ocean-continent convergent plate boundary as depicted in the following figure, this cold slab (i.e. the ancient sandstone strata) was subducted to great depths. Consequently, this quartzite was created from high pressure-low temperature metamorphism as the oceanic lithosphere of the paleoocean, the Iapetus Ocean, subducted beneath the paleocontinent Laurentia just prior to the Taconic Orogeny (described in the next section). For supporting work cited, see Appendices C & D: Shown as Cc (Cheshire quartzite) in Appendix C [Herz Ref.2] with its geological age of Lower Cambrian in Appendix D [Herz Ref.1].

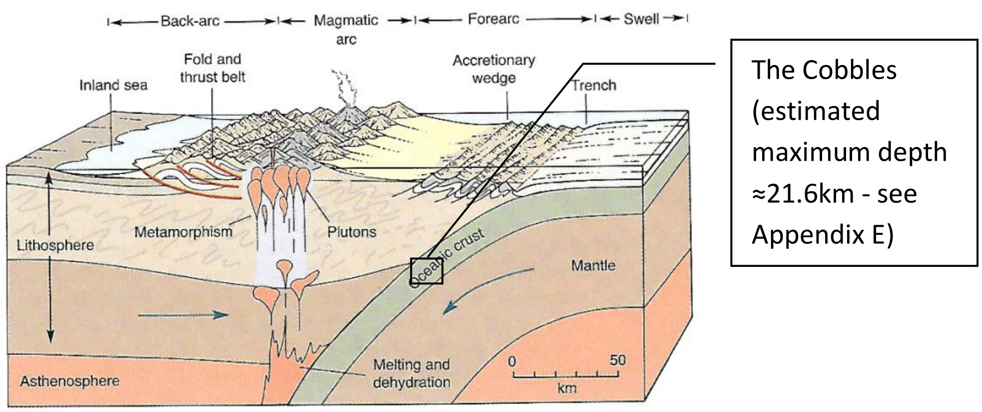

Figure 3.1: Ocean-Continent Convergent Plate Boundaries
Reprint: Figure 21.3 ocean-continent convergent plate boundaries, pg632 [Christiansen & Hamblin]

Geological characteristics of many ocean-continent convergent plate boundaries include the following [Christiansen & Hamblin]:

- accretionary wedge

- continental margin deformation into a folded mountain belt
- high pressure-high temperature metamorphism in the mountain roots
- partial melting of the continental mantle
- igneous rock formation: volcanic (e.g. andesite) and plutonic (e.g. diorite)
- volcanism
- granitic batholiths
- deep zone orogenic metamorphosed sedimentary rocks

It is this last characterization, metamorphosed sedimentary rock, that represents the petrogenesis of The Cobbles. This is supported by Herz [Ref. 1] in the following excerpt:

> *"Metamorphism during the Paleozoic changed sediments to their metamorphic equivalents. The sandstones became quartzites."*

A great force, called slab-pull, pulled the relict sandstone strata (slab) to the great depths to metamorphose into the quartzite; and rotated it from horizontal to vertical as can be seen by the preserved vertical relict bedding structure of the outcrop in my field study photographs. This slab-pull force pulled the lithosphere of the epicontinental sea into the aesthenosphere as a result of subduction at this ocean-continent convergent plate boundary. In effect, the denser heavier oceanic plate (i.e. slab) sunk beneath the lighter continental plate. However, The Cobbles did not descend into the asthenosphere (see previous figure for estimated maximum depth).

Following the subduction (≈500 mya) towards the end of the Cambrian, the final geologic environment was tectonically convergent (ocean-continent); with The Cobbles plunged to great depths and metamorphosed into quartzite.

3. Tectonic Convergence and The Orogenies

Between 500 to 300 mya, tectonic processes from a series of three mountain building events uplifted The Cobbles, moved the area northward, and would transform this epicontinental sea into a great mountain range comparable to the Himalayas of today [Mt. Greylock Visitors Center]. Mountain ranges are generally classified as young or old, 0-100 or 100-500 million years of age respectively. The Rocky Mountains are an example of a young mountain range. The Cobbles is a part of an old mountain range – the Appalachain Mountains. This mountain building event is also supported by Christiansen & Hamblin as follows:

> *"The Appalachian Mountains in the eastern United States were deformed several times in the Paleozoic Era (about 500 to 300 mya)." During some part of its history..."experienced subduction of oceanic lithosphere beneath a continental margin."*

The Appalachian Mountains were formed from a series of three orogenies: Taconic, Acadian, and Alleghenian.

Compression of the Appalachians was due to the subduction of oceanic lithosphere during the first two orogenies; followed by a continental collision which represents the third and last of the orogenies.

The first two orogenies were ocean-continent tectonic convergent type – Taconic and Acadian. The Taconic Orogeny started about 470 mya [Jamestown] when the Taconic island arc converged with Laurentia. This first orogenic event continued for the next 25 million years, creating tight folding, thrust faulting, and volcanism. The Acadian Orogeny started about 430 to 425 mya [Jamestown] when Baltica and Avalonian arc converged with Laurentia. This second orogenic event continued for the next 40 million years, also creating tight folding, thrust faulting, and volcanism. The following figures provide an overview of these two mountain building processes that added most of what is now New England to the east coast of Laurentia – and represents the series of collisions that added land from eastern Canada to the Carolinas. Note the Latitude 0 to 30°S (compared to present day of 30°N to 60°N respectively) and the shallow seas covering the eastern coast of North America; with The Cobbles approximate location indicated by an asterisk (*). This environment and location is also supported by the Mt. Greylock Visitors Center as follows:

> *"Near the beginning of this period, this was an area still underwater, located where Brazil is today, about 500 million years ago."*

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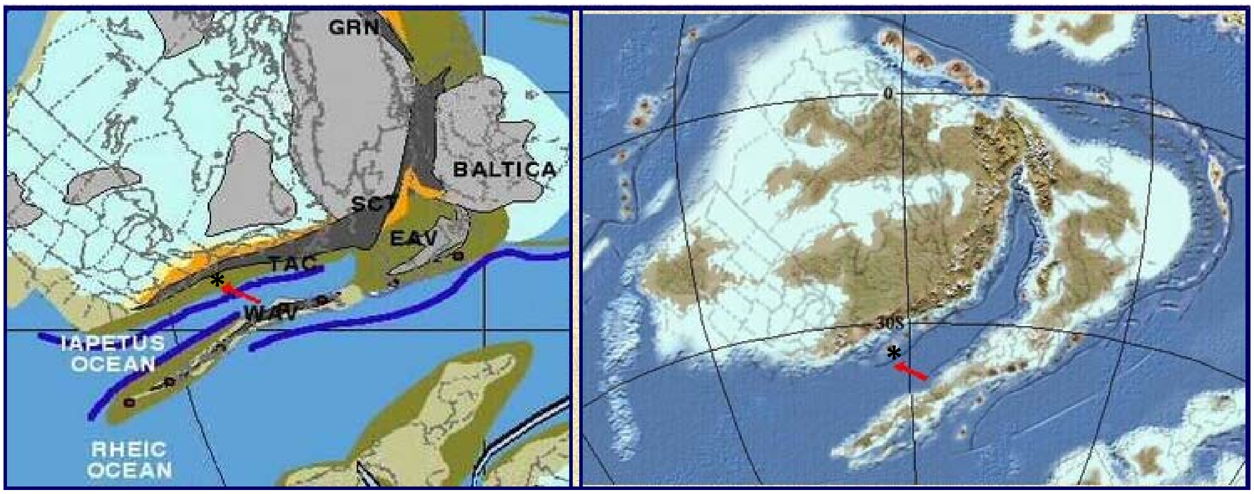


Schematic View **Pictorial View**

Key: TAC-Taconic island Chain, WAV-Western Avalonia, EAV-Eastern Avalonia

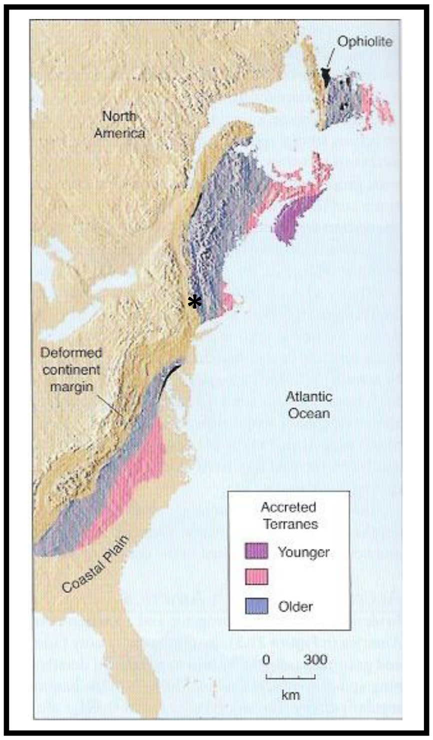
Figure 3.2: Orogenies - Taconic & Acadian Paleographic Views

Reprint: [Jamestown] Credit: Dr. Ron Blakely, Northern Arizona University

The previous views show how Western & Eastern Avalonia (Part of the Acadian Orogeny) followed the Taconic Arc and therefore closed the Iapetus Ocean – accreting both (Avalonia & oceanic crust) to the eastern coast of present day North America [Jamestown].

The Alleghenian Orogeny, the third and final of this series of mountain building events, was a continent-continent tectonic convergence which included the complete subduction of the oceanic crust. This was the convergence of Laurasia and Gondwanaland starting about 356 mya [Jamestown]; joining present day Eastern United States with North Africa. Laurasia, the ancient continental landmass that consisted of: Europe, Asia, North America, and Greenland; converged with Gondwanaland, the ancient continental landmass that consisted of: South America, Africa, India, Australia, and Antarctica; to form the supercontinent Pangaea. This orogenic event continued for tens of millions of years which created tight folding and thrust faulting, and represents the final process in the creation of the Appalachian Mountains.

Consequently, as a result of these three orogenies, eastern North America contains accreted (i.e. added or accumulated) terranes as shown in the following figure; with The Cobbles approximate location indicated by an asterisk (*). These accretions were parts of ancient Europe, Africa, island arcs, and oceanic islands.



Eastern North America Accretions
Reprint: Figure 21.30 Accreted terranes, pg662 [Christiansen & Hamblin]

New England Accretions
Reprint: [Jamestown]

Figure 3.3: Accreted Terranes

The accretions shown in the two views in the previous figure correlate well, and are from two different sources. The Iapetus Ocean was accreted to Laurentia, forming a band of younger terrane between the older Laurentian and Avalonian terranes [Jamestown]. This terrane is shown in both views of the previous figure, the "Older" blue in left figure, and is light grey in right view. This now metamorphosed material is found in the present states of Maine, New Hampshire and Vermont plus major parts of Massachusetts and Connecticut. Iapetus Terrane typically contains schist, phyllite, gneiss and granite. Avalon Terrane is shown in dark grey in right view. This also correlates well with the accretions depicted in the other source, as you can see the Eastern North America Accretions as pink in the left view. Avalonian Arc material can also be found south in South Carolina and north in New Brunswick, Newfoundland, and Nova Scotia [Jamestown]; as can also be seen as pink in the left view.

Most likely, Mt. Greylock represents part of the previously mentioned accretion. This is also supported by Herz [Ref.1] referencing nearby Mt Greylock and its principal rock unit – schist as follows:

"The Greylock schist, in fact, appears to represent a flysch of the Taconic orogeny."

However, nearby The Cobbles is not an accretion, although accretionary cycles helped uplift The Cobbles towards the surface. Accretionary wedges contain folds of all sizes as can be seen in the following figure.

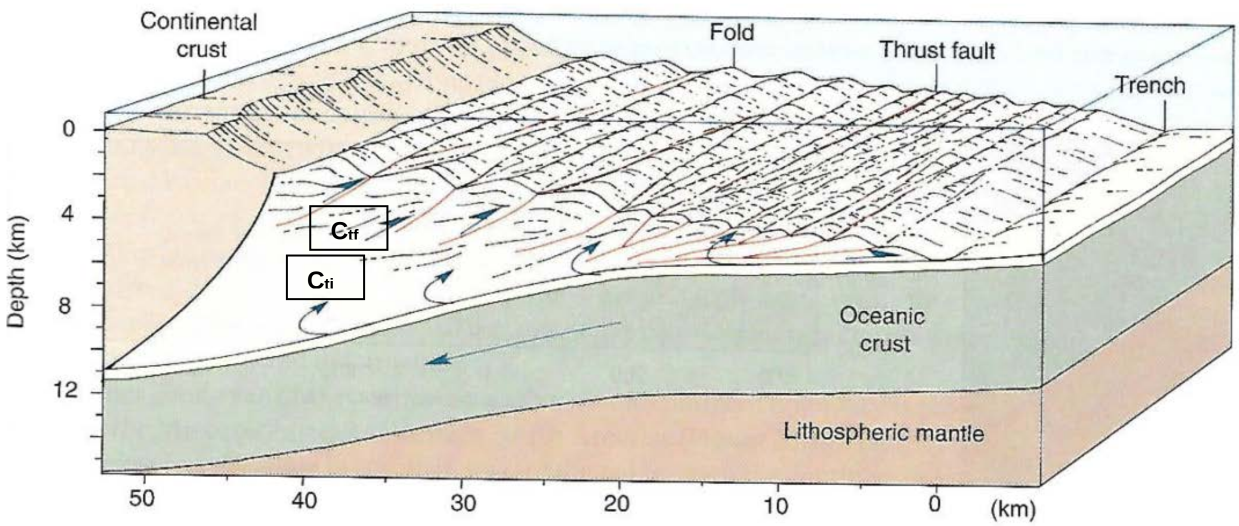


Figure 3.4: Accretionary Cycles
Reprint: Figure 21.10 Accretionary wedges, pg639 [Christiansen & Hamblin]

Continuous subduction of the oceanic crust scrapes off more sediment, which pushes older deeper rocks like The Cobbles above it higher (as depicted in the previous figure). This is represented by C_{ti} (The Cobbles at its initial time) and C_{tf} (The Cobbles at its final time); where ti (time initial) is the start of the first accretionary cycle and tf (time final) is the end of the last accretionary cycle. Note: use of previous figure was used to help describe uplift by accretionary cycles; actual values for these depths of The Cobbles is thought to be much deeper, where $C_{ti} \approx$ 21.6km and $C_{tf} \approx$19.8km.

This 200 million year span represents a "violent" time in the petrogenesis of The Cobbles; where scars in the form of joints and microcracks as a result of brittle deformation can be observed on the outcrop. This deformation is due to the excessive compression that was applied to the rock structure; where the compressive forces exceeded the rock units compressive strength, consequently causing it to fracture.

This fracturing can also be described by the following general Hooke's Law equation for anisotropic rocks and minerals, a stress vs strain relationship; where each of the 9 components of strain (ε) is linearly related to the 9 components of stress (σ) as follows, for example, ε_{xx}:

$$\begin{aligned} \varepsilon_{xx} = \; & s_{1111}\sigma_{xx} + s_{1112}\sigma_{xy} + s_{1113}\sigma_{xz} \\ & + s_{1121}\sigma_{yx} + s_{1122}\sigma_{yy} + s_{1123}\sigma_{yz} \\ & + s_{1131}\sigma_{zx} + s_{1132}\sigma_{zx} + s_{1133}\sigma_{zz} \end{aligned}$$

...where each variable is defined as

ε_{ij} = strain, 9 components as defined by subscripts ***ij***

s_{ijkl} = constants of proportionality;
where subscripts ***ij*** = strain component, and ***kl*** = stress component

σ_{ij} = stress, 9 components as defined by subscripts ***ij***

Where as defined by the rocks stress-strain function (i.e. deformation curve), a failure will occur if any of the 9 strain components reaches its fracture point.

Following the three orogenies (≈300 mya) towards the end of the Pennsylvanian, the final geologic environment was orogenic – high, much like today's Rocky Mountains; where The Cobbles was uplifted by accretion cycles and compression.

4. Tectonic Divergence and Erosion

Continual erosion and simultaneous isostatic adjustment (uplift) best describe the **last 300 million years** of The Cobbles. About 179 million years ago to present, the North American and African plates began to diverge as the mid-atlantic ridge formed and began moving the plates apart by sea-floor spreading; and consequently, a long period of erosion and isostatic adjustments.

Isostasy is a state of equilibrium which may best be described using the sequence in the following figure. As erosion removes rock, there is an isostatic adjustment up, similar to what would happen after rocks were removed from a rock pile ontop a trampoline – a Δmass adjustment.

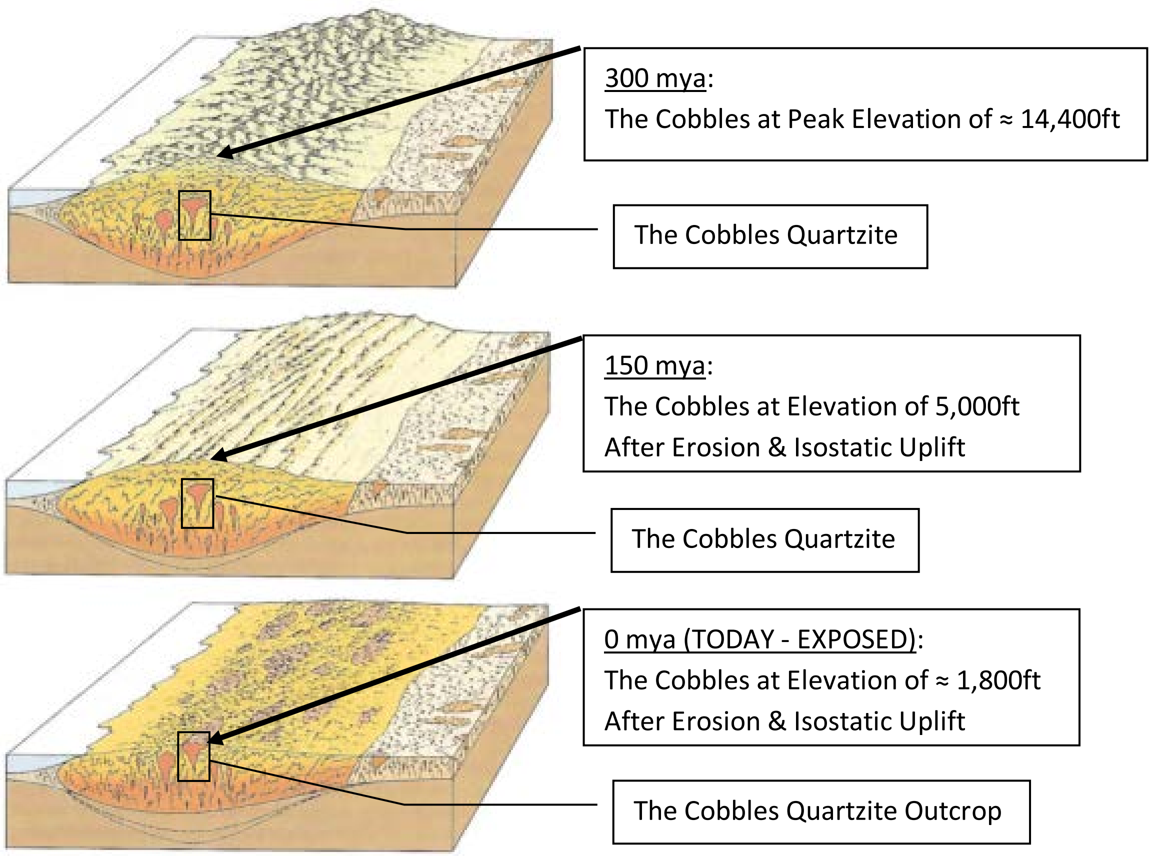


Figure 3.5: The Cobbles Erosion & Isostasy
Reprint: Figure 23.4 A Continental Shield Develops, pg701 [Christiansen & Hamblin]

Climate changes also impacted the area as The Cobbles moved towards the northern latitudes from the equatorial region. Erosion by less rain and the introduction of a new erosive agent, ice, occurred over the last 100 million years.

More recently, within the last 20 million years, The Cobbles became exposed as an outcrop. After rock fracture joints are exposted to the weather; these joints act like a highway for weather to include: rain, wind, gas, and ice to penetrate deep into the rock unit. Consequently, the weather was able to attack the exposed rock unit; widening the deformation joints and scouring its lower base as can be seen in field study photos. The wide joints were primarily created by frost wedging (synonmous with ice wedging) as a result of the ice age cycles; acting like a wedge to physically weather the rock as water freezes to ice (expanding) then melts back to water.

Following ≈300 million years of erosion and isostatic adjustment, The Cobbles finally breached the ground surface and is now exposed as an outcrop. Its final geologic environment in today's Cenozoic, is orogenic – low, representative of an old mountain range that is part of The Appalachains.

5. Deposition and The Nonconformities

As the quartzite inched closer to sea-level, **20-40 mya**, the sandstone and chert unconformities formed. Unconformities in geology generally means that a rock structure or unit does not "conform" to the surrounding geological structures or units; in other words, an unusual or unexpected rock. This type of unconformity is known as a nonconformity; that is, sedimentary rock on metamorphic (or igneous) rock.

The major factors in the petrogenesis of these nonconformities were derived from two characteristics attributed to the shallower depths as The Cobbles neared sea-level. At these depths, a combination of lower pressure and groundwater flow conditions prevailed. Lower pressures allowed pore spaces to open around the massive quartzite and groundwater transported the weathered silica sediments or aqueous solutions into them.

Porosity (***n***) variations with depth can also be described by the following equation, an exponential function; where depth and effective stress have a linear correlation, as depth and stress increase, porosity exponentially decreases.

$$n = n_0 e^{-\sigma_e \beta}$$

...where each variable is defined as

n	=	porosity
n_0	=	surface porosity (assumed)
σ_e	=	effective stress
β	=	compressibility

The first nonconformity identified from my field study are the remnants of a dike, consisting of the clastic sedimentary rock – sandstone. Quartz sediments (i.e. sand) weathered from the quartzite principal rock unit and filled the pore spaces by a combination of solute and mechanical transportation; which subsequently compacted and cemented into a sandstone dike.

Under these same environmental conditions, another nonconformity spawned the chemical sedimentary rock – chert. Thin chemical sediments in the form of silica oozes, transported in solution, filling some gaps as a pore fluid in the primary quartzite rock units; subsequently forming a solution and recrystallizing into a chert vein or cavity filling. Some of this chert also bonded to some of the sandstone and quartzite rock as can be seen in three of the five rock samples collected during my observations in the field.

As previously discussed, within the last 20 million years, The Cobbles Cheshire quartzite became exposed as an outcrop; and with it – these nonconformities.

IV. Conclusion

This course demonstrated how tectonic and hydrologic systems have shaped our landscapes of today. Based on my field study observations and interpretations, this course recreated the petrogenesis of The Cobbles outcrop over the last 600 million years.

The final two pages of this section includes both a table and a figure respectively; these provide a summary of my interpretation – both should tell the complete story of The Cobbles petrogenesis individually, and compliment each other when analyzed together.

The curves track the elevations of quartzite (The Cobbles Track) along with the elevations of the surface terrain above (Peak Track). Refer to Appendix E for elevation curve data point details. Assumptions were first made for the starting Cambrian and ending Cenozoic elevations. Using assumptions for erosion and isostatic uplift rates based on Christiansen & Hamblin, the remaining middle time periods were interpolated and filled in. Note, the elevations do not factor in the sea level changes during this time period which ranged from +350 ft to -150 ft (relative to present day).

As for the future of The Cobbles? Along with the rest of the Appalachian Mountains, it should erode into a shield (<100m (328ft)), unless there are changes in plate tectonics, i.e. direction, velocity; or other significant geological event that can alter the landscape.

Table 4.1: The Cobbles Petrogenesis Summary w/ Major States & Events

Geologic Time (Younger to Older)	State of The Cobbles	Dominant Contributing Event(s) or Geologic Environment	Time Scale (mya)
CENOZOIC	Erosion; & Isostasy Adjustment now EXPOSED	Rain, Ice; Tectonic Divergence	--20
	Erosion & Isostasy Adjustment, Nonconformities	Rain, Ice; Tectonic Divergence; Groundwater	--40
	Erosion & Isostasy Adjustment	Rain, Ice; Tectonic Divergence	--60
CRETACEOUS	Erosion & Isostasy Adjustment	Rain, Ice; Tectonic Divergence	--80
	Erosion & Isostasy Adjustment	Rain, Ice; Tectonic Divergence	--100
	Erosion & Isostasy Adjustment	Rain; Tectonic Divergence	--120
	Erosion & Isostasy Adjustment	Rain; Tectonic Divergence	--140
JURASSIC	Erosion & Isostasy Adjustment	Rain; Tectonic Divergence	--160
	Erosion & Isostasy Adjustment	Rain; Tectonic Divergence	--180
	Erosion & Isostasy Adjustment	Rain; Tropical Equitorial Climate	--200
TRIASSIC	Erosion & Isostasy Adjustment	Rain; Tropical Equitorial Climate	--220
	Erosion & Isostasy Adjustment	Rain; Tropical Equitorial Climate	--240
	Erosion & Isostasy Adjustment	Rain; Tropical Equitorial Climate	--260
PERMIAN	Erosion & Isostasy Adjustment	Rain; Tropical Equitorial Climate	--280
	Erosion & Isostasy Adjustment	Rain; Tropical Equitorial Climate	--300
PENNSYLVANIAN	Uplift by Compression	Tectonic Convergence - Alleghenian Orogeny	--320
MISSISSIPPIAN	Uplift by Compression	Tectonic Convergence - Alleghenian Orogeny	--340
	Uplift by Compression	Tectonic Convergence - Alleghenian Orogeny	--360
DEVONIAN	Erosion & Isostasy Adjustment	Rain; Tropical Equitorial Climate	--380
	Uplift by Accretion Cycles	Tectonic Convergence - Acadian Orogeny	--400
	Uplift by Accretion Cycles	Tectonic Convergence - Acadian Orogeny	--420
SILURIAN	Erosion & Isostasy Adjustment	Rain; Tropical Equitorial Climate	--440
ORDOVICIAN	Uplift by Accretion Cycles	Tectonic Convergence - Taconic Orogeny	--460
	Uplift by Accretion Cycles	Tectonic Convergence - Taconic Orogeny	--480
CAMBRIAN	Uplift by Accretion Cycles	Tectonic Convergence: ocean-continent	--500
	Subduction: 1) Vert. Strata 2) Quartzite Meta.	Tectonic Convergence: ocean-continent	--520
	Sandstone Horizontal Strata	Epicontinental sea - horizontal bedding	--540

Note: Scale for simplicity: each row represents about 20 million years.

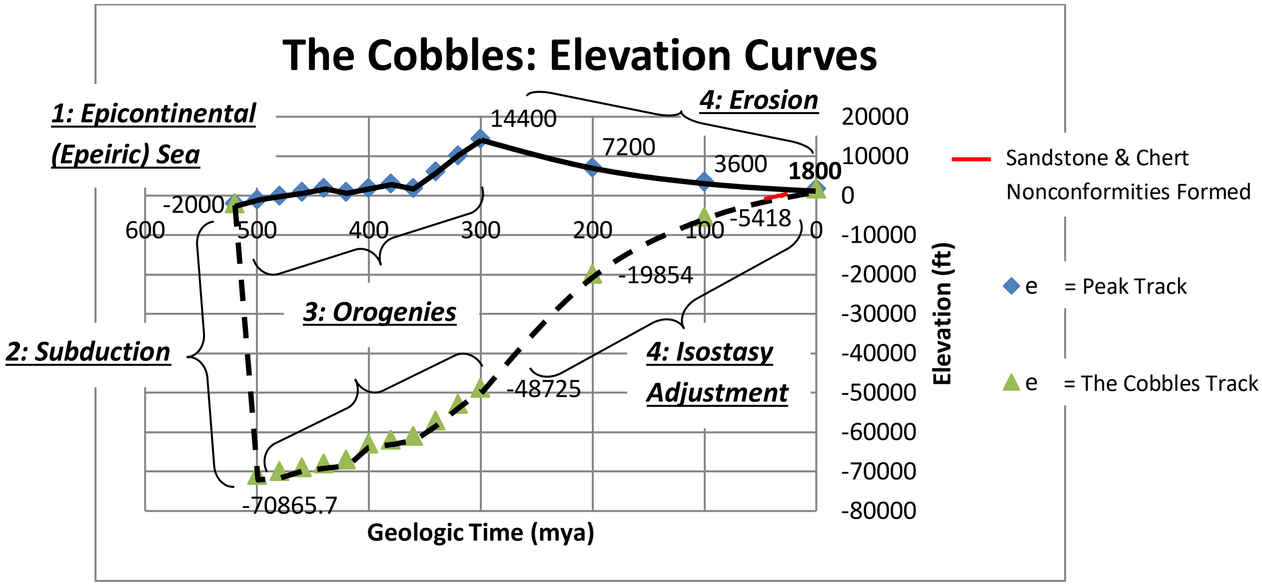


Figure 4.1: The Cobbles Petrogenesis Summary Elevation Curves

Appendix A – Field Study Recommendations

The following is as described in "Geology in the Field", by Robert R. Compton; recommended field study content and order of notes:

"

1. Stratigraphic name of the unit, or its relations to named units.
2. Area to which description applies.
3. Nature of the terrain underlain by the unit— its topography, soils, vegetation, and outcrops.
4. Overall shape or structure of the rock unit in this area.
5. Thickness of the unit.
6. Principal kinds of rocks and their distribution in the unit.
7. Unusual rocks and their stratigraphic (or other) position and genetic implications.
8. Primary structures in the unit.
    a. How bedding or other layer-structures (as flow structures) are expressed, as by color, texture, induration, and so on.
    b. Range of thicknesses and typical thicknesses of beds or other primary layer-structures.
    c. Shapes of beds or other layer-structures.
    d. Primary structures within beds or other structures, as grading, laminations, cross-stratification, channeling, and inclusions.
9. Fossils.
    a. Distribution of fossils, stratigraphically and laterally.
    b. Special characteristics of the more fossiliferous rocks.
    c. Positions and condition of fossils, as growth position, fragmental, rounded, and any signs of reworking (Section 3-7).
10. Description of rocks, most abundant kind first.
    a. Color—fresh, weathered, moist, dry (Appendix 6).
    b. Firmness of fresh and of weathered rock (Appendix 4).
    c. Grain sizes—range and average (or typical) sizes.
    d. Degree of sorting or equigranularity.
    e. Typical shapes of the principal kinds of grains.
    f. Fabrics (orientations) of tabular or linear grains, especially in relation to rock structures.
    g. Kinds and proportion of mineral cements, matrix, or groundmass.
    h. Nature and proportion of pores (porosity) and indications of permeability.
    i. Kinds of grains and the approximate percent by volume of each.
11. Contacts (fig. 3-1).

   a. Sharp or gradational (describe gradations).
   b. Indications of scour, unconformity, intrusive relations, or faulting.
   c. Criterion or criteria for locating the contact in the field.
12. Characteristic secondary features, such as cleavage (fissility), concretions, veins or other fillings, presence of hydrocarbons, and deformational structures, including joints.
13. Characteristics that are particularly useful in distinguishing this unit from all others in the area.
14. Interpretation of the unit.
   a. Geologic environment or conditions under which the unit was originally deposited or crystallized.
   b. Specific processes contributing to its origin.
   c. Genetic relations to associated rocks.
   d. Later modifications within the rock at grain-scale, as cementation, compaction, autometamorphism, and recrystallization.
   e. Tectonic and other structural modifications, as folding (Section 12-3), fracturing (Sections 12-4, 5, and 6), and homogeneous strains (Section 12-2).
   f. Geologic age of the unit or age relations to other rock units.

"

Appendix B – Mount Greylock

Resource used to help support my interpretation based on its local (close) proximity. Therefore, assumption is that they share a similar geological history. Mount Greylock, Adams, MA and The Cobbles, Cheshire, MA are about 6.21 miles (10km) apart: summit-to-summit.

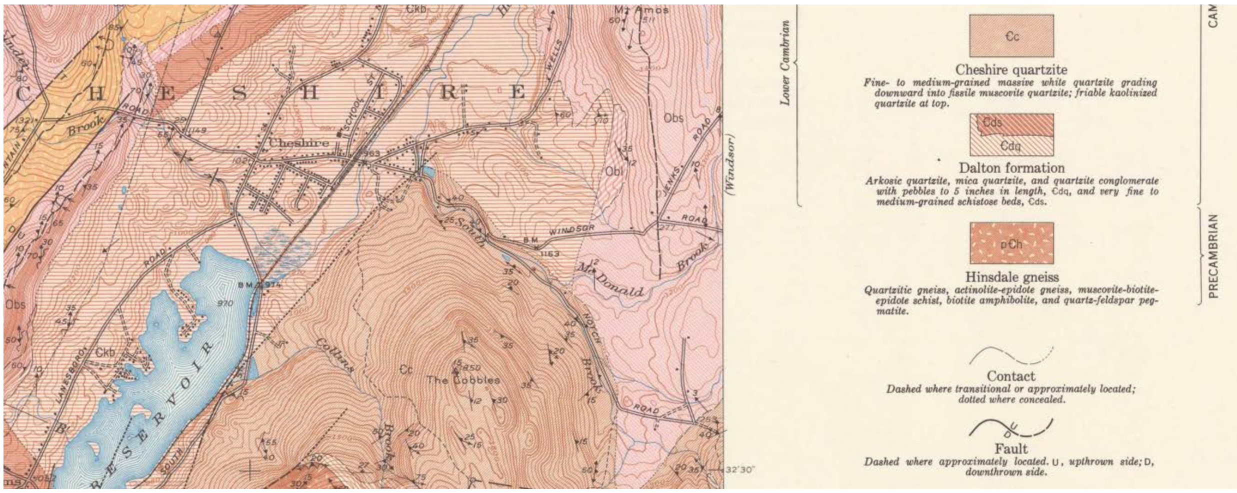
<u>Monument at Summit</u>

"Mount Greylock, Elevation 3,491 Feet

Six hundred million years ago, this area was under a warm, shallow ocean. As the underlying tectonic plates shifted, their continents collided, pushing the land upward into a great range of mountains. The ocean sediments were compressed with tremendous pressure and heat, forming the quartzite, marble, and schist of Mount Greylock. Three hundred million years of continual erosion by wind and rain have created the landscape we see."

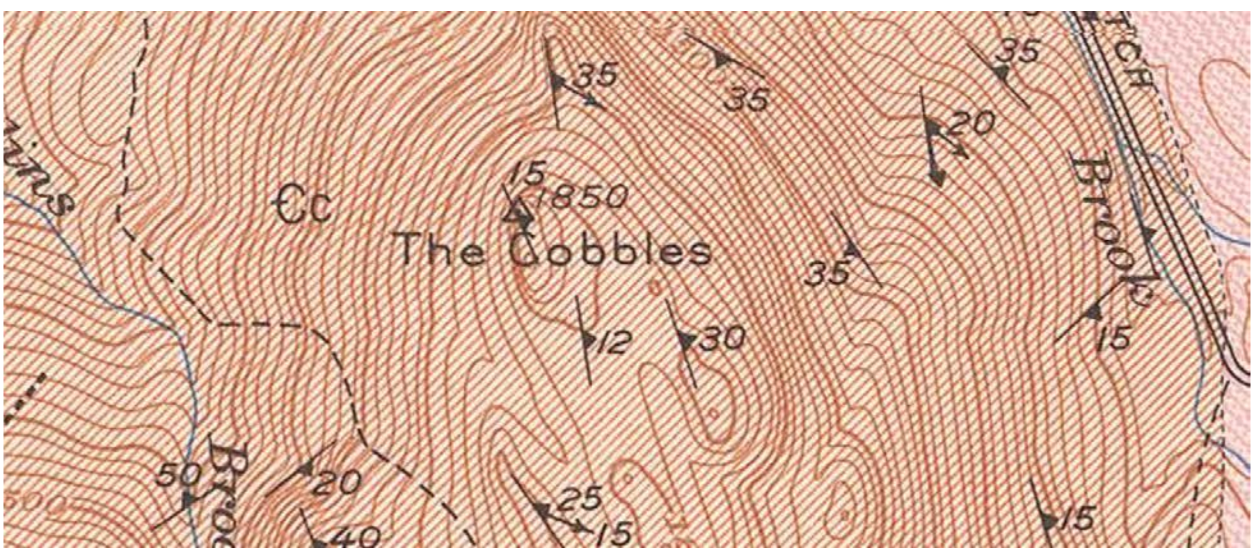
Appendix C – Partial Geologic Map, The Cobbles, Cheshire, MA

Cheshire Quadrangle - 1958



Partial Geologic Map, showing The Cobbles relative to the town of Cheshire, MA
[Herz, Ref.2]

The figure below, is a "Zoomed-In" view of the map above, captures the strike and dip of the outcrop, along a N-S strike line, dipping to the East at 15 degrees (near vertical).



Partial Geologic Map - "Zoomed-In", The Cobbles, Cheshire, MA [Herz, Ref.2]

Appendix D – Correlation Table of Metamorphosed Sedimentary Rocks

Cheshire Quadrangle - 1958: Table 1. [Herz, Ref.1]

Used as supporting evidence for beginning petrogenesis of The Cobbles – Cheshire quartzite during the Lower Cambrian. Note: All four sources (columns) support this interpretation of the geological time for the Cheshire quartzite petrogenesis.

TABLE 1. CORRELATION OF METAMORPHOSED SEDIMENTARY ROCKS

SYSTEM	SERIES	CHESHIRE, MASS. This report	BENNINGTON, VT. MacFadyen (1956)	RUTLAND, VT. Brace (1953)	WESTERN MASSACHUSETTS Dale (1923), Emerson (1917)
ORDOVICIAN	Middle	Greylock schist	Mt. Anthony formation	Hortonville slate	Greylock schist
ORDOVICIAN	Middle	Berkshire schist: Schistose marble; Black schist; Schistose marble, schistose quartzite, graphitic schist	Mt. Anthony formation; Walloomsac slate	Hortonville slate	Bellowspipe limestone; Berkshire schist
ORDOVICIAN	Lower	Stockbridge group: Bascom formation; Shelburne marble	Canadian limestone	Marble	Stockbridge group: Calcitic limestone Horizon III
CAMBRIAN	Upper	Clarendon Springs dolomite	Clarendon Springs dolomite	Clarendon Springs dolomite	Dolomitic limestone Horizon II
CAMBRIAN	?	Danby (?) formation equivalents	Danby formation	Danby formation	
CAMBRIAN		Kitchen Brook dolomite	Winooski dolomite; Monkton quartzite; Dunham dolomite	Winooski dolomite; Monkton quartzite; Dunham dolomite	
CAMBRIAN	Lower	Cheshire quartzite	Cheshire quartzite	Cheshire quartzite	Cheshire quartzite
CAMBRIAN	Lower	Dalton formation: Schistose, Quartzose	Mendon formation: Moosalamoo member, Nickwacket member	Mendon formation: Moosalamoo member, Forestdale member, Nickwacket member	Dalton formation
PRECAMBRIAN		Hinsdale gneiss	Stamford granite gneiss; Mount Holly gneiss	Wilcox formation; Mount Holly complex	Hinsdale gneiss

Appendix E – The Cobbles Elevation Curve Data Points

Elevations based on: assumptions, calculations, observations, estimations, interpolations and extrapolations.
Assumption: Isostatic adjustment occurs constantly at a ratio of 4:5; a net lowering of 100m of the mountain surface means that 400m of isostatic uplift occurred for every 500m of rock that was removed by erosion [Christiansen & Hamblin].

t	520	500	480	460	440	420
e	-2000	-1000	0	1000	2000	1000
t	520	500	480	460	440	420
e	-2000	-70865.7	-69865.7	-68865.7	-67865.7	-66865.7
	Start - Epi. Sea	Subduction & Taconic Orogeny				Erosion & Isostasy

(1) (2) (f)

(1) Assumption: Based on Maximum Epicontinental Sea Depth
(2) Average of -10km to -40km range of metamorphism; estimated -21.6km is within this range; estimated generally by extrapolations from current elevation. Note: Isostatic adjustments during last 300 million years support this extreme depth.
(f) 1000ft = 305m/100m = 3.05 = 3 adjustments x 500m; 5/4 ratio = 1,500m rock removed : 1,200m (3,937ft) iso. uplift

400	380	360	340	320	300
2000	3000	2000	6133.333	10266.67	14400
400	380	360	340	320	300
-62928.7	-61928.7	-60928.7	-56991.7	-52858.3	-48725
Acadian Orogeny - Small Scale Mountain Building Event		Erosion & Isostasy	Alleghenian Orogeny - Large Scale Mountain Building Event		

(f) (g)

(f) 1000ft = 305m/100m = 3.05 = 3 adjustments x 500m; 5/4 ratio = 1,500m rock removed : 1,200m (3,937ft) iso. uplift
(g) 14,400ft peak: Assumption based on 300 million years of erosion and isostasy, and extrapolated from current 1,800ft elevation. Note: This interpretation is supported by nearby Mt. Greylock, 6 miles away, which may have been 20,000ft in peak elevation [Mt. Greylock Visitors Center] – and is now 3,491ft.

340	320	300	200	100	0
6133.333	10266.67	14400	7200	3600	1800
340	320	300	200	100	0
-56991.7	-52858.3	-48725	-19854	-5418	1800
Alleghenian Orogeny - Large Scale Mountain Building Event			Erosion & Isostasy		

(a) (b) (c) (x)

(a) 7200ft = 2195m/100m = 21.95 = 22 adjustments x 500m; 5/4 ratio = 11,000m rock removed : 8,800m (28,871ft) iso. uplift
(b) 3600ft = 1097m/100m = 10.91 = 11 adjustments x 500m; 5/4 ratio = 5,500m rock removed : 4,400m (14,436ft) iso. uplift
(c) 1800ft = 549m/100m = 5.59 = 5.5 adjustments x 500m; 5/4 ratio = 2,700m rock removed : 2,200m (7,218ft) iso. uplift
(x) 1800ft, by objective scientific data from measurements: Today's Elevation

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