Take a walk through the geological history of Manhattan at Hernshead in Central Park

A short field guide

GPS coordinates for relevant outcrops:

Graphic granite - N40°46.650, W073°58.365

Vein quartz - N40°46.650, W073°58.373

Granofels - N40°46.654, W073°58.373

Metapelite - N40°46.653, W073°58.370

Biotite-garnet schist (amphibolite) - N40°46.655, W073°58.363

Fold hinge - N40°46.645, W073°58.374

Decompression cracks - N40°46.662, W073°58.358

Note: all GPS datum is record using WGS-84 in degrees, decimal minutes

The information and data presented in this document were created by the graduates of the Masters of Arts in Teaching (MAT) program at the American Museum of Natural History in 2016. Among the goals of this research program is the production/development of engaging and educational exercises in Earth Science that can be conducted in the urban Manhattan environment. Contributors to this work include Arthur Funk, Hali Englert, Sean Krepski, Caitlan Tully, Nicholas Tailby, George Harlow, James Webster and Denton Ebel.

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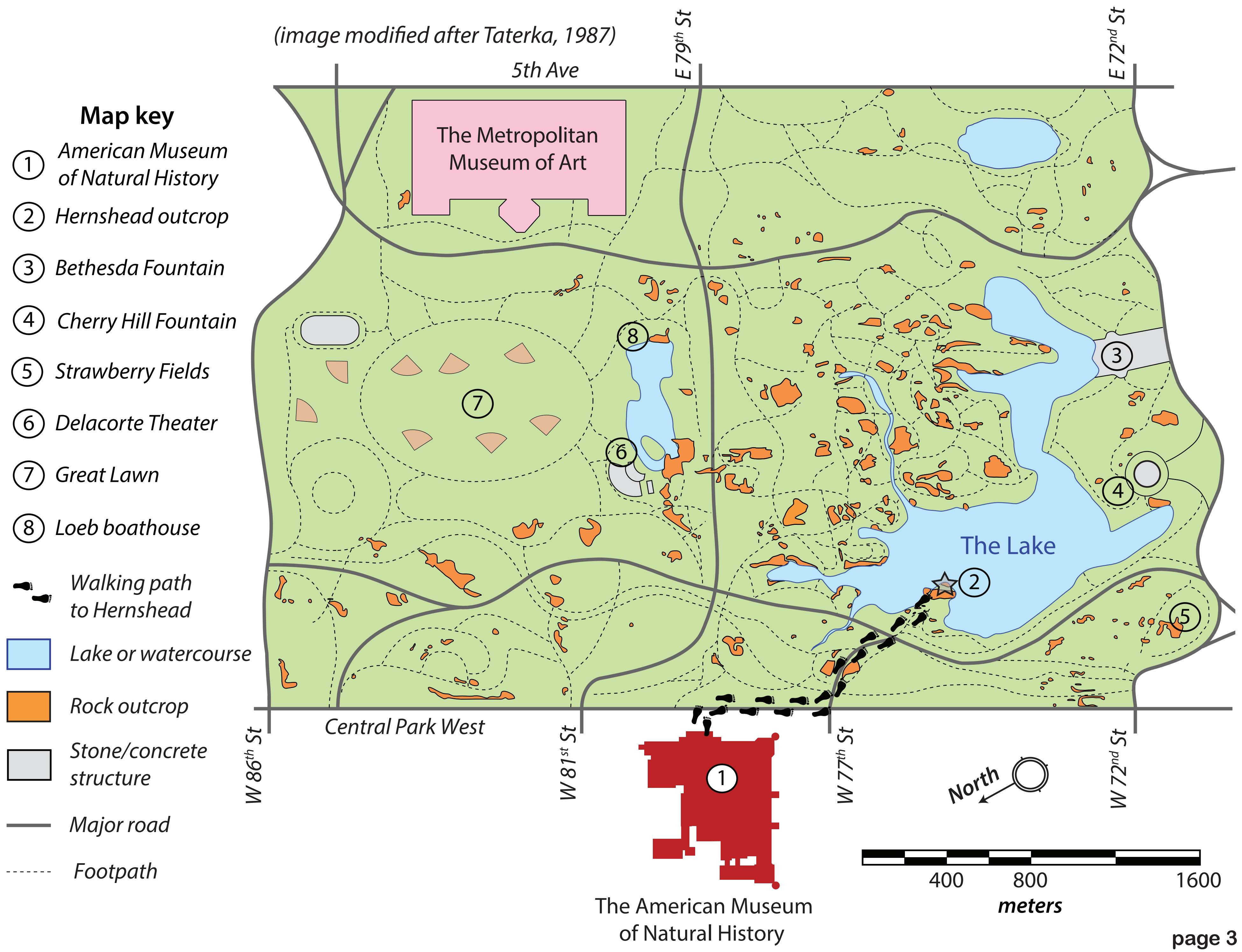
American Museum of Natural History

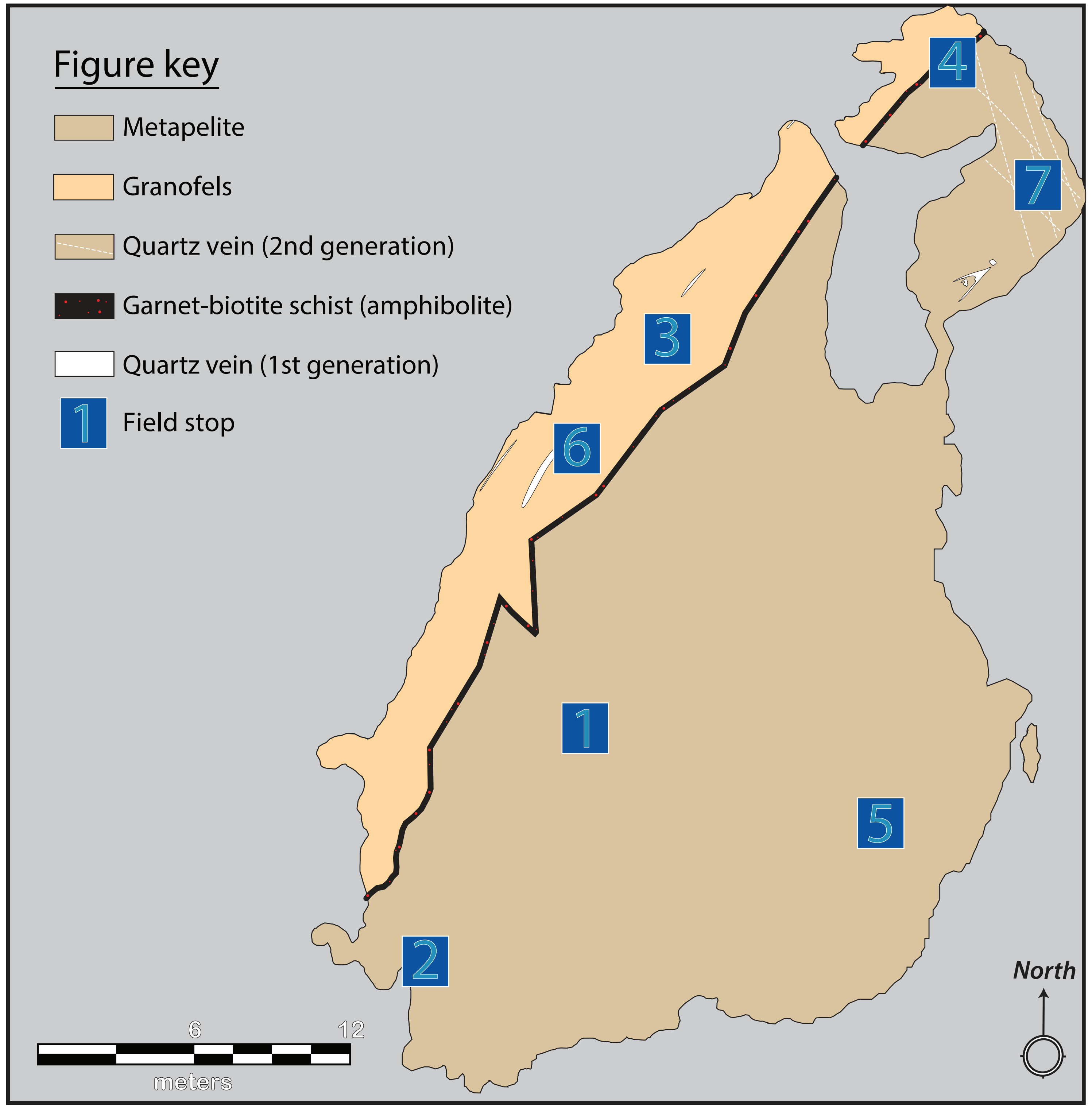
Directions to Hernshead outcrop (follow the footsteps)

(i) Exit the American Museum of Natural History from the main entrance on Central Park West (see point ①)
(ii) Walk downtown until you reach the 77th St entrance to Central Park (~160 meters)
(iii) Enter Central Park at 77th St and walk to the junction with West Dr (~160 meters)
(iv) Cross West Dr and head south until you intersect the first walkway to your left (~15 meters)
(v) Follow the path until you reach the Ladies Pavilion and outcrop at the edge of "The Lake" (indicated by star below; ~75 meters)



Field stops at Hernshead

Once arriving at Hernshead, you can use the map attached below to investigate the various geological features at this location. If you have a GPS or smartphone, you can use GPS coordinates provided on page 2. If you do not have a GPS or compass, we recommend you orientate yourself with the outcrop outline provided in the figure below in order to find key features. Note that specific field stops (with numerical value and blue box) are listed in the figure below and are presented in the corresponding, later sections of this field guide.



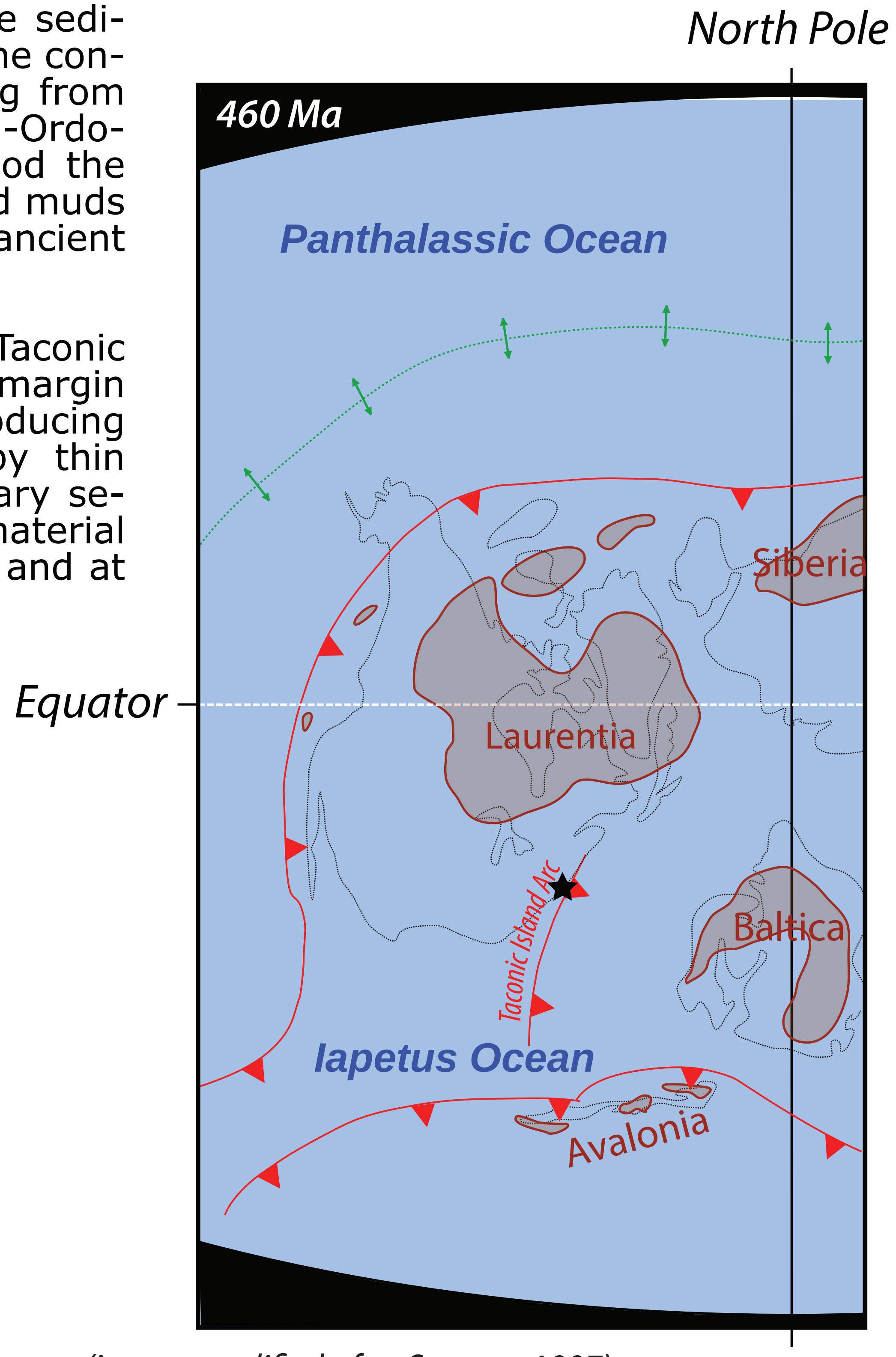
Depositional environment of the metasediments at Hernshead

The main metamorphic units observed at Hernshead were originally deposited as marine sediments (e.g., detrital material at or near the continental margin) over a timespan ranging from the late Cambrian (~500 Ma) through mid-Ordovician (~450 Ma). During this time period the strata consisted of a series of interlayered muds and sands that were weathering off the ancient continent of Laurentia.

During this same period of time the Taconic Island Arc was approaching the eastern margin of Laurentia, actively and cyclically producing volcanic material that is represented by thin mafic layers within the overall sedimentary sequence (e.g., the dark Fe- and Mg-rich material still observed as thin units at Hernshead and at various locations within Central Park).

At Hernshead the geological units represent a very small section of the larger "Manhattan Prong"

Paleoreconstruction of Laurentia



(image modified after Scotese, 1997)

Figure key

= mid-ocean ridge

= estimated outline of current continents

= subduction zone

= locus of the Manhattan schist

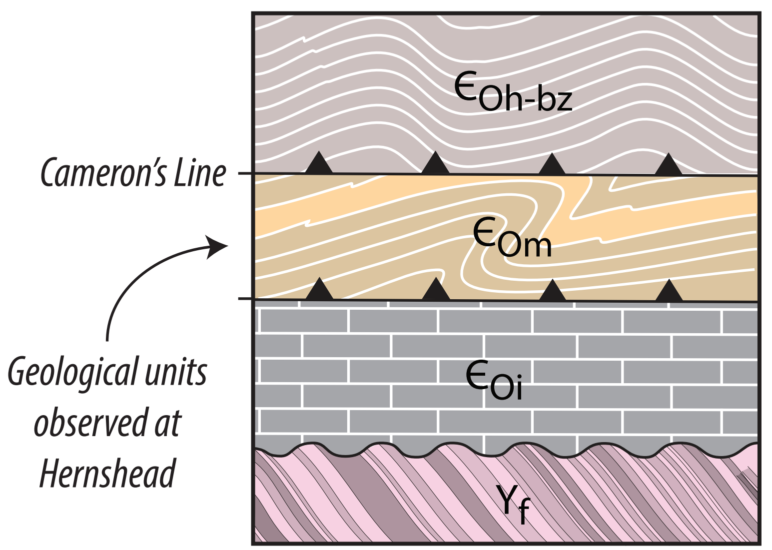
= continental landmass

= ocean

Stratigraphy in Manhattan (with a focus on Hernshead

The metasedimentary units observed at Hernshead are part of a large allocthonous block (e.g., a volume of rock moved from the locus of formation via a low angle thrust fault) that was tectonically displaced during the Taconic Orogeny. This movement of material likely involved numerous faults, such that the general stratigraphy in Central Park is often difficult to resolve. With this in mind, it should be noted there is some debate about the position of Cameron's line within Central Park and this is important with regards to classifying geological units at Hernshead. A good summary of the various interpretations of the structure and stratigraphy of Central Park is presented by Puffer et al. (2010). A great uncertainty in the geology of Central Park is the fault-bound contact between the Manhattan and Hartland schist, a contact known as Cameron's line. Similarly, much debate exists regarding the Hartland schist in Central Park and whether it is akin to units seen at Pelham Bay Park or if it represents a different subunit (Brock and Brock, 2001). Taterka (1987) places Cameron's Line at positions between ~87th Street (Central Park West) and 82nd Street (Park Ave) which makes Hernshead a member of the Hartland schist. Merguerian and Merguerian (2004) by contrast, place Cameron's Line close to the outcrop at Hernshead at 72nd Street (Central Park West) and 67th Street, and this would make Hernshead a member of the Manhattan schist. It is worth noting that for thermobarometry purposes (the focus of this guide), unit designation is not important. Future work, particularly geochronology, would do well to place accurate constraints on the position and relationship between the various fault-bound units in Manhattan.

Simplified stratigraphy of Manhattan



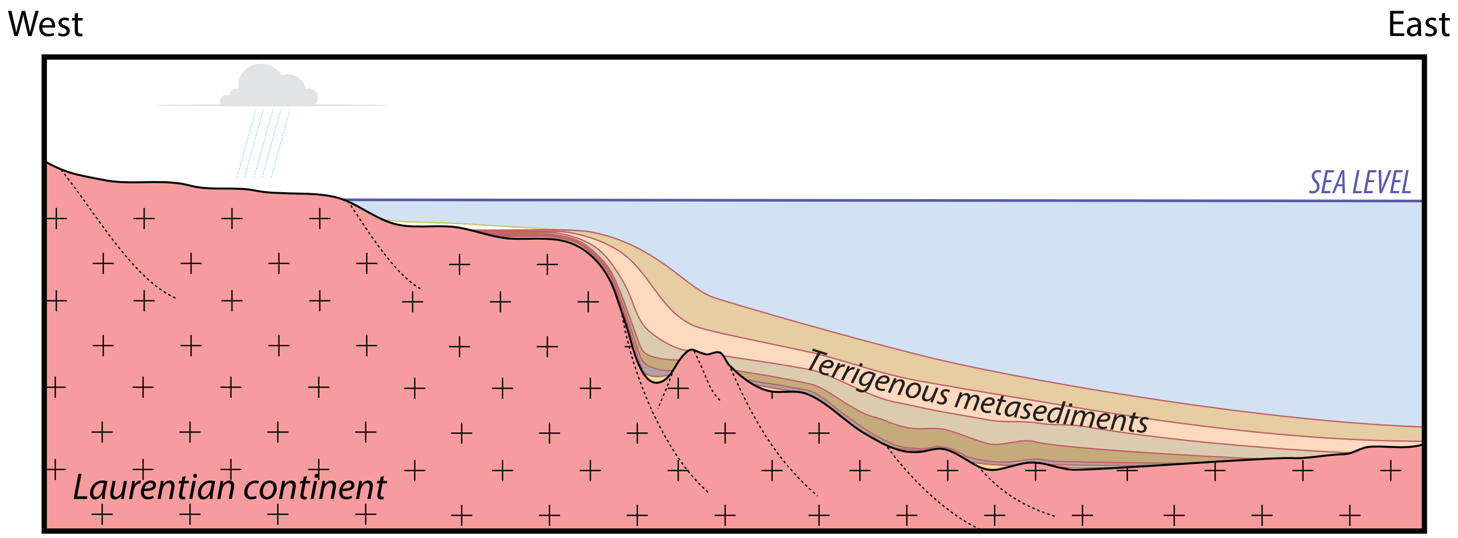
Ɛ$_{Oh-bz}$ = Hartland schist (Bronx Zoo-type)

Ɛ$_{Om}$ = Manhattan schist

Ɛ$_{Oi}$ = Inwood marble

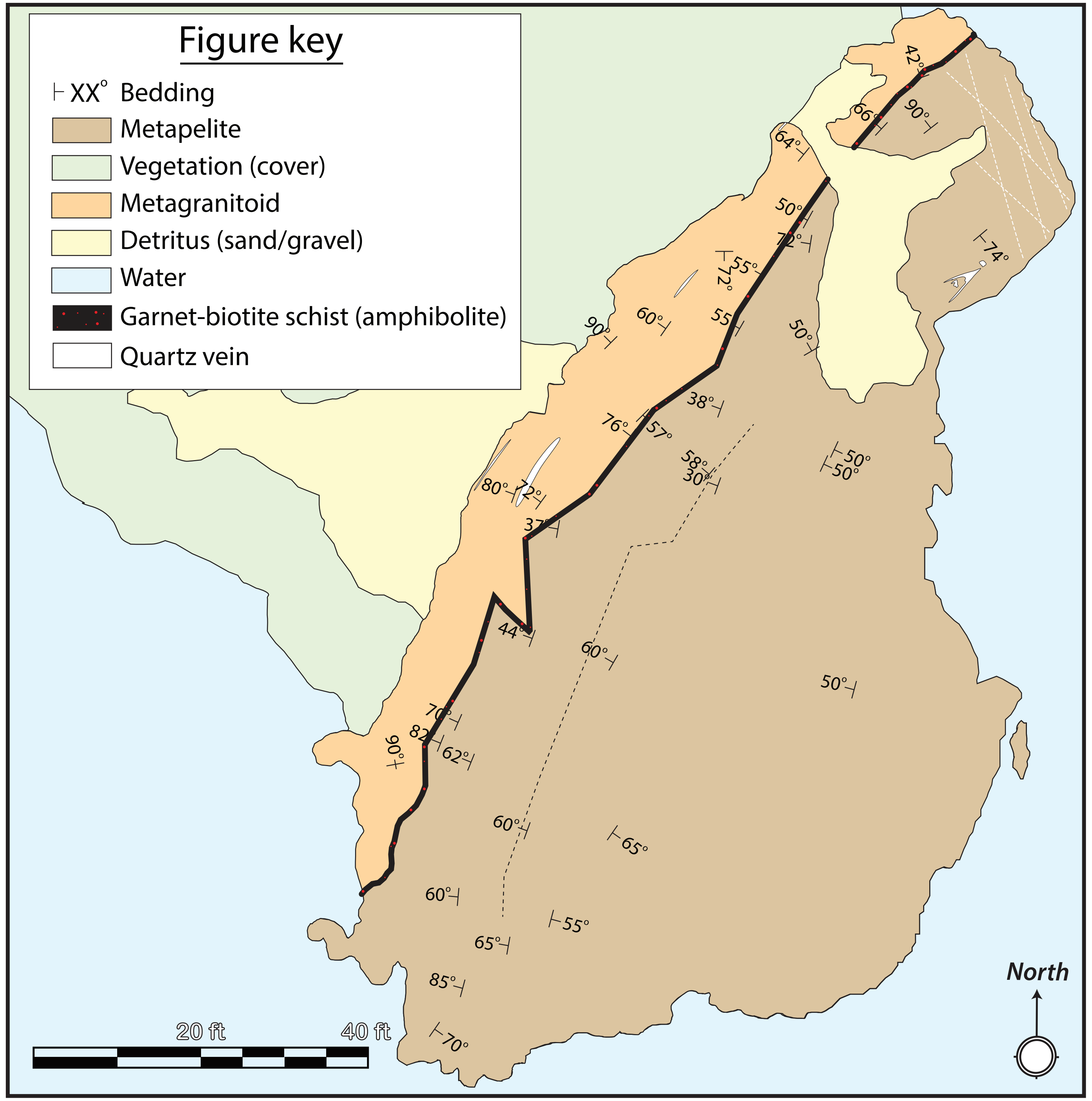
Y$_f$ = Fordham gneiss

Theoretical cross section of the Laurentian continental margin and depositional environment for the Manhattan schist



Simplified Geological Map of Hernshead

The outcrops at Hernshead, located immediately adjacent to the Ladies Pavilion, get their name from the outline of the rocks when looking back at the outcrop from the northeast - with the outline somewhat resembling the bended neck and head of a hern or heron. A number of geological units, metamorphic fabrics and later geological events are recorded at Hernshead and give clues to the overall geological history at this location. The purpose of this document is to provided the interested reader with a guide to reading and interpreting these features.

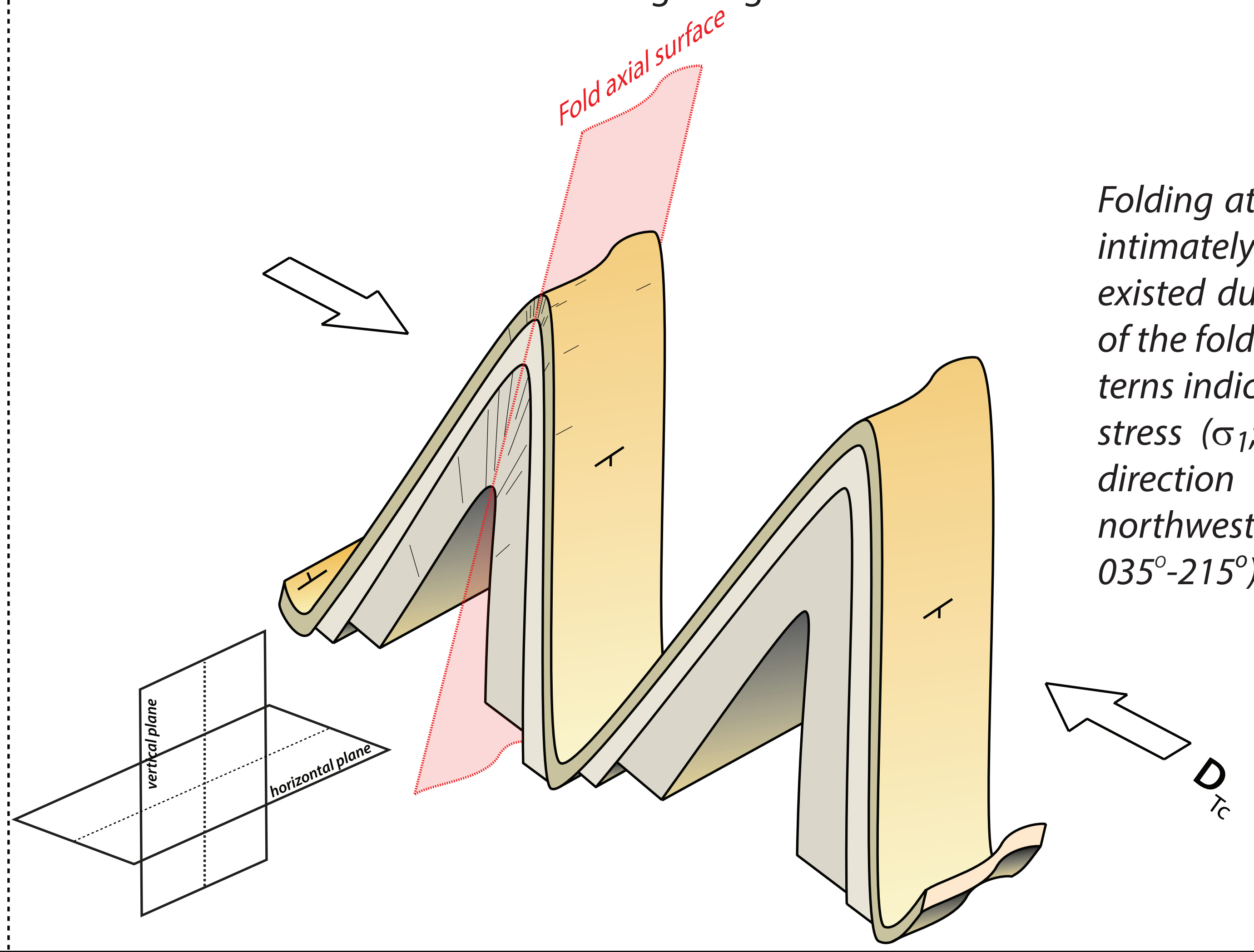


Folding and foliation development

The dominant style of fabric or texture observed in regionally metamorphosed rocks like Hernshead is a planar fabric that is generally referred to as foliation. It is formed by the parallel or subparallel arrangement of platy (e.g., micas) and elongate minerals within a rock. Most other rock types we see in nature tend to have a random orientation, but because metamorphic rocks develop in the presence of deviatoric stress, they develop a texture or foliation during the processes of recrystallization or neocrystallization.

Minerals that crystallize or grow in a differential stress field, like sheet silicates (e.g., micas), will grow with their sheets orientated perpendicular to the direction of maximum stress (indicated by arrows in the figure below, where D_{Tc} denotes deformation during the Taconic Orogeny). Similarly, some minerals contained within the original sediment may undergo dynamic recrystallization or develop subgrain boundaries in the presence of this stress field, producing textures indicative of metamorphism (e.g., undulose extinction).

The outcrops at Hernshead show a series of steeply dipping isoclinal folds that show a shallow plunge to the southwest. Strike and dip measurements from Hernshead show steep bedding, typically towards the northwest that is repeated throughout the outcrop. In addition to folding, a micaceous fabric subparallel to the fold axial surface is observed in most geological units.



Folding at and foliation at Hernshead are intimately related to the stress field that existed during the Taconic Orogeny. Most of the fold axial surfaces and foliation patterns indicate that the maximum principle stress (σ_1; which can be considered the direction of maximum shortening) is a northwesterly-southeasterly direction (e.g., 035°-215°).

1 Folds and their orientation at Hernshead

The rocks of Central Park record a complex history of continental growth through sedimentation and tectonic processes that spans millions of years and multiple orogenic events. The outcrops at Hernshead (see detailed map on 7) record a complex series of events that can collectively be used to help interpret the geological history of Manhattan. The rocks have seen multiple episodes of deformation, including ductile (e.g., where the rocks deform plastically) and brittle (e.g., where the rocks accomodate strain through breaks or mechanical failures) styles.

The original bedding within metasediments at Hernshead can be traced by small compositional variations that are manifest in changes in color, mineralogy and fabric. By mapping the orientation of these beds across the the outcrop it is possible to get a sense for the style and orientation of the dominant folds observed in outcrop.

Mapping the orientation of these beds demonstrates most of the observed folds represent steep, southwesterly dipping isoclincal folds with fold axial traces trending towards ~ 033°. It is also worth noting that these folds appear to be overturned at various locations and are also locally affected by younger generation folds at a high angle to the dominant fold axial plane.

Adjacent image: isoclinal folds developed in metapelite from Hernshead. See page 10 for a simplified geological map of this outcrop

Image below: bedding planes measured at Hernshead. Note that the planes show a repeating patterns of planes roughly to the north-northeast (striking at ~033°)

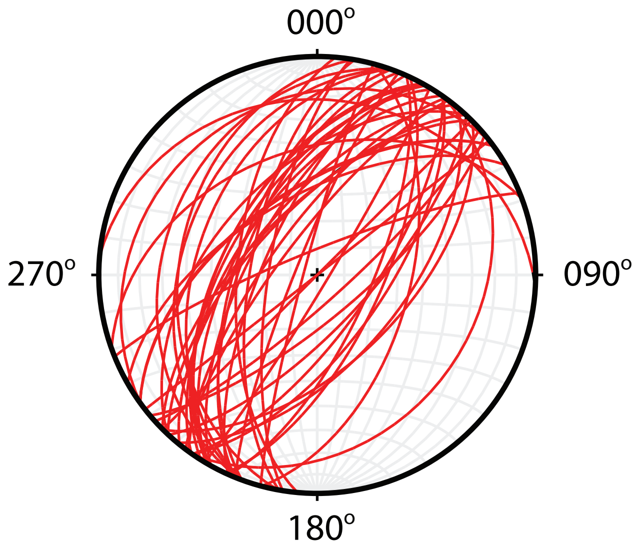
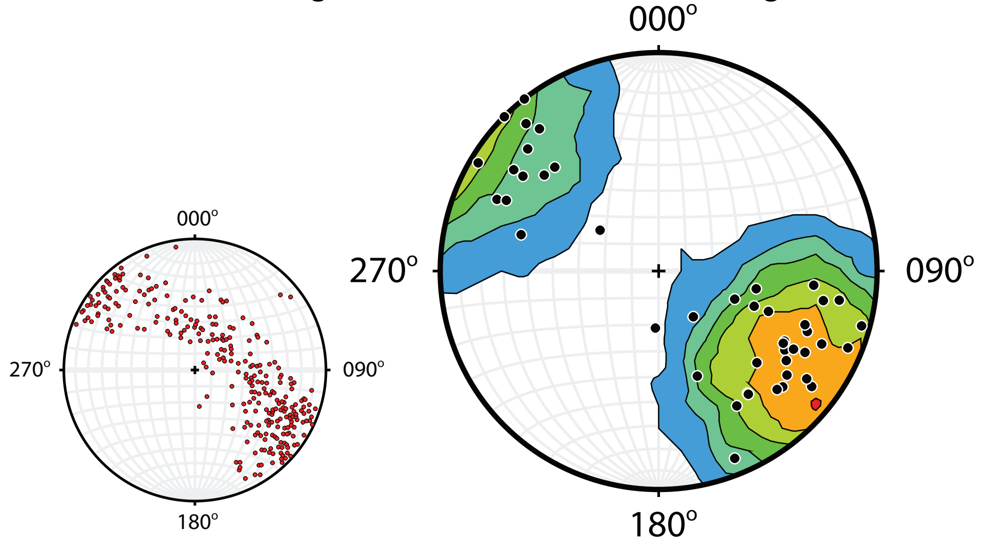
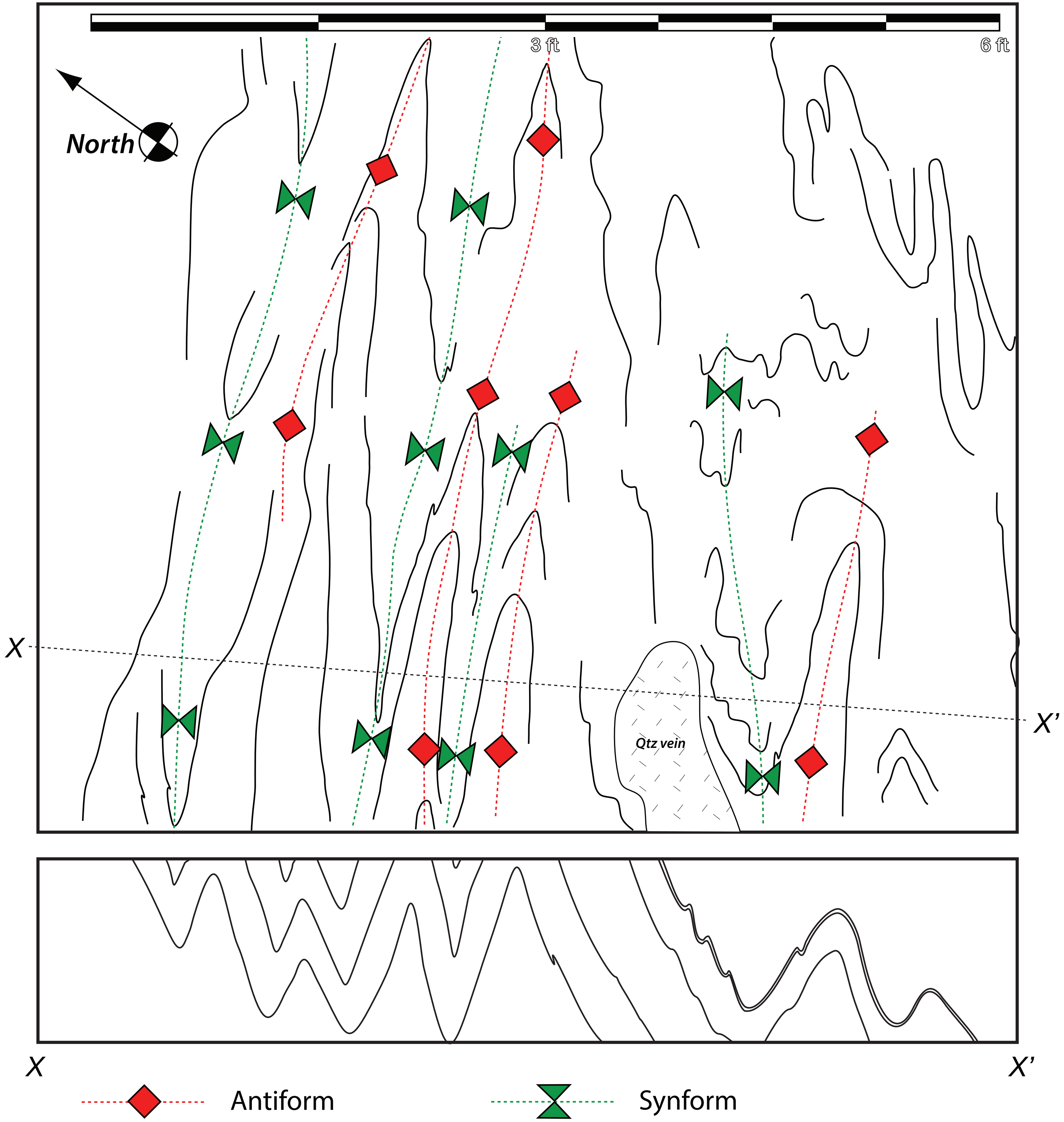


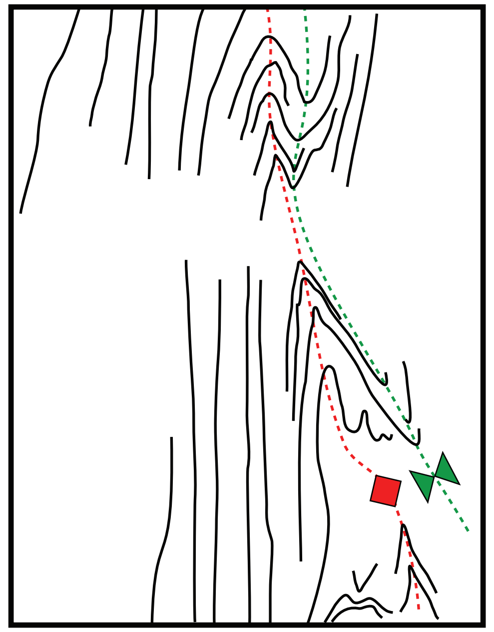
Image below: pole to planes (p plot) from Hernshead with 2s contour interval (larger plot on the right). This plot is excellent agreement with measurements made by Taterka (1987; smaller image on the left) over the same region of the Park





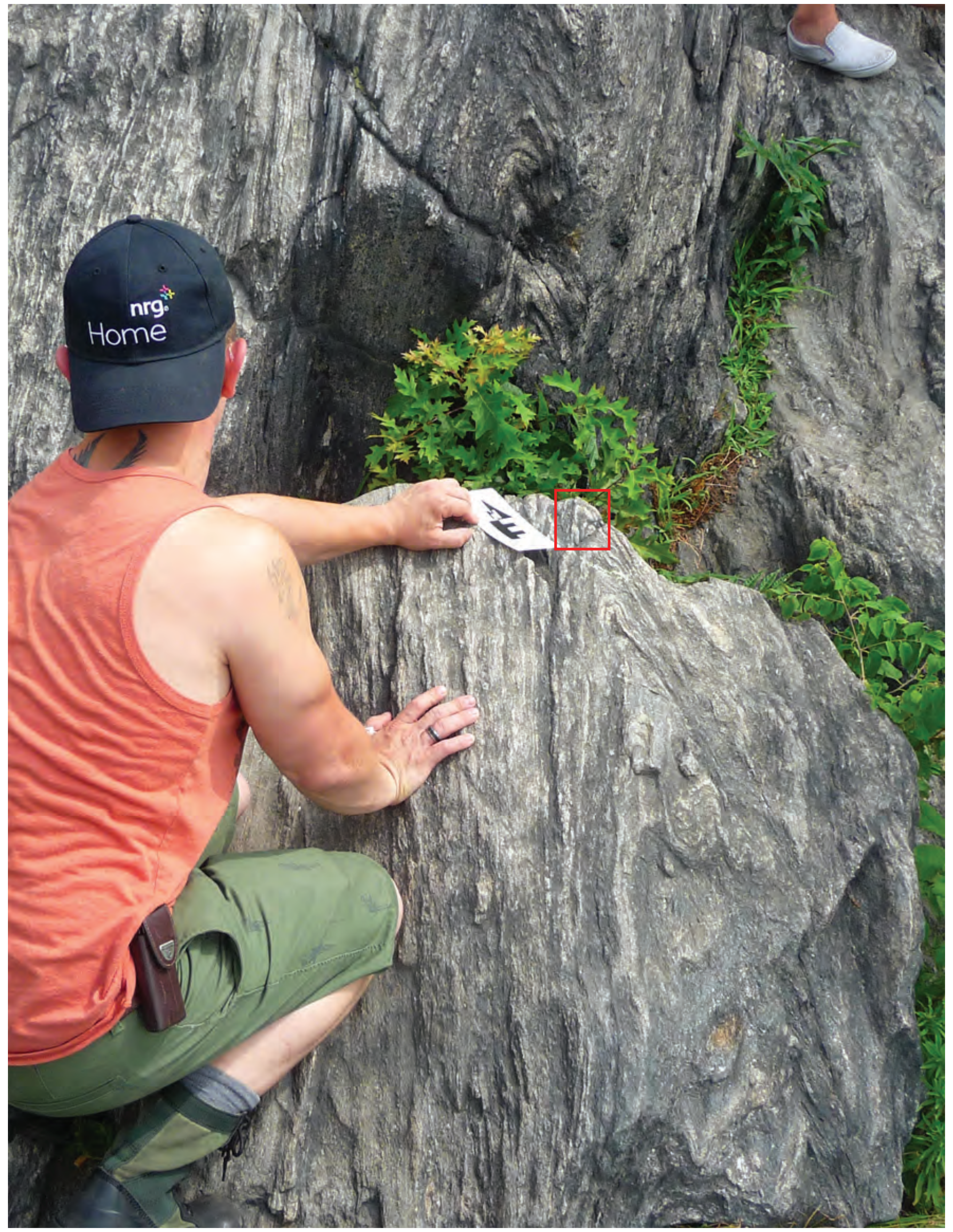
2 Metapelite

The dominant geological unit at Hernshead is an interbedded metapelite. This unit is characterized by a rougher and more pitted texture than other units at Hernshead (namely the granofels). This unit also displays a darker greyish-brown color and is highly interbedded. The layering observed in this unit is caused by subtle variations in quartz:mica:feldspar, which in turn likely represents small perturbations in the sediment supply during the Ordovician. This layering or strata make it possible to observe detailed metamorphic fabric and structure (e.g., folds) across the outcrop (see anticlinal fold in images adjacent and below).



The metapelite contains biotite (sometimes altered to chlorite), altered feldspars, quartz, muscovite and minor kyanite. The feldspars and quartz crystals show rounded edges indicative of the weathering and sediment transportation process, while also showing the development of undulose extinction. Biotites and muscovites show a long axis that is roughly sub parallel to the fold axial plane, and are often found in clusters that likely represented clay-rich beds in the sedimentary cycle. Other minor phases from the metapelite include magnetite (with exsolved ilmenite), apatite and zircon. Like most units at Hernshead the metapelite is characterized by an abundance of magnetite (e.g., it will draw a handheld magnet), which can be seen as small dark minerals within the matrix.

At the base of the north-easternmost part of the outcrop, an anticlinal fold axis is exposed and traceable through the outcrop.



Adjacent images: isoclinal anticline in the metapelite found at the southern tip of the Hernshead outcrop. Top image shows a rough outline of the fold axial trace from the photographed area. The red rectangle corresponds to the thin section image shown on page 12

Metapelite continued

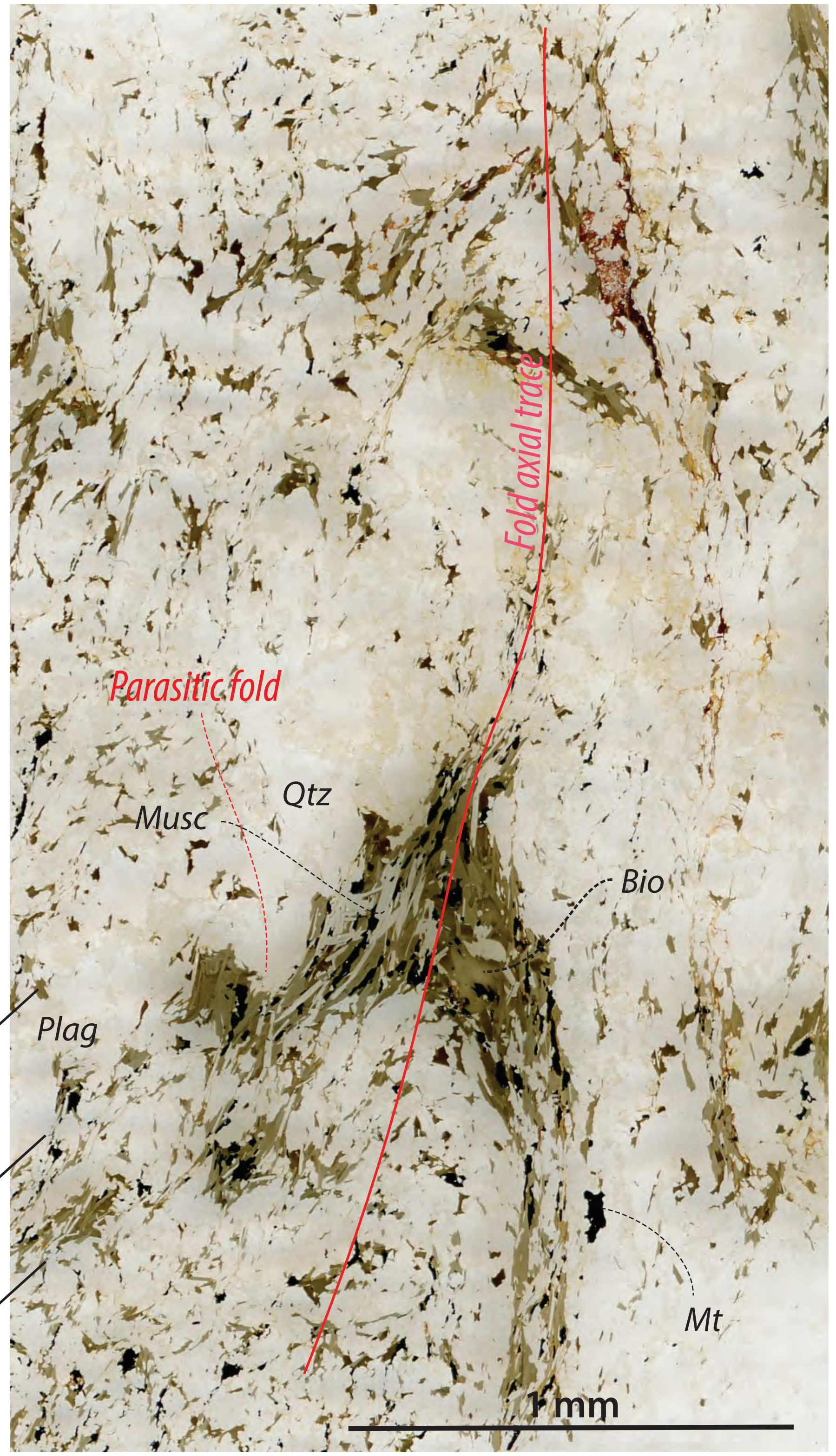
Detailed petrography of thin sections from the metapelite show that large scale structures (e.g., folds and fabrics) are observed at the microscale. In the thin section image provided in the adjacent figure it is clear to see the mineralogical and compositional variation among strata (layers). Metasediments that initially contained more clay show mineralogical domains richer in muscovite and biotite (+ magnetite). These muscovites show a long axis that follows the fold axial trace (see red curve in adjacent figure). It is also apparent in thin section that a small parasitic fold is present on the left-hand limb of the anticline, an observation that is seen at many locations at the macroscale (see image on page 11).

Immediately above the mica rich layer in the metapelite is a quartz-feldspar-rich layer that is clear to white in color. The dusty light-brown to grey crystals represent the slightly altered plagioclase feldspar. In outcrop this would correspond to the prominant, white to light grey colored layers.

Adjacent image: Plane Polarized Light (PPL) image from a thin section of the metapelite. Note the small anticlinal fold running vertically through the center of the section. See image on page 11 for sample location

Sandy (quartz-plagioclase rich) strata

Muddy (muscovite-biotite rich) strata



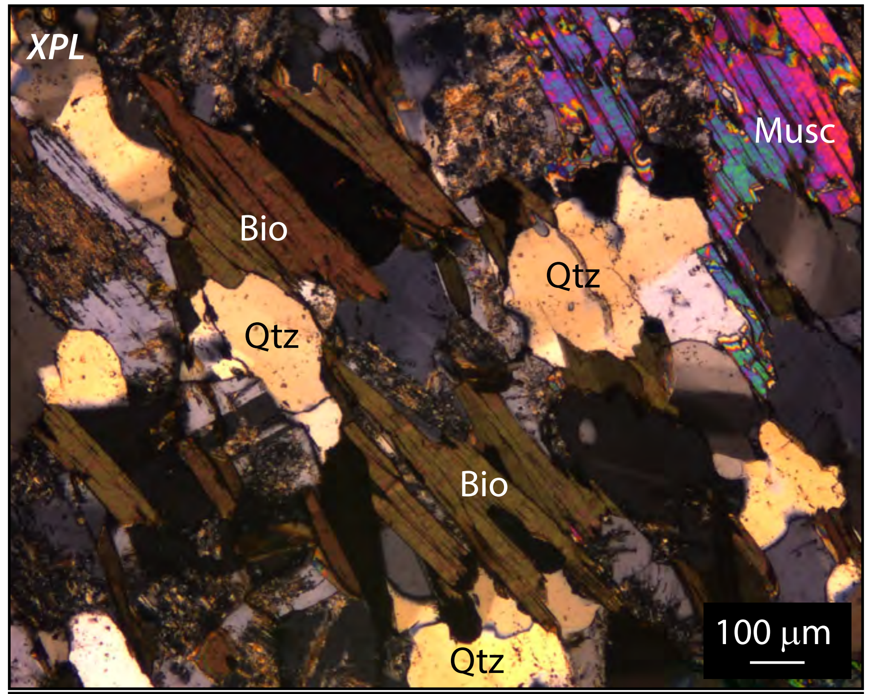
3 Granofels

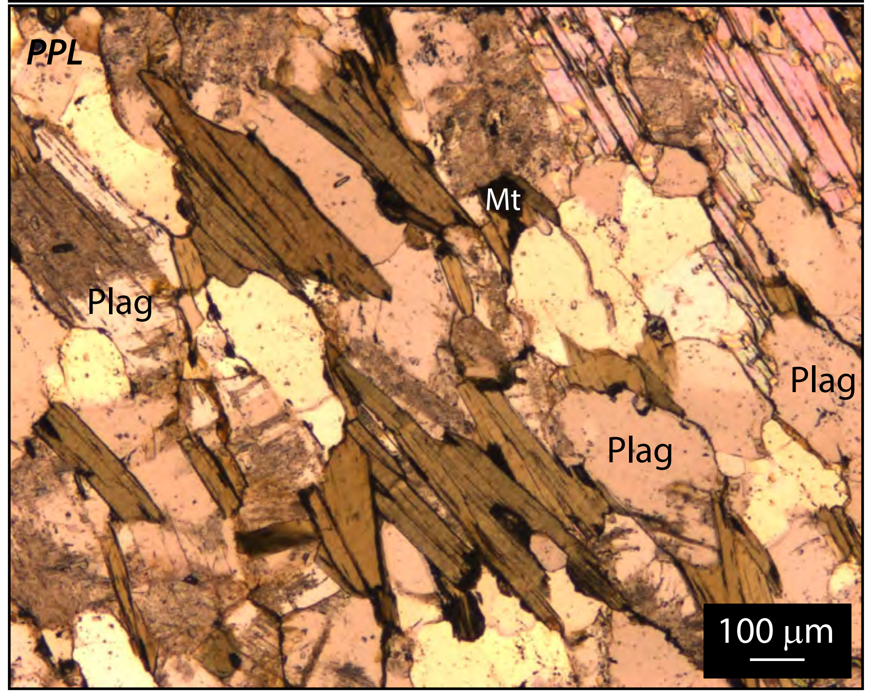
The granofels at Hernshead is a light brown geological rock that can be seen extending to the easternmost areas of "The Pond". The term granofels refers to the granoblastic texture and quartz-feldspar rich nature of this rock (noting that the quartz and feldspar crystals are broadly equal in size), such that the rock generally lacks the micaceous foliation observed in the metapelite. This is the most obvious unit at Hernshead because it has a coarser grainsize and higher quartzofelspathic content when compared to the surrounding metapelites.

These "quartzofeldspathic" units are found at a number of locations within Central Park (e.g., see the outcrop immediately north of the Delacorte Theater) and have variously been described as a granulite (Taterka, 1987), granofels (Merguerian and Merguerian, 2004) and as a metamorphosed plutons (Schuberth, 1968).

The mineralogy of this unit consists of plagioclase, quartz, biotite and muscovite. Accessory phases from this unit also include zircon and apatite.

Image below: contact between the granofels and metapelite at Hernshead. Note the light brown color and lake of layering in the granofels. Image taken looking northeast.



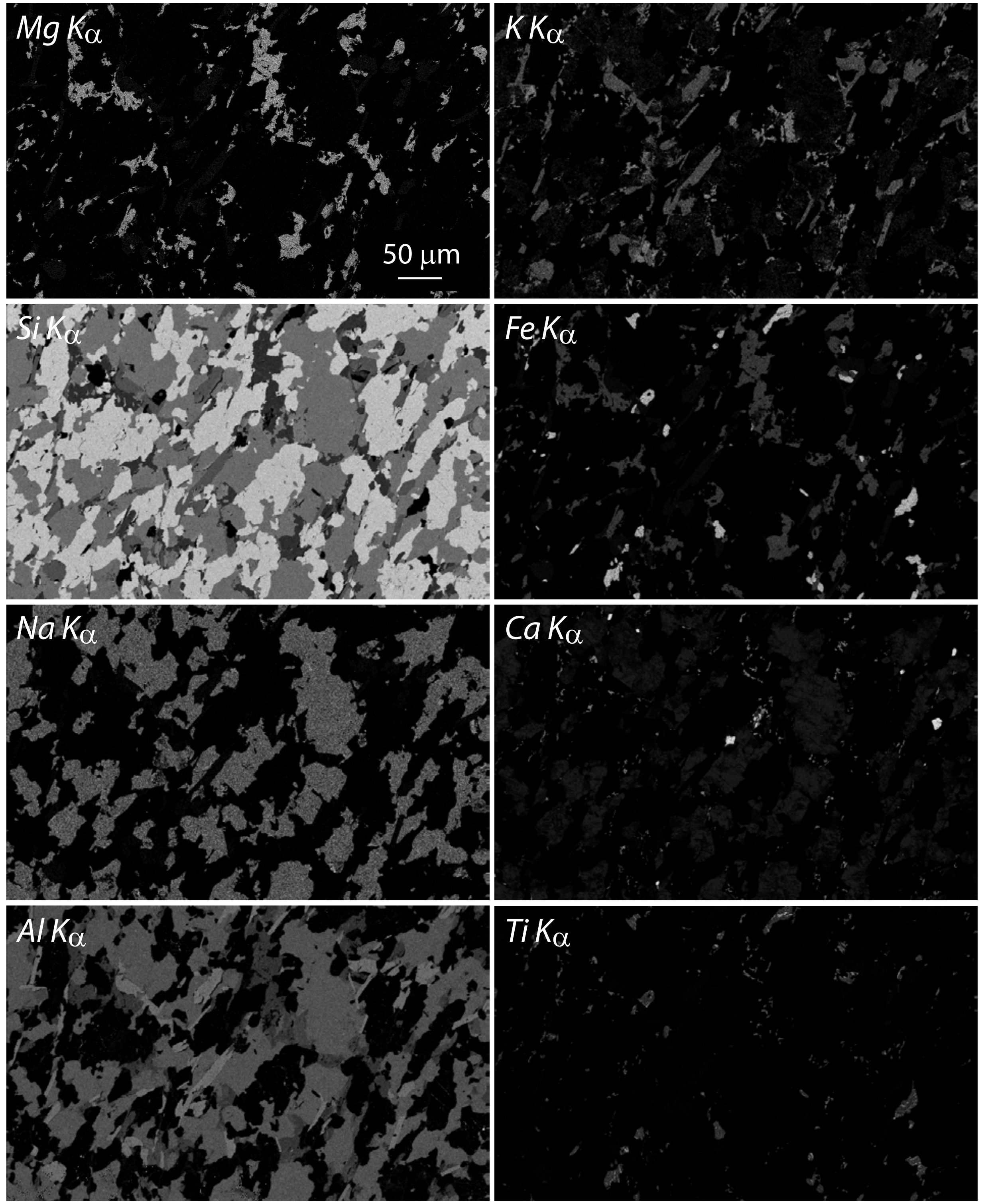


Petrographic images in cross-polarized light (XPL; top micrograph) and plane-polarized light (PPL; bottom micrograph) from the granofels. Note the alignment of mica long axes as an indication of formation/recrystallization in the presence of a deviatoric stress field. Similarly, the undulose extinction in both quartz and feldspar indicate the formation of subgrain boundaries due to deformation during metamorphism

It is also worth highlighting that the feldspar and muscovite grains show signs of chemical (fluid) alteration.

Granofels continued

The mineralogy of the granofels at Hernshead is simple and appears to be homogenous at the outcrop scale. X-ray element maps from thin sections at this location show that the sample is dominated by a single feldspar (albitic plagioclase), quartz, biotite and minor muscovite. The quartz and feldspar crystals often show undulose extinction in cross polarized light, indicating the formation of subgrain boundaries during deformation. Similarly, the biotite and muscovite crystals show long axis alignment. This again, is an indication of re-/crystallization in the presence of a metamorphic stress field.



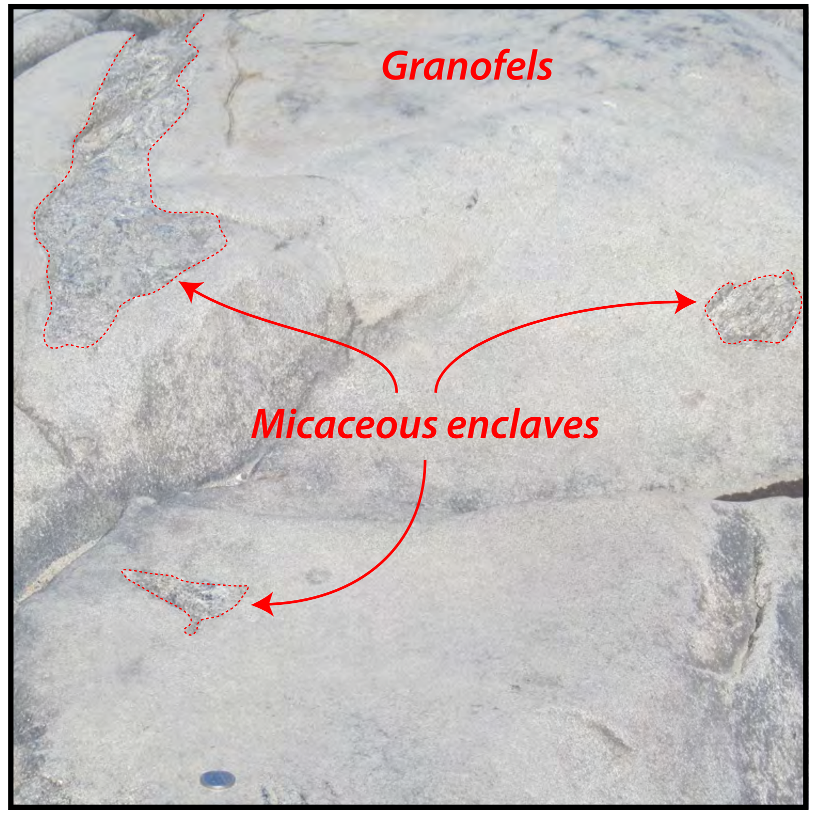
3 Granofels continued

One of the intriguing questions at Hernshead pertains to the origin of the granofels - is it a metamorphosed igneous rock (e.g., granitoid) or a ,metamorphosed sedimentary rock (e.g., arkose)? The process of fluid-assisted metamorphism of an arkosic sediment can give rise to a simple mineralogy that resembles a granitoid (e.g., quartz-feldspar-muscovite-biotite).

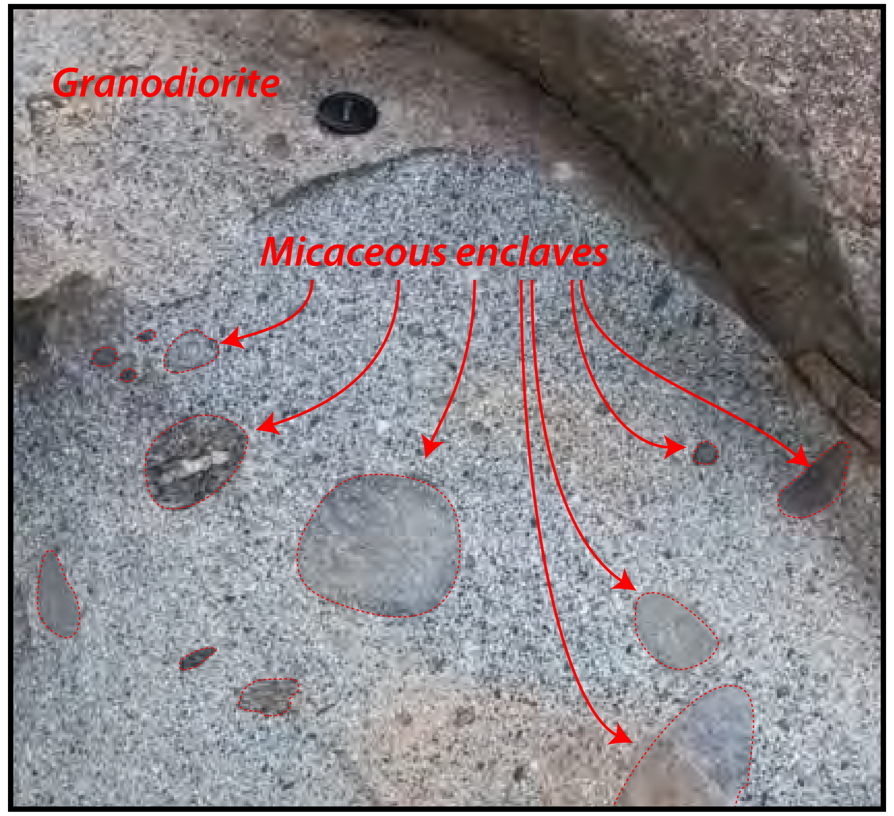
Several observations can be used to help elucidate the origin of this granofels. Firstly, the general strike of this unit mimics the general bedding observed at Hernshead which could be used to indicate this is a sedimentary unit. Similarly, the unit lacks a number of minerals that are typically present in most granitoid plutons - namely hornblende and two feldspars (this unit tends to be dominated by albitic feldspar - see x-ray maps on previous page). Neither of these observations are singularly conclusive, as the granofels may have been tectonically superimposed on the metapelite to produce a bedding parallel contact. Similarly, fluid alteration of a granitoid during metamorphism has potential to significantly alter the general minearlogy.

The homogenous nature of the granofels, which shows no clear layering or compositional variability tends to suggest a magmatic origin. The granofels also shows a number of isolated micaceous enclaves (e.g., rafts of metapelite) that suggests this unit was injected as a magma into which the surrounding countryrock fell (see images below). It should be noted that a number of granitoids exist within both Hartland and Manhattan schists, such that this is a region of known plutonism.

Hernshead granofels, Central Park, NY, USA



Cowra granodiorite, NSW, Australia



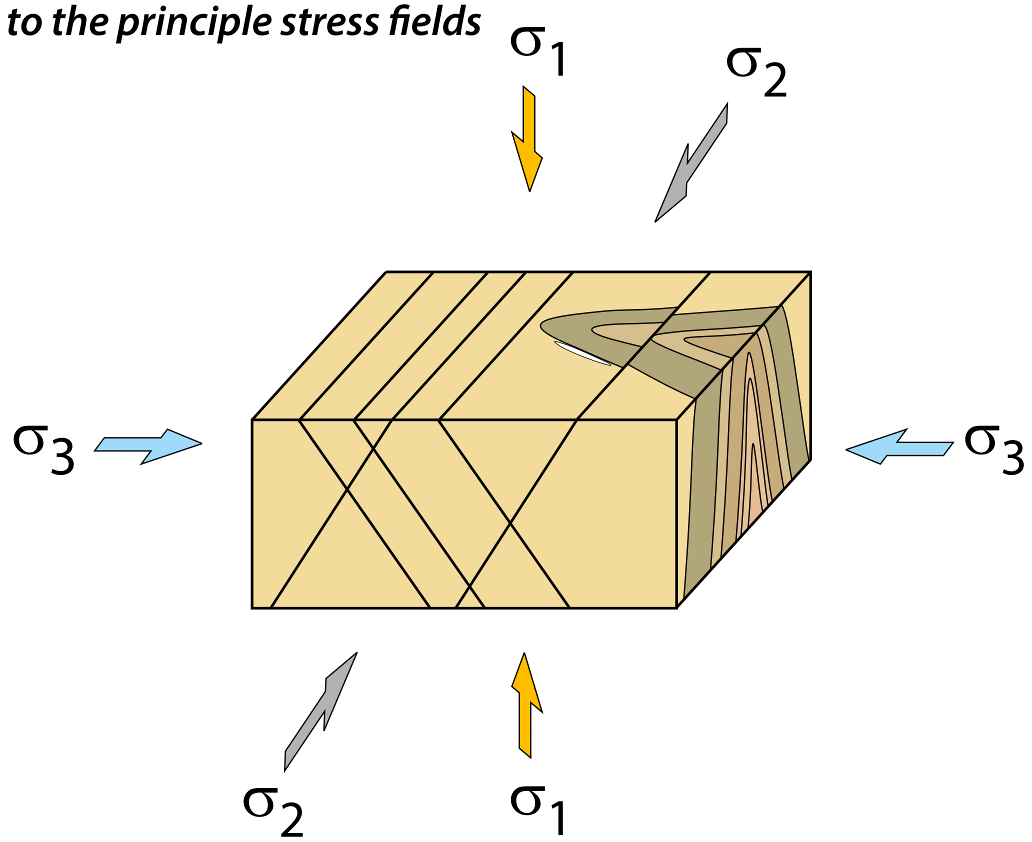
Joint sets

One of the last geological processes to occur at Hernshead was brittle failure of the rock (particularly among the granofelsic unit) to form a series of conjugate joint sets. Unlike the metamorphic minerals and fabrics that form during prograde metamorphism, a process that occurs under ductile flow (e.g., plastic deformation), this form of deformation must occur at lower pressure-temperature conditions in order to occur under brittle failure.

These joints sets represent crude, subparallel and often interconnected fractures within the rock that are seperated by angles of ~60 or 120°. The development of these joint sets gives sections of the outcrop the apperance of interlocking rhomboidal blocks.

The development of these fractures likely occurred after the orogenic event, during uplift of the rocks as the continent underwent weathering and erosion of the Taconic Mountains.

Formation of the conjugate joint sets relative to the principle stress fields



Adjacent image: joint sets observed in the granofels from Hernshead as indicated by dashed lines. Note that one of the three joint sets is in the horizontal plane and is represented by the red rhomboid in the adjacent image.

6 Forms of brittle deformation at Hernshead

Vein quartz

Quartz veins are a common feature at HH and are found at many locations across the outcrop. The large quartz veins (like that presented in the adjacent image) show high aspect ratios and generally display a long axis that is parallel to the dominant fold axial surface at HH. These veins can be recognized from their gray to milky white color, high aspect ratio and resistance to weathering (i.e., generally protruding from the outcrop). The gray to white color of the quartz veins stems from the abundant fluid inclusions and healed fractures found within the host quartz crystals (see image of fluid inclusions from Hernshead at bottom right).

The development of quartz veins at HH likely represents a dramatic change in the style of deformation relative to the dominant metamorphic fabric and mineralogy observed in the metasediments. These veins formed at a time after peak metamorphism where the system entered the brittle regime. In other words the rocks at HH likely underwent decompression and cooling prior to the development of these veins.

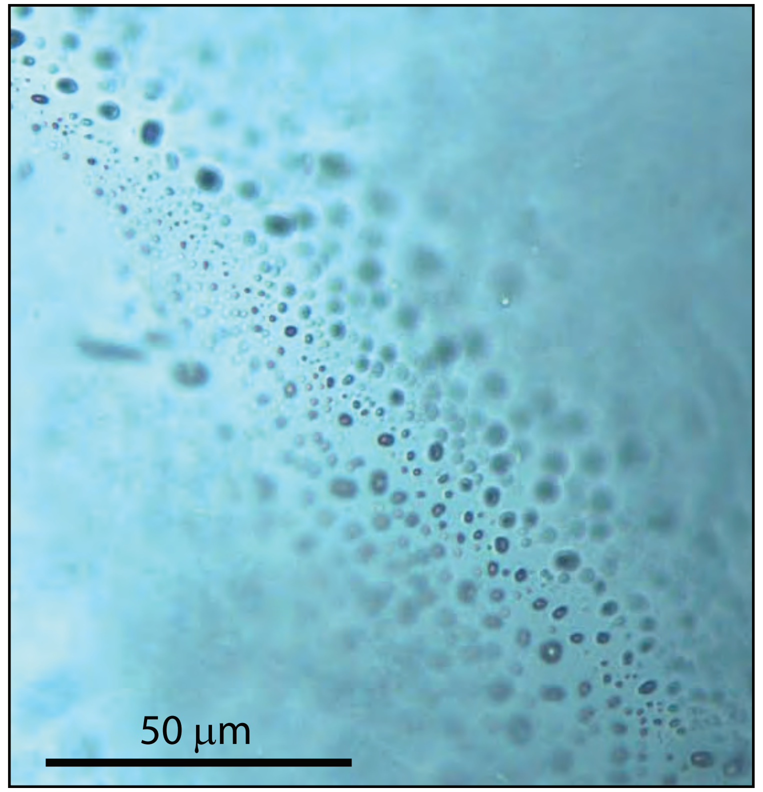


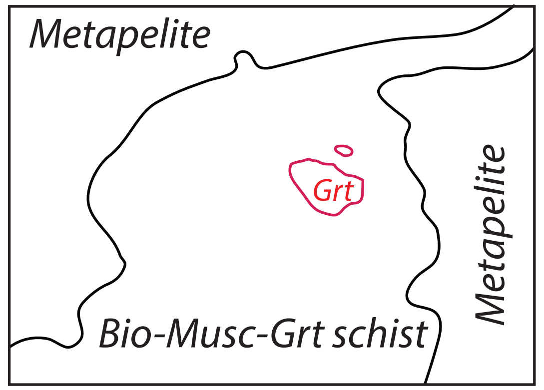
Image adjacent and above: large quartz veins are found at numerous locations at Hernshead. As can be seen from the double polished thin section in the adjacent image, many of these quartz grains contain abundant fluid inclusions (multiple generations). These quartz veins precipitated from hydrothermal fluids permeating the country rock. Additional phases present in these veins include rare feldspar and chlorite.

4 Biotite-Muscovite-Garnet schist ("amphibolite")

Several bands of thin, black (e.g., rocks rich in iron and magnesium) bands are observed at Hernshead. Here it is possible to observe garnet (red), biotite (black), muscovite (clear to white) and small plagioclase (white) and quartz (gray to colorless) crystals. Typically, these mafic units have been labeled as "amphibolites" due to the dark appearance and presence of garnet (in other words, they look similar to a basalt metamorphosed to amphibolite grade). Inspection of thin secions and epoxy mounts from this location reveal a complete lack of amphibole (e.g., hornblende), demonstrating this unit is more appropriately labelled a "biotite-muscovite-garnet schist". The dark color and mafic mineralogy observed within this unit clearly demonstrates it has a more mafic composition than either the granofels or metapelite. It is thought this unit likely represents a volcanic sample, likely an ashflow deposit (e.g., a volcanic tuff) that derived from the approaching Taconic arc during the Ordovician.

The biotite-muscovite-garnet schist is arguably the most useful unit at Hernshead with regard to calculating metamorphic conditions. This unit contains a number of key phases required for exchange thermometry (e.g., Mg-Fe partitioning among co-existing garnet and biotite) or net transfer barometry (e.g., plagioclase and garnet).

In addition to the dominant mineral phases, this unit also contains minor amounts of zircon, kyanite and magnetite (with exsolutions of ilmenite). As will be discussed in later sections of this field guide, some of these additional phases can also be used for thermobarometry purposes.



Adjacent image: "amphibolite" unit from northern end of Hernshead with Quarter for scale. Note the dark color of this unit, which relates to the high abundance of biotite. A large, red garnet crystal, with sharp contact with co-existing biotite-muscovite-plagioclase is seen in the center of this image.

Garnet-biotite thermometry

Garnet-biotite thermometry (sometime going by the acronym GARB) is a method for evaluating the temperature experienced in a rock based on an exchange reaction involving Mg and Fe cations (e.g., elements) among two co-existing minerals at equilibrium. The thermodynamic description of this reaction (Ferry and Spear, 1978) appears complex, but the fundamental application is straightforward. By measuring the Mg and Fe content of co-existing garnet-biotite [be it Mg/Fe or Mg/(Mg+Fe)] it is possible to calculate the equilibrium distribution coefficient, which can be written:

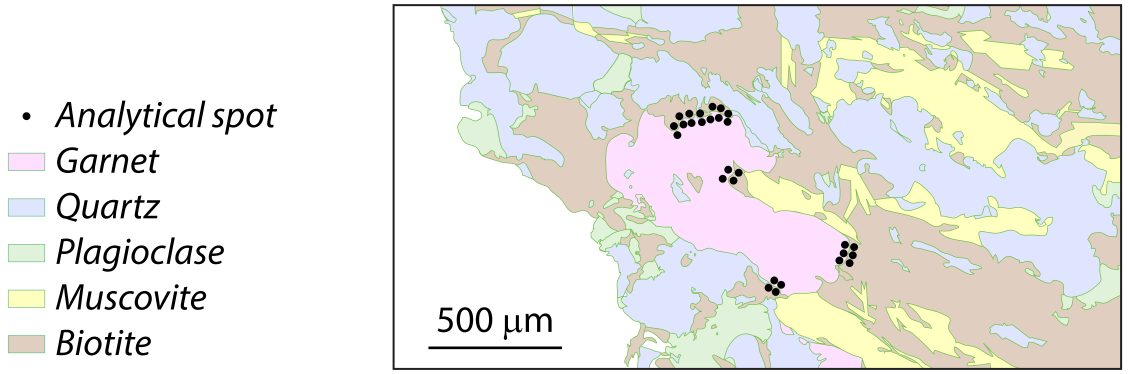
$$K_D = \frac{(Mg/Fe)^{Garnet}}{(Mg/Fe)^{Biotite}}$$

Because the Mg and Fe cations have similar ionic size the exchange reaction involves very little volume change ($\Delta V = 0.238$ J/bar) but is associated with a large entropy and enthalpy change. It is for this reason that the lines projecting constant equilibrium distribution coefficients (or equlibrium constants) for this reaction are near vertical in P-T space.

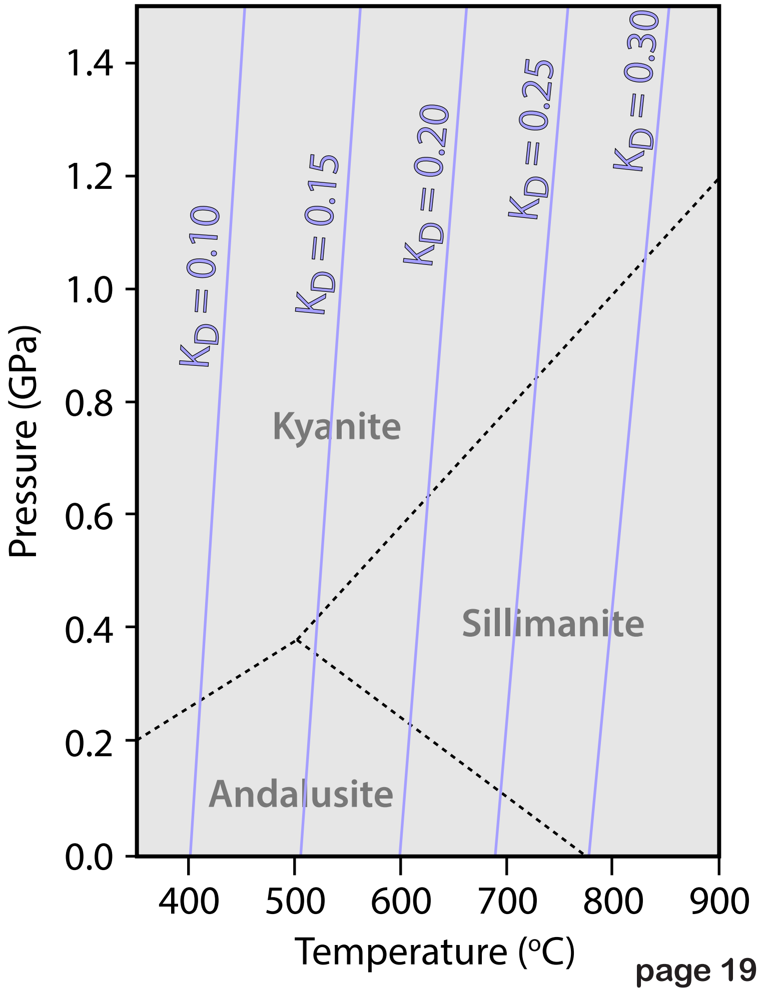
How to measure K_D (thermometry)

Textures observed within a mineral assemblage is crucial to establishing equilibrium and reaction history. The garnet-biotite pairs at Hernshead show sharp grain boundaries (green in figure below), with no signs of resorption or alteration. Analysis of the minerals (see black circles in the figure below) are conducted at locations where the two phases share immediate grain boundaries, a condition that ensures that cation diffusion can maintain equilibrium in a system undergoing metamorphism.

Sketch of thin section from Hernshead biotite-muscovite-garnet schist showing the distribution of mineral phases and grain boundaries



Equilibrium distribution coefficients for the garnet-biotite Mg-Fe exchange thermometer reaction (modified after Ferry and Spear, 1978)



Garnet-biotite thermometry continued

Garnet-biotite thermometry from Hernshead was carried out on the garnet-biotite schist (e.g., "amphibolite" units) because, among the various rock types at this location, this is the most suited to thermobarometry on the basis of mineralogy. The 17 measured garnet-biotite pairs show equilibrium distribution constant projections (red lines in adjacent image) that cluster at temperatures that generally fall between 650-750 °C.

Image adjacent: temperature-pressure projection for garnet-biotite exchange reaction (GARB) from the Hernshead garnet-biotite schist. Note these lines are superimposed on the aluminosilicate stability fields for reference. This figure indicates the co-existing mineral equilibrated at conditions somewhere along the near-veritcal lines (i.e., at temperatures between ~650-750 °C). Representative analyses from both garnet and biotite are provided in the adjacent table (

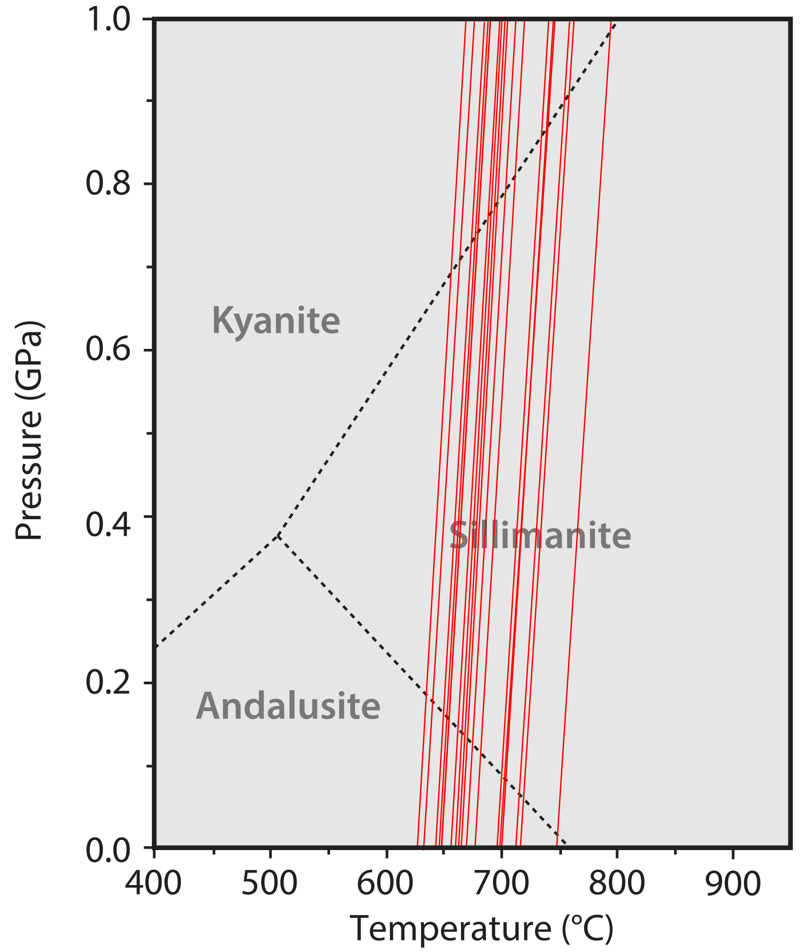
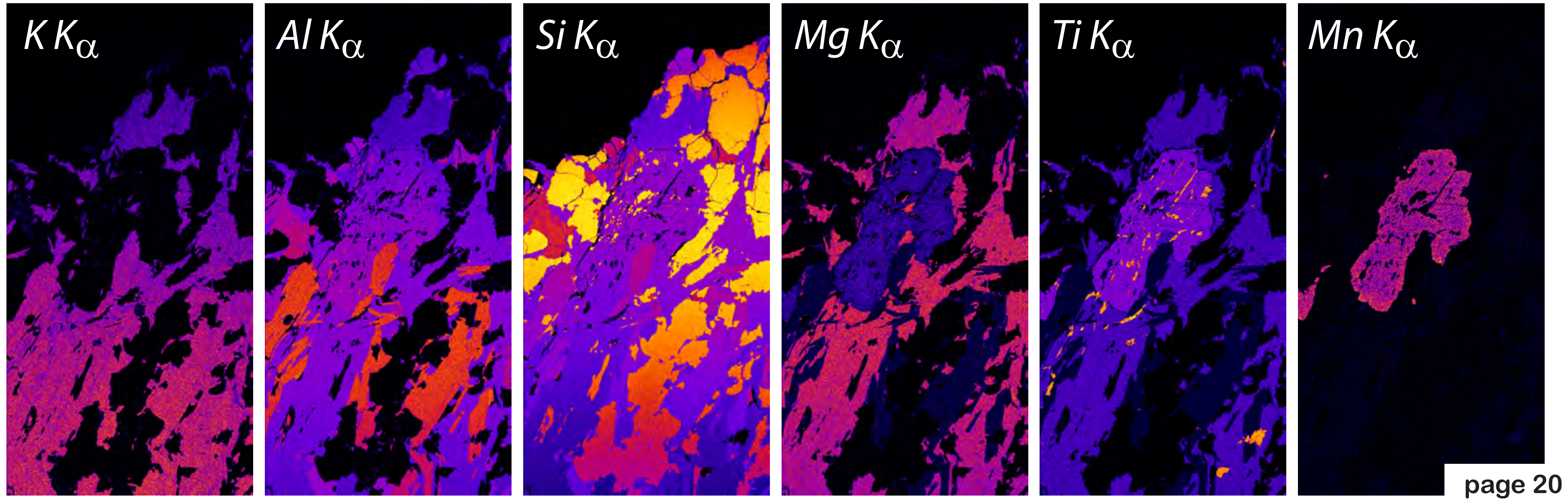


Image below: compositional x-ray maps (measured via electron microprobe) can be used to map out the distribution of different mineral phases present in the garnet-biotite schist at Hernshead. Note this is the same thin section as presented on page 19, and predominately consists of garnet, biotite, quartz, muscovite, plagioclase and magnetite. These maps also show that garnet displays some notable zonation (see Mn) which likely reflects garnet growth in a changing metamorphic environment

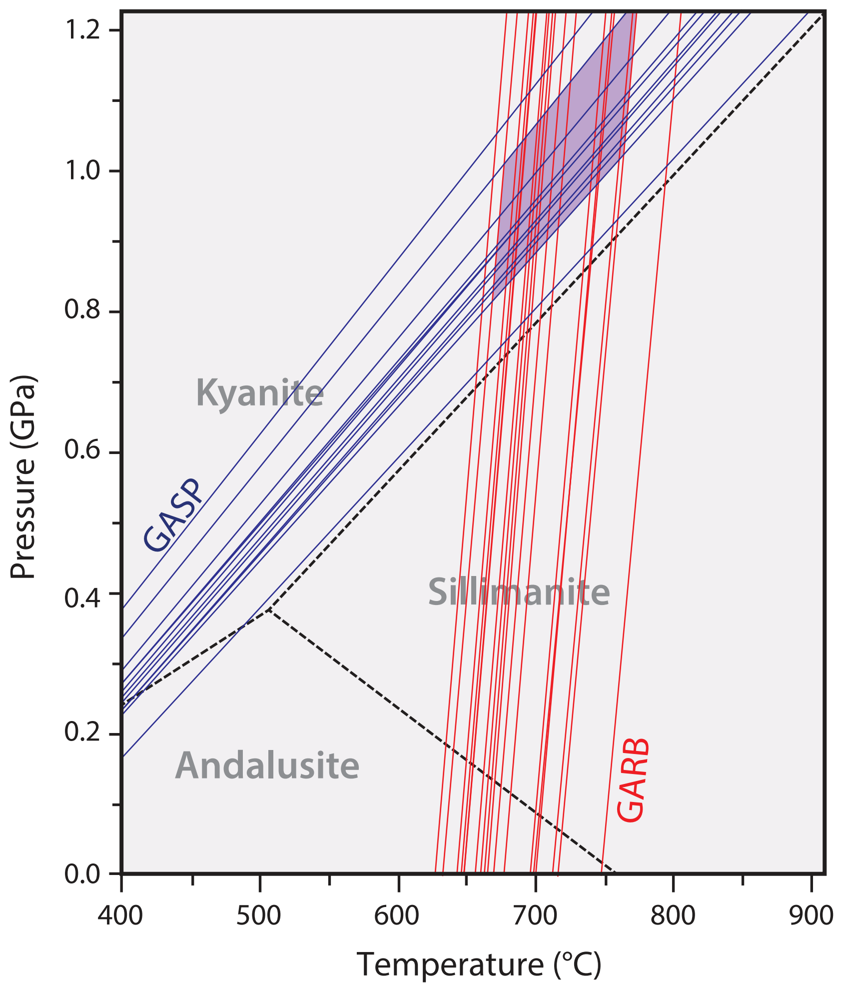


Garnet-plagioclase barometry

Where temperature can be estimated from the exchange reaction involving garnet and biotite, pressure can be evaluated from a net transfer reaction. This type of reaction involves the introduction and consumption of phases as they react (thus involving the transfer of material). As the introduced/consumed minerals have different unit cell volumes, this type of reaction can involve large volume changes (ΔV) making them particularly sensitive to pressure. Arguably the most common barometer applied to metamorphic rocks involves the exchange of material defined by the reaction:

$$\underset{\text{anorthite}}{3CaAl_2Si_2O_8} = \underset{\text{grossular}}{Ca_3Al_2Si_3O_{12}} + \underset{\text{kyanite}}{2Al_2SiO_5} + \underset{\text{quartz}}{SiO_2}$$

Like the garnet-biotite reaction, garnet and plagioclase analyses (in the presence of kyanite and quartz - required for the reaction) can be used to plot equilibrium distribution coefficients for this reaction (this barometer is commonly called "GASP" on the basis of the 4 phases involved).



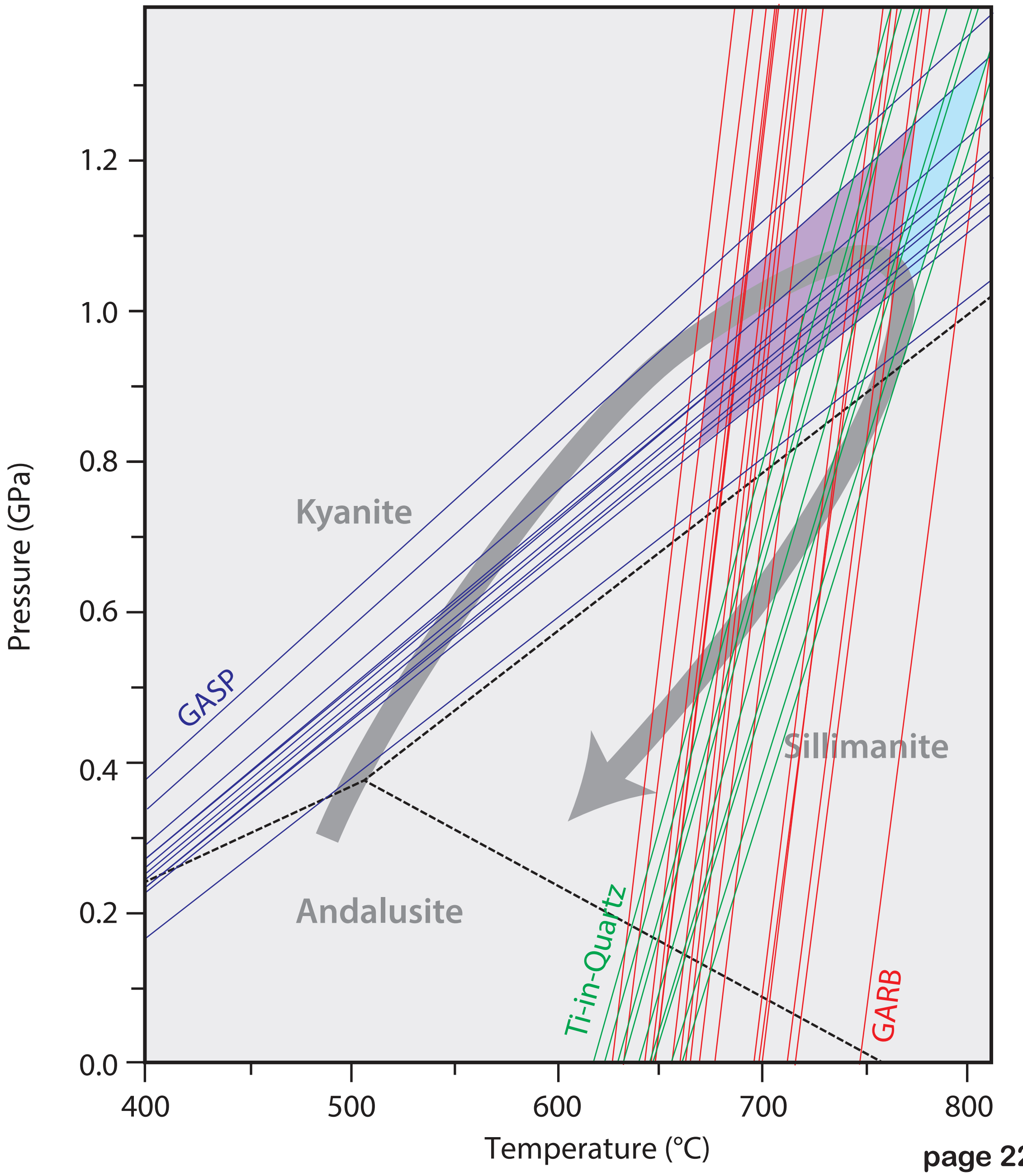
By combining the exchange reaction (red curves; GARB) and the net transfer reaction (blue curves; GASP) at Hernshead we can estimate the P-T conditions at which the rock equilibrated. As shown in the purple shaded region in the adjacent image, the P-T conditions at Hernshead existed at ~1 GPa and ~700 °C. This indicates that the metasediments reached a metamorphic facies of upper amphibolite pressure-temperature conditions.

Ti-in-quartz thermobarometry

Quartz is one of the most common phases at Hernshead and can also be used to make some estimation of metamorphic conditions. The Ti-in-quartz thermometer is a trace element thermometer that utilizes the solubility of Ti within the quartz structure as a means to predict crystallization conditions. This equilibrium constant is defined by the equation (Thomas et al., 2010):

$$K = \frac{a^{quartz}_{TiO_2}}{a^{rock}_{TiO_2}}$$

In order to plot Ti-in-quartz isopleths on a P-T grid (green curves in the image below), we first need to evaluate how close the rock is to rutile saturation (e.g., titania activity; a_{TiO_2}). To do this we can use the composition of co-existing magnetite and ilmenite, which report an average value of 0.45 (noting that calculated values range from 0.25-0.65). The isopleths are then constructed using Ti measurements made from an electron probe. The measured quartz isopleths are consistent with the P-T estimates made from GARB-GASP calculations indicating conditions marked by the light blue region in the adjacent figure.



The Ti-in-quartz isopleths can be combined with GASP and GARB estimates in order to evaluate metamorphic conditions. These three, independent thermobarometers all converge to a specific region in P-T space that represents the conditions of metamorphism. This assemblage assemblage of garnet, biotite, muscovite, plagioclase, quartz (and other phases) equilibrated at ~0.8-1.1 GPa and ~660-780 °C.

This indicates that the original oceanic marine sediments got buried to a depth of ~25-35 kilometers during the Taconic Orogeny. A simplified P-T path for rocks at Hernshead is shown by the thick grey arrow.

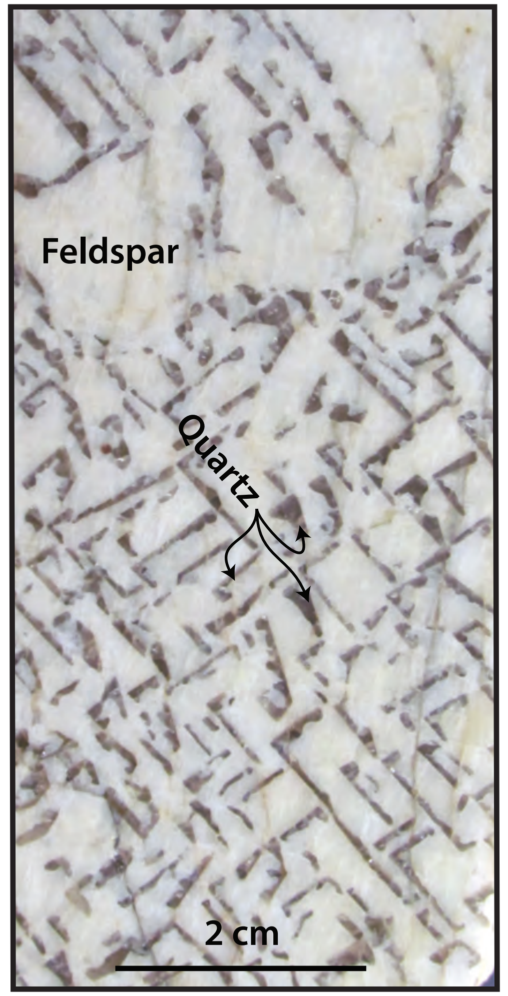


Image above: photomicrograph of a graphic quartz-feldspar intergrowth from polished section of graphic granite (AMNH collection). Note that quartz and feldspar show growth about a common axis.

5 Graphic granite

At this location we see small veinlets of "graphic granite" injected into the metapelite. The magmatic texture observed at this outcrop is common to highly silicic (e.g., SiO_2-rich) granitoids, particularly pegmatites. The term "graphic" refers to the coarse intergrowth of quartz and alkali feldspar, which somewhat resembles a runic or cuneiform text. The origin of graphic intergrowth is somewhat controversial, with the leading hypotheses including crystallization at the liquid eutectic (e.g., an equilibrium process; Vogt, 1931) or crystallization that includes an imbalance between crystal growth rate and diffusion within the melt (e.g., a disequilibrium process; Lentz and Fowler, 1992).

Unlike the metapelite and granofels, the cuneiform texture at Hernshead shows no indication of deformation. The quartz-feldspar intergrowths show sharp linear contacts that are not aligned with the dominant stress field observed in the metamorphosed sediments. This indicates that the granitic veinlets were likely injected post peak metamorphism. Although the age of this graphic granite is unconstrained, it is possible it is Devonian in age and is related to other plutonic rocks observed in Manhattan (Brock and Brock, 2001).

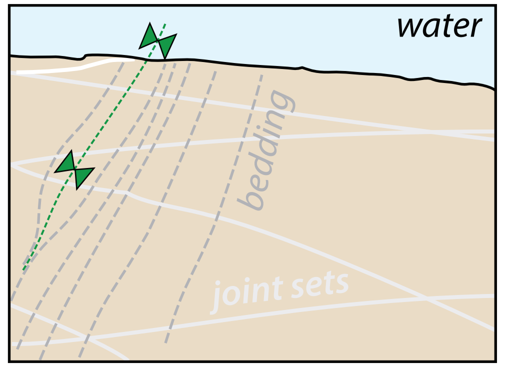
Adjacent image: field image of a graphic granite from Hernshead (with penny for scale). The granite shows sharp contacts with the surrounding schist while displaying no obvious metamorphic fabric. This indicates that the plutonic rock was likely injected at a time that post-dates metamorphism. Feldspars appear a milky white color with discernable cleavage (2 @90^{o}) while quartz is discernable from a dull grey color and concoidal fracture.

7 Quartz-rich joints

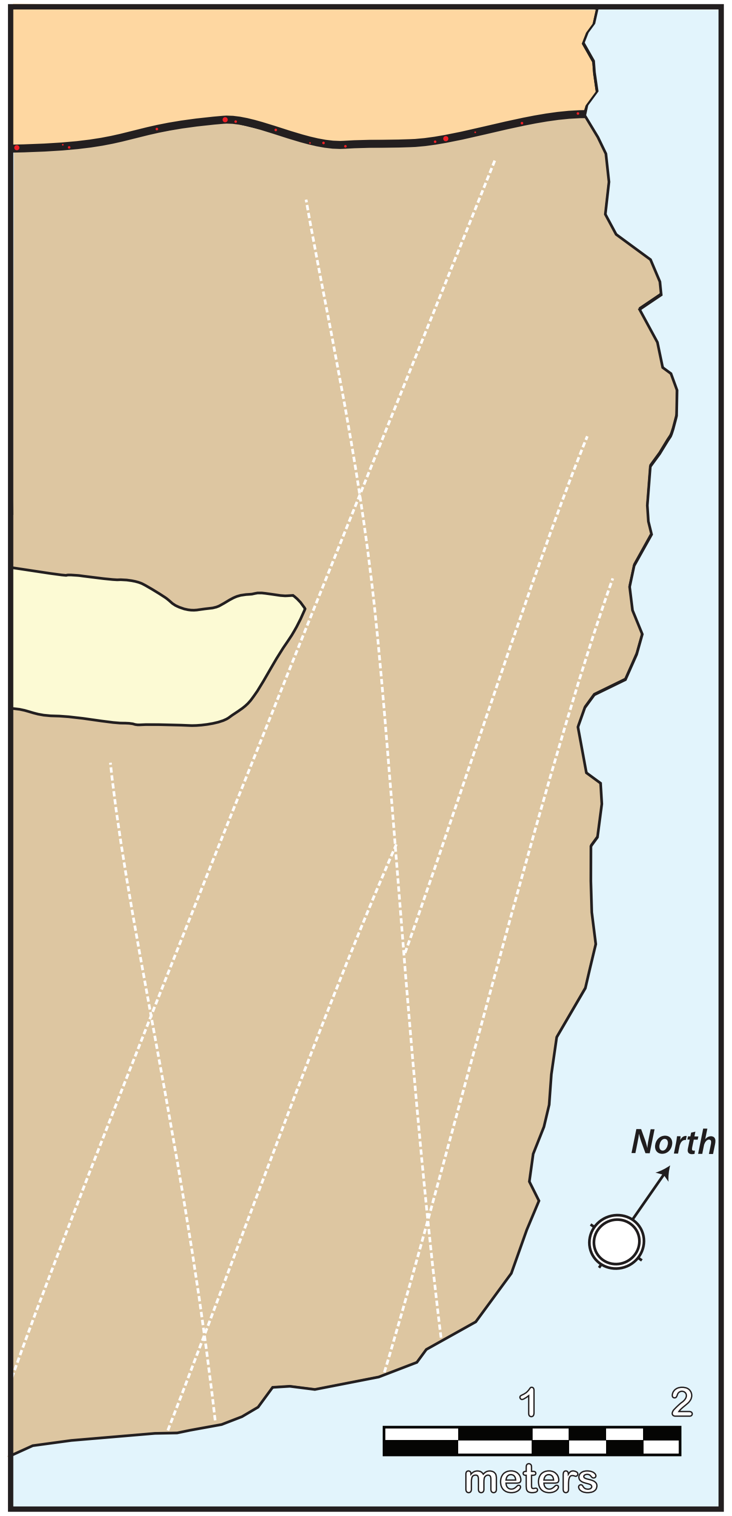
A series of late (relative to peak metamorphism), brittle deformation events are also evident at Hernshead and are easiest to observe on the platform at the northeast end of Hernshead. Here a series of quartz-rich joints can be seen as slightly raised, near-linear ridges that cross the dominant metamorphic fabric at high angles (see images below).

These quartz-rich joints form when fluids circulating the deformed metamorphic succession precipitate quartz (and other minerals) from solution. This quartz acts like a cement that makes these joints more resistant to chemical and physical weathering than the surrounding metapalite, thus giving rise to the observed ridges.

Image below/adjacent: oblique view looking northeast at the northern tip of Hernshead. Note the general metamorphic fabric and bedding trending to the northeast (e.g., grey dashed curves in upper image). The second generation of quartz veins



Simplified geological map over the northern platform at Hernshead. Dashed white curves represent quartz-rich joints cutting the overall metamorphic fabric.



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