# A Field Trip to Ancient Plate Tectonics Structures in Massachusetts and New York
## October 10-12, 2014

## 12.001: Introduction to Geology

## Led by Profs. Oliver Jagoutz and Taylor Perron

Paleogeographic map of North America removed due to copyright restrictions.

**Equipment Checklist**

Boots or sturdy shoes
Change of clothing for two days
Sweater or sweatshirt
Warm hat
Raincoat
Pens and pencils
Water bottle
Camera
Sunscreen
Notebook
Colored pencils
Brunton compass*
Hand lens*
Hammer*

*We will provide these for you

**Keeping a Field Notebook** *(for this trip you can use the blank pages in the back of this guide for a field notebook):*

As practicing geologists, your field observations provide all of your data once you are back in the lab. Your memory is not as good as you think it is. It is therefore important that you take complete, organized, and neat notes. At each site you should make a series of notations about the site, the characteristics of the outcrop, and the individual rock units.

1. Setting the stage
a. Your name, date, name of site, companions, and coordinates
b. Formation name, probable stratigraphic level/age of rocks

2. Outcrop description
a. Step back and look over the outcrop. Note its gross features. Are there any folds, faults, or unconformities evident? Are there any stratigraphic subdivisions that are visible at this scale?

b. Make a sketch of the outcrop, including on it your observations from above. Be sure to include an estimated scale and compass orientation of the view (e.g. 'looking towards the NE'). If you take a picture, note the picture number.

3. Rock description
a. General appearance: Note bedding character, the thickness and lateral continuity of the beds; color of weathered and fresh surfaces; weathering characteristics (does it fall to bits, turn to mud, or remain blocky, etc.?), response to hammering (does it ring or thud, crumble, or is it tough, how does it fracture, etc.).

b. Rock Type: Describe features encompassed by

i. Grain size and shape.
ii. Mineralogy.
iii. Sedimentary structures.
iv. Fossils.

4. Integration
a. Suggest the probable paleoenvironments represented at each stop.

**Introduction**

The purpose of this field trip is to introduce you to geologic evidence for the past action of plate tectonics. We will see various rocks from different tectonic settings that have been used to reconstruct the complex Paleozoic history of the eastern United States and Canada. The geology of the eastern U.S. is dominated by multiple rifting and collision events related to at least two complete sequences of the Wilson cycle, the hypothesized cyclical opening and closing of ocean basins that accompanies the formation and breakup of supercontinents. In particular, we will see evidence for the assembly and disassembly of the supercontinent Rodinia from ~0.5-1.3 billion years (Ga) ago, the subsequent collision of two volcanic islands arcs with Laurentia (proto-North American continent that rifted from Rodinia) between 440-350 million years ago (Ma), and the disassembly of the supercontinent Pangea after 250 Ma. We will *not* see any geologic evidence for the assembly of Pangea (the Allegheny orogeny), which occurred between ~350 and 250 Ma, since most of the affected rocks were rifted away during its breakup.

We will begin the trip in the West, on the passive margin sequences of Laurentia, and work our way towards the East through a complex arc-continent collision zone. We will visit rocks formed or metamorphosed during the following events, listed in order of time of occurrence (see Fig. 1).

1. The Grenville orogeny associated with formation of the supercontinent Rodinia (Proterozoic eon ~1 Ga): Stop 1
2. Rift deposits associated with breakup of Rodinia (Ediacaran period): Stop 1
3. Passive margin of Laurentia (Cambrian to Ordovician periods): Stop 1
4. Taconic Orogeny associated with collision of Laurentia with the Shelburne Falls island arc (Middle Ordovician epoch): Stops 2-10
5. The Acadian orogeny associated with the collision of Laurentia with Avalon island arc (Early Devonian epoch)
6. Rifting from opening of the Atlantic Ocean associated with breakup of supercontinent Pangea (Jurassic to Triassic periods): Stop 11

An overview of the geologic structures in our field area is shown in Fig. 2.

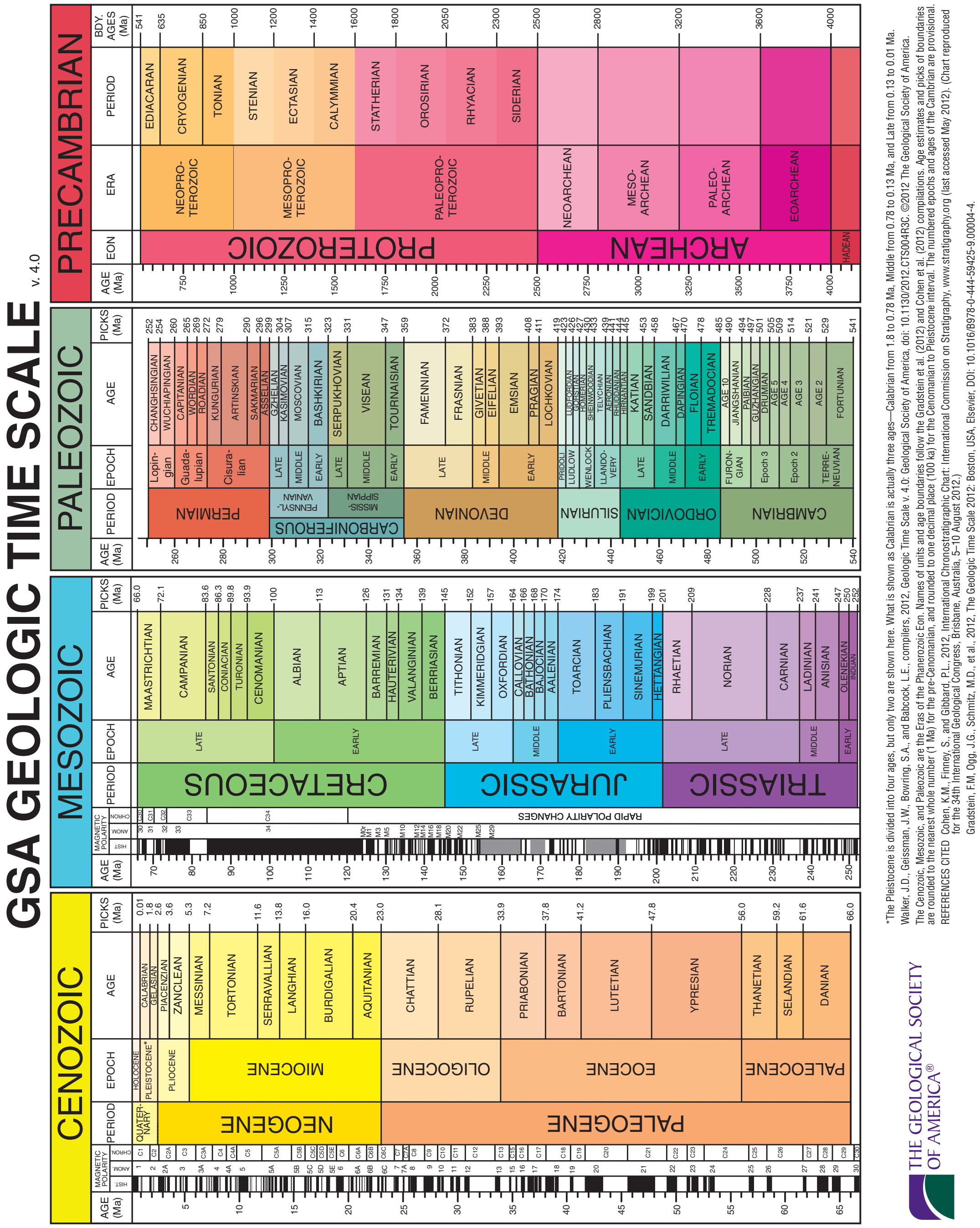



**Fig. 1.** The geologic time scale.

Courtesy of The Geological Society of America. Used with permission.

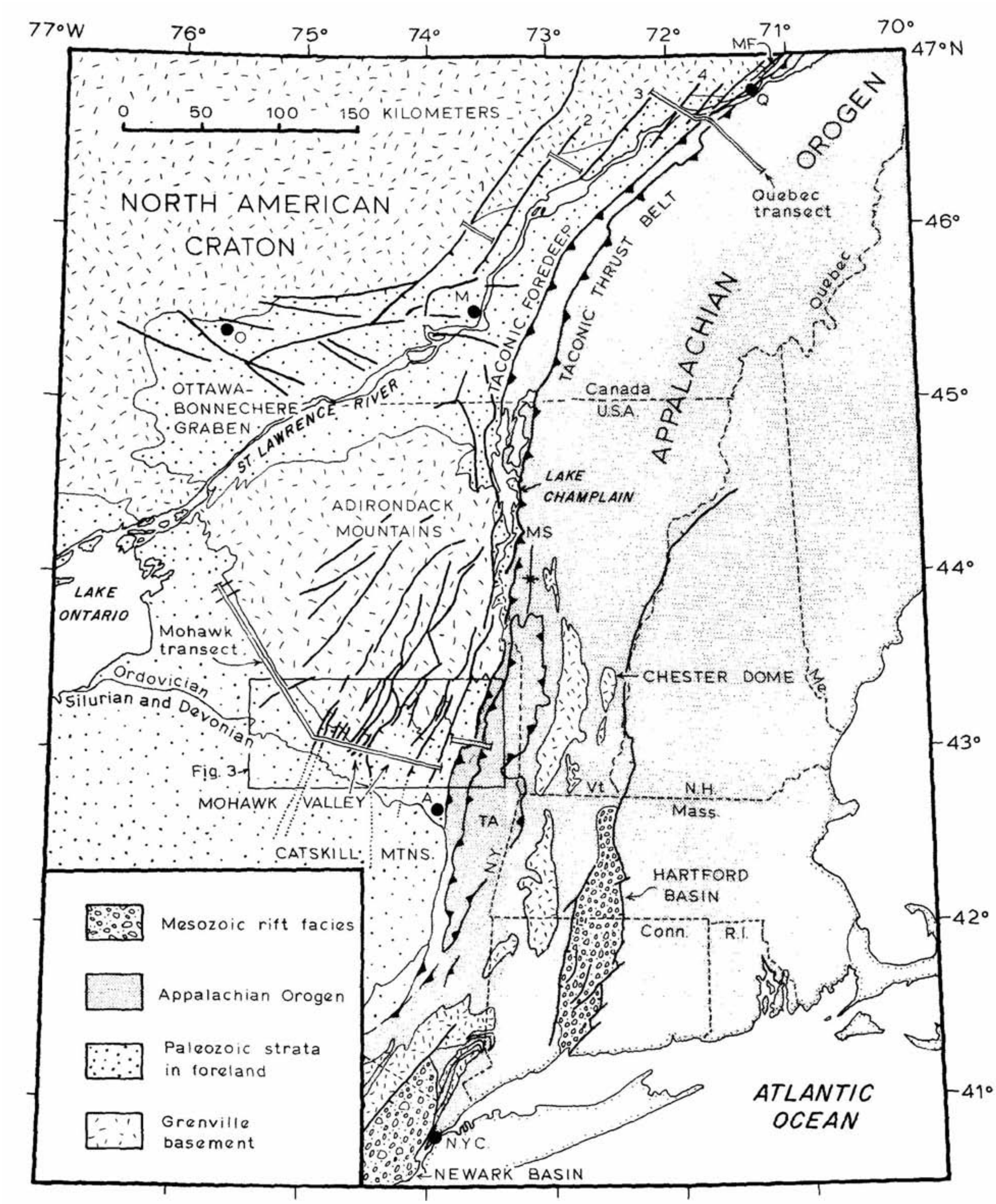
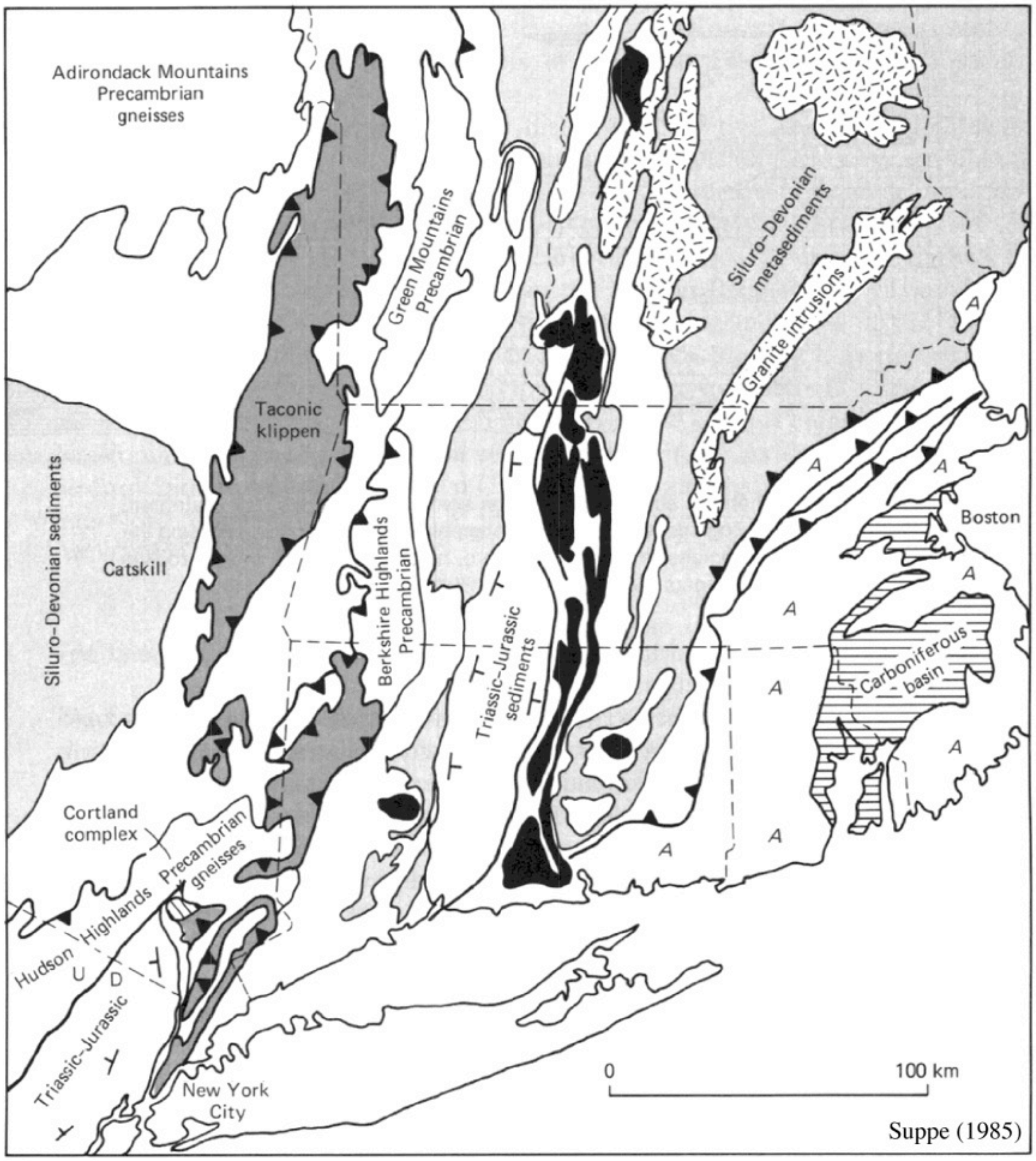



**Fig. 2a.** Overview of rocks and structures to be visited on this field trip (after Bradley and Kidd 1991).


Source: Bradley, D. C., and W. S. F. Kidd. "Flexural Extension of the Upper Continental Crust in Collisional Foredeeps." *Geological Society of America Bulletin* 103, no. 11 (1991): 1416-38.

Northern Appalachians

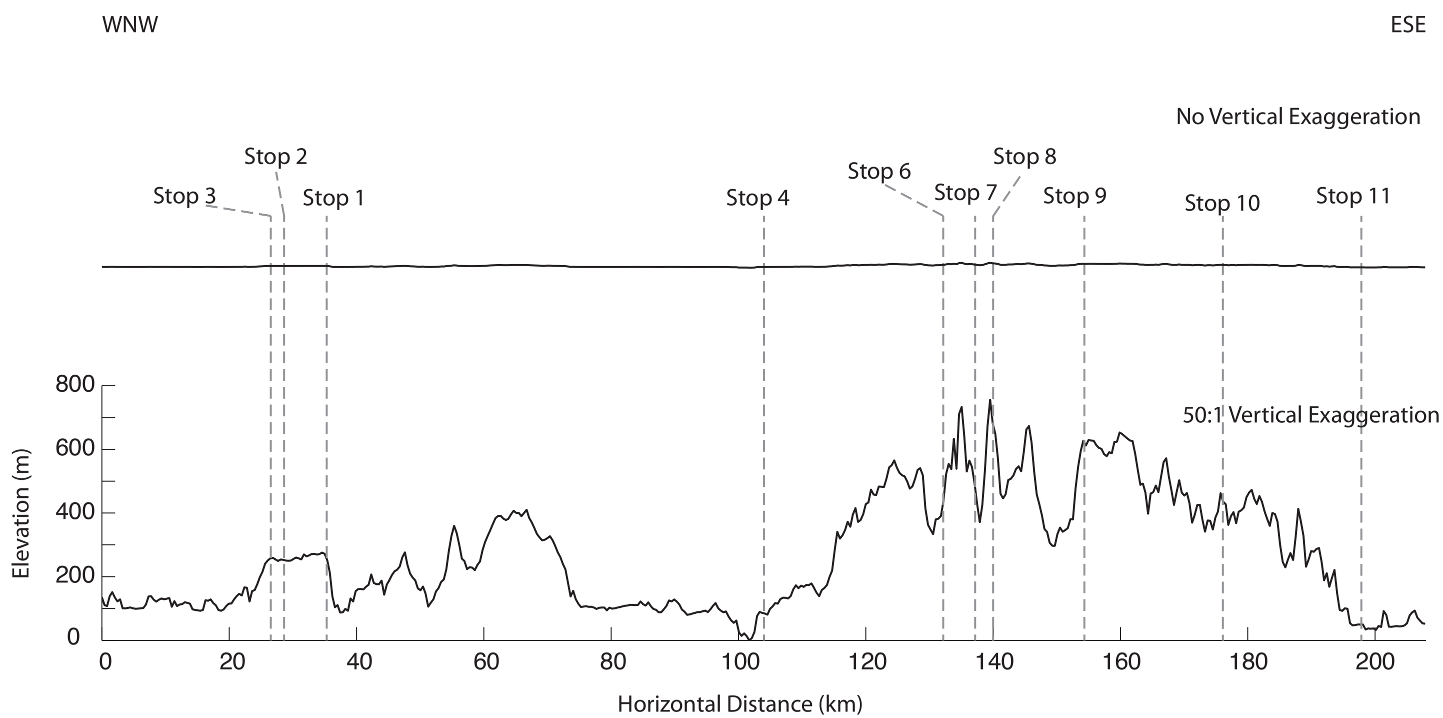



The Appalachian orogenic belt in southern New England. Black bodies are Ordovician and older gneisses lying along the Bronson Hill anticlinorium. Unlabeled white areas are generally Cambrian and Ordovician sediments and metasediments, except possibly in the east where ages are less certain. Areas labeled *A* are underlain by metamorphic rocks of known or probable Avalonian affinities, that is, Upper Precambrian and Cambrian metasedimentary volcanic and plutonic rocks exotic to North America; the metasediments contain rare fossils of European affinities. Light screened areas represent Siluro-Devonian strata above the Taconic unconformity. Dark screened areas are underlain by Ordovician, Cambrian, and Upper Precambrian strata of the allochthonous Taconic sequence. (Compiled from maps of Williams, 1978, and Robinson and Hall, 1980.)

**Fig. 2b.** Overview of rocks and structures to be visited on this field trip (Suppe 1985).

**Summary Exercise**

One of the main objectives of this field trip is to understand the tectonic relationships between the various terranes we will visit in New York and Massachusetts. We want you to keep track of the orientation of the rock bedding and/or foliation (e.g., planar fabric). For this you will use a Brunton compass to measure the strike and dip of the rocks that we will visit. You will then plot the apparent dip (the dip you would see in a vertical section) on the topographic cross section shown below. After you have created this, provide a general interpretation of the structures in the diagram in the context of the tectonic history of North America.


WNW
ESE
No Vertical Exaggeration
Stop 3
Stop 2
Stop 1
Stop 4
Stop 6
Stop 7
Stop 8
Stop 9
Stop 10
Stop 11
50:1 Vertical Exaggeration
Elevation (m)
0
200
400
600
800
0
20
40
60
80
100
120
140
160
180
200
Horizontal Distance (km)

**October 10**

*Assemble under Green Building (42.360271°, -71.089412°) at 12:45 pm. Depart no later than 1:00 pm.*

*Drive to Thompson's Lake State Park Campground, 68 Thompsons Lake Road, East Berne, NY 12059, about 4 hr. We will camp here on Friday and Saturday nights.*

**October 11**

*Eat breakfast and pack lunches at campground. Depart campground by 8:00 am. 1 hour drive to Stop 1.*

**Stop 1. Noses Fault and breccia (42.902359°, -74.458448°)**

*Old railroad cuts, along what is now a bike path, just south of NY 5S about a mile west of the junction of County Highway 112 in the village of Randall (the village doesn't appear on Google Maps).*

The supercontinent Rodinia was formed by the collision of nearly all of the world's existing continents ~1.3-1.0 Ga ago (Fig. 3a-c). This included the collision of Laurentia with other continental blocks in what is called the Grenville Orogeny (i.e., mountain-building event). This led to the formation of a thickened crust and associated metamorphism of various rock types at great depths. This mountain belts extended from what is now eastern New York up to New Brunswick in Canada (Fig. 3c). Subsequent rifting of Rodinia during the period ~800-530 Ma led to its breakup (Fig. 3e-l). The margins of the rifted continents experienced subsidence, leading to a vast marine transgression (i.e., landward migration of the shoreline) in the Cambrian.

At this stop, you can see highly metamorphosed and strongly deformed biotite gneisses unconformably overlain by (i.e., separated by a paleo-erosion surface from) unmetamorphosed Cambrian dolostones. The age of the metamorphism is associated with the ~1.3-1.0 Ga Grenville orogeny that resulted in the assembly of Rodinia. The protolith of the metamorphic rock was a sediment (e.g., shale or sandstone) that was buried during the Grenville orogeny to mid-crustal depths. In the Cambrian, these rocks were again exposed on the surface and formed the basement on which the Cambrian and younger passive margin sequences were deposited during the break up of Rodinia. At road level to the southwest are outcrops of the Grenville meta-sandstone; to the northeast and overlying them are Cambrian carbonates of the Beekmantown Group. The contact between the two appears to be covered. The face of the outcrop above the bike path is plastered by a thin breccia containing blocks of sandstone in a sandstone matrix. The basal deposits of the transgression become younger from east to west and generally consist of flat-lying sandstones of the Potsdam Formation.

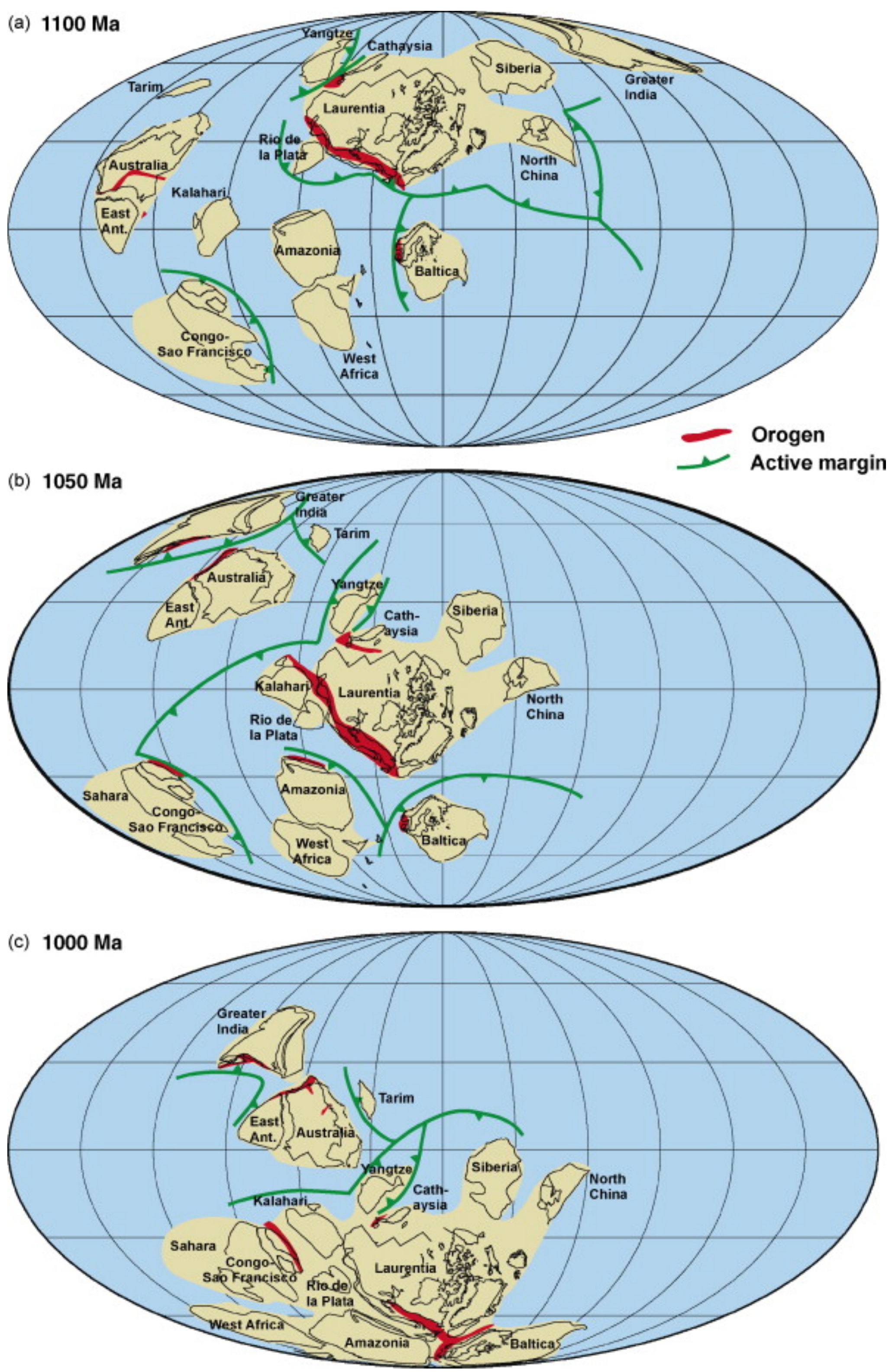
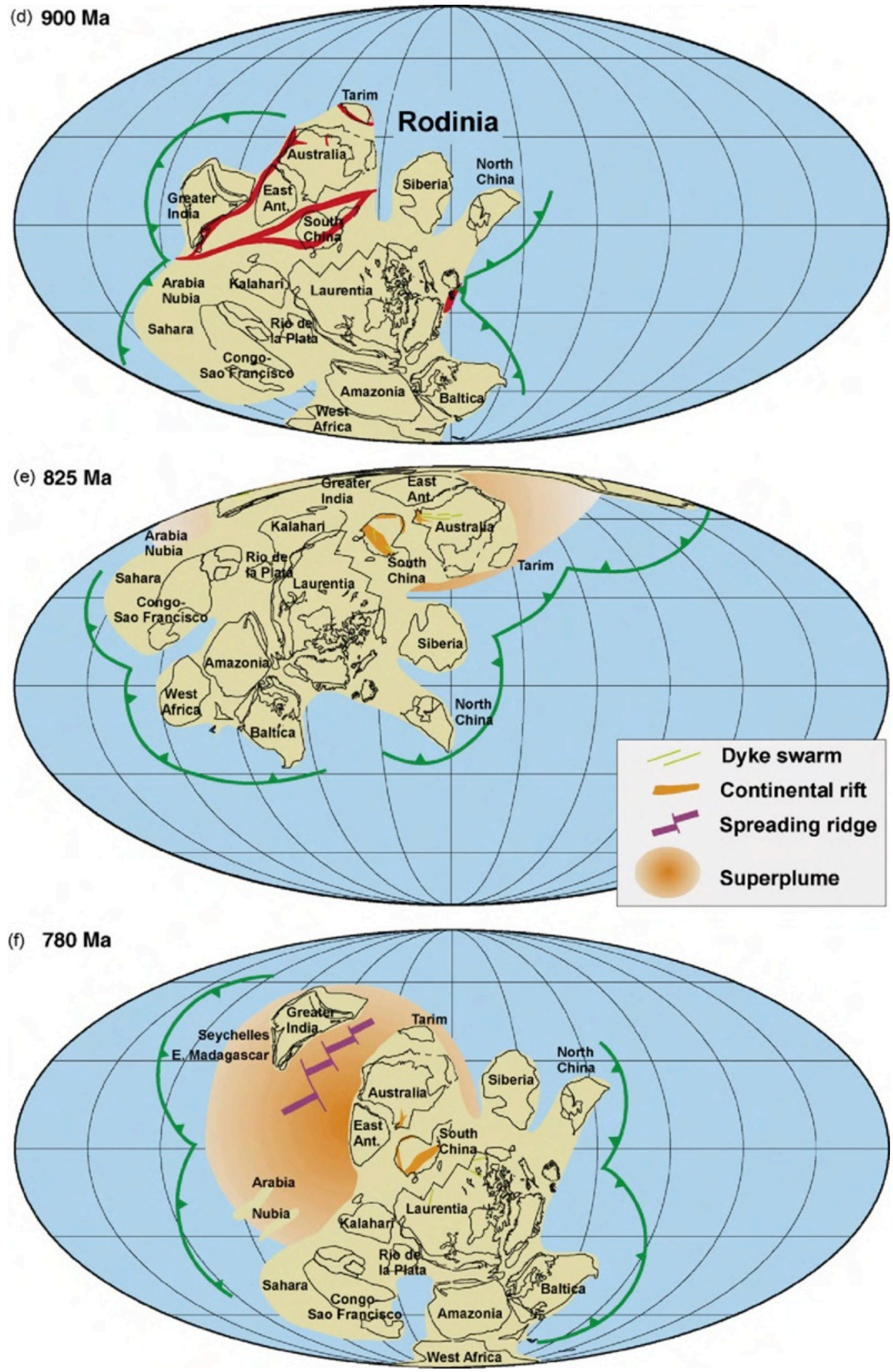



**Fig. 3.** The assembly and breakup of Rodinia (from Li et al. 2008).




Courtesy of Elsevier, Inc. http://www.sciencedirect.com. Used with permission.
Source: Li, Zheng-Xiang et al. "Assembly, Configuration, and Break-up History of Rodinia: A Synthesis." *Precambrian Research* 160, no. 1 (2008): 179-210.

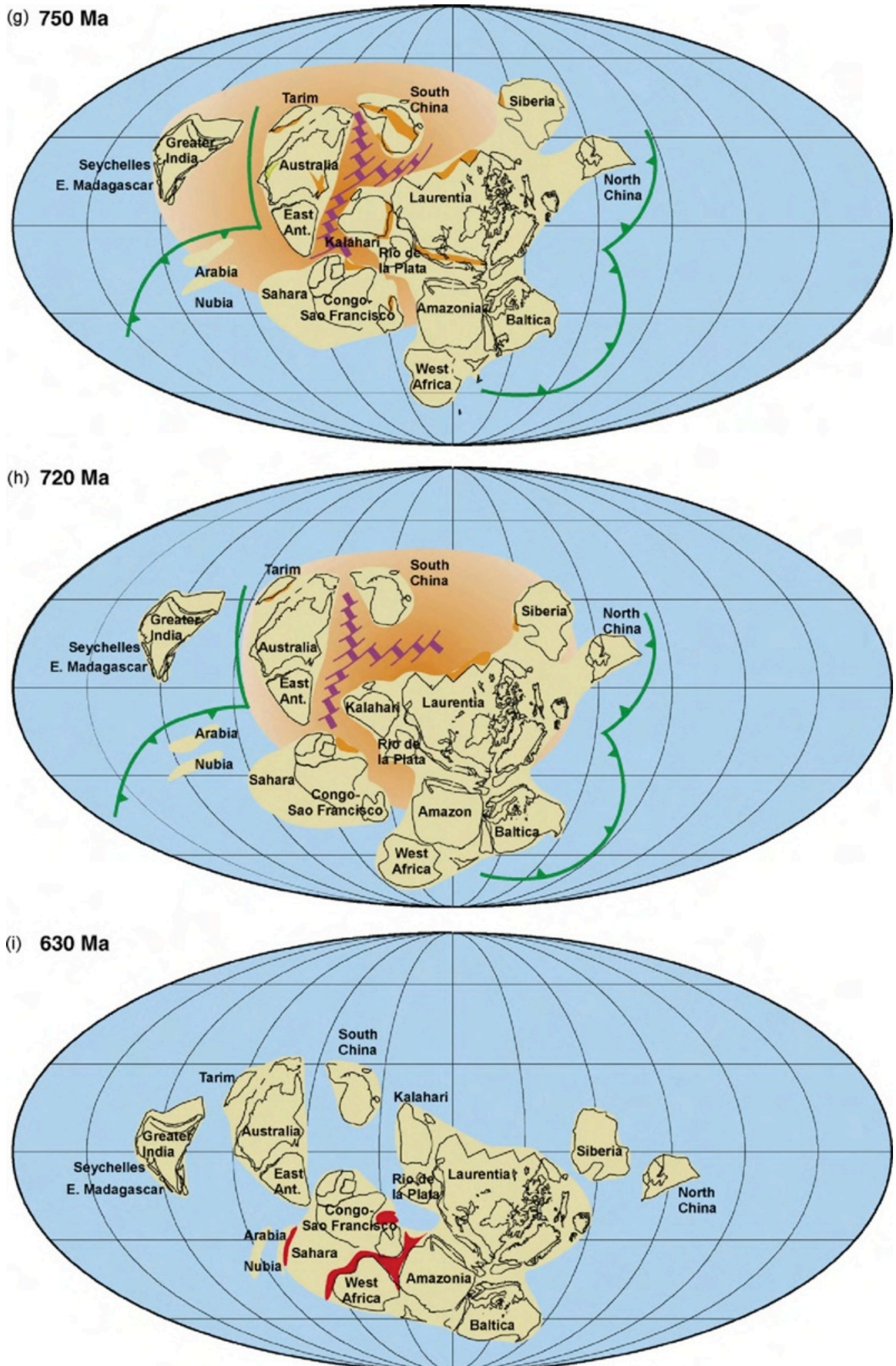



**Fig. 3 continued.**

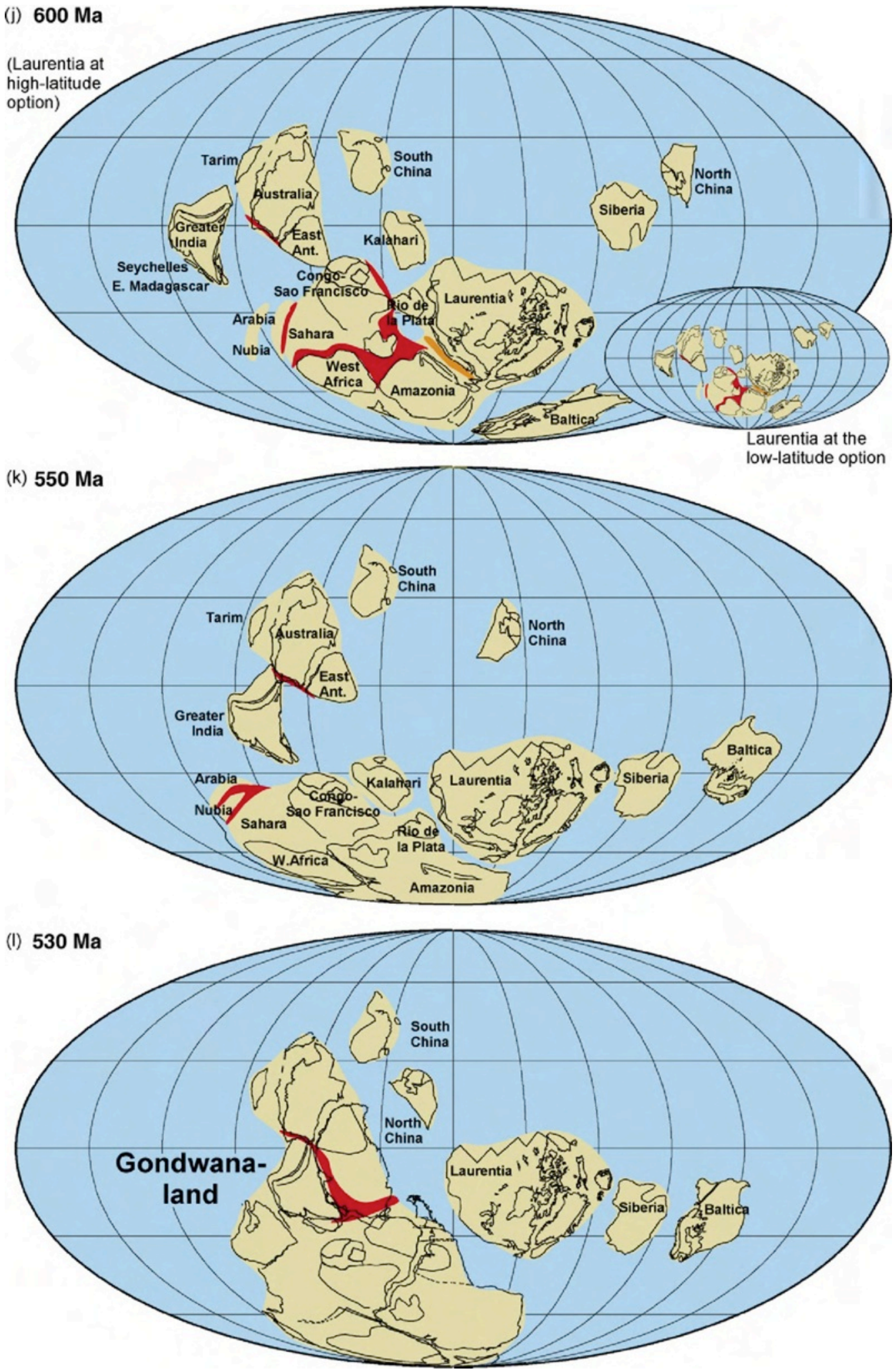



**Fig. 3 continued.**

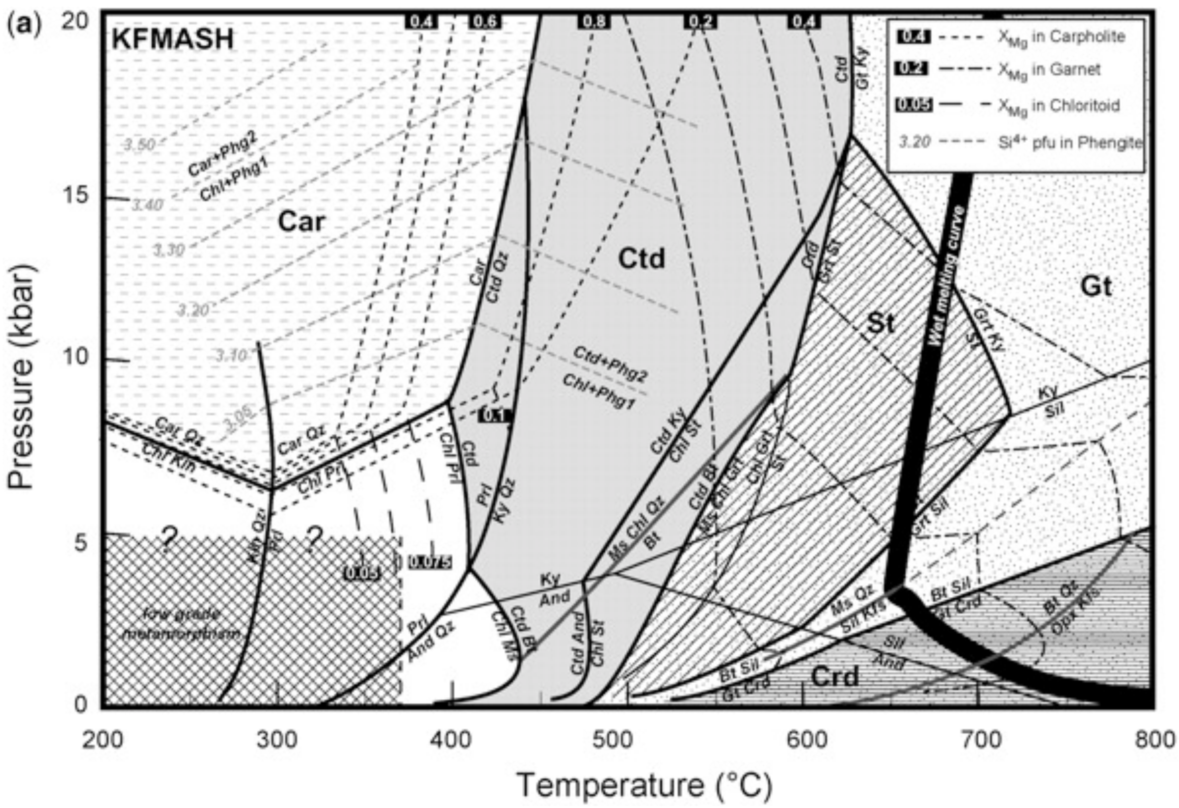

Source: Li, Zheng-Xiang et al. "Assembly, Configuration, and Break-up History of Rodinia: A Synthesis." *Precambrian Research* 160, no. 1 (2008): 179-210.

**Stop 1 Exercise:**

1a. First, take a look at the Grenville rocks. What minerals can you identify (note in particular red, equant mm-sized crystals)?

1b. Now look at the overlying dolostones. Hypothesize how the breccia was created. Provide support for your interpretation with a diagram.

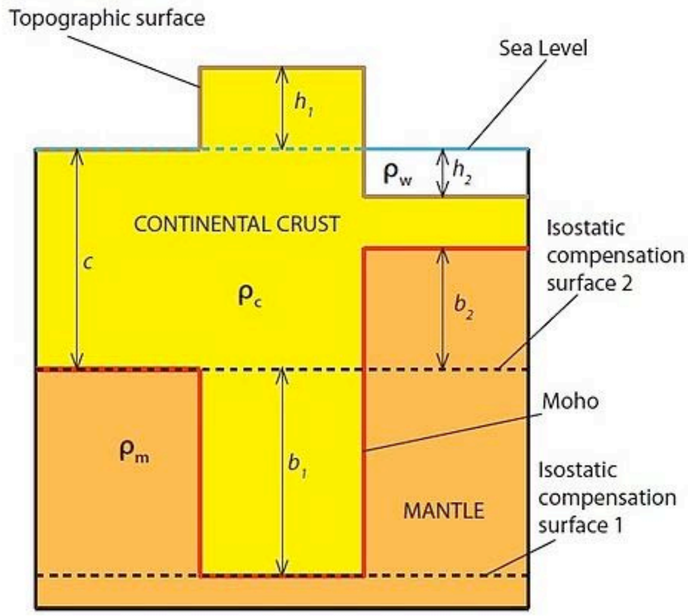
1c. Now you will estimate the height of the Grenville mountains using the basement rocks exposed here. Use the figure below to estimate which temperature these rocks have experienced based on the minerals you identified in the rocks. Assuming a geothermal gradient of ~ 20°C/km, estimate the minimum depth these rocks have experienced.




Petrogenetic grids for metapelites (KFMASH ($K_2O$–$FeO$–$MgO$–$Al_2O_3$–$SiO_2$–$H_2O$)) system for a temperature range from 200 to 800 °C (from Bousquet et al., 2008).


Source: Bousquet, Romain, Roland Oberhänsli, et al. "Metamorphism of Metasediments at the Scale of an Orogen: A key to the Tertiary Geodynamic Evolution of the Alps*." *Geological Society, London, Special Publications* 298, no. 1 (2008): 393-411.

1d. These rocks were exhumed from your inferred depth to the surface in the Proterozoic times. Assume that the exhumation occurred only by erosion (instead of by tectonic denudation or other processes). The crustal thickness at this location today is ~30 km. Assume that this thickness of crust was the same underneath the gneisses during the Grenville orogeny. Use the isostatic principle (see figure below) to calculate the total crustal thickness during the Grenville orogeny, and estimate the average topography of the mountain belt. How do these compare to present day mountain belts like the Alps or the Himalaya? Assume an average density for the crust and mantle of 2800 kg $m^{-3}$ and 3300 kg $m^{-3}$, respectively. You may show your work on the next page.




$h_1$ = elevation of mountain belt (above sea level)
$h_2$ = depth of marine basin (below sea level)
$b_1$ = thickness of crustal roots (below depth of Moho in a cratonic area)
$b_2$ = thickness of lithosphere mantle bulge (above depth of Moho in a cratonic area)
$c$ = thickness of continental crust in an undeformed (cratonic) area (ca. 35 km)

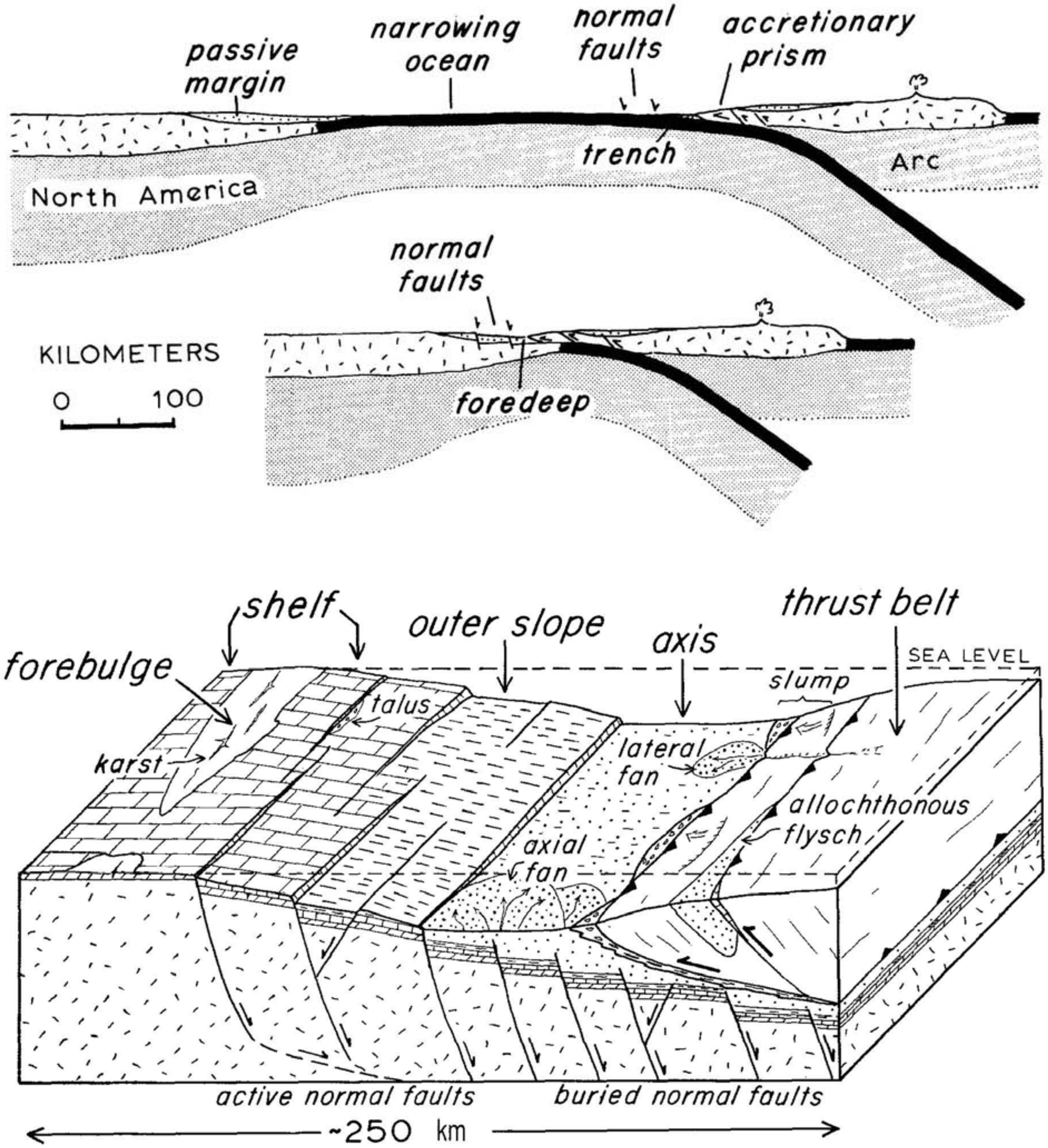
$\rho_w$ = density of sea water (ca. 1,000 Kg/$m^3$)
$\rho_c$ = density of continental crust (ca. 2,800 Kg/$m^3$)
$\rho_m$ = density of mantle (ca. 3,300 Kg/$m^3$)

*10 min drive to Stop 2.*

**Stop 2. Canajoharie Creek (42.898073°, -74.571264°): forebulge unconformity**

Beginning in the Middle Ordovician (~470 Ma), a volcanic island arc (referred to as the Shelburne Falls arc) collided with Laurentia. This is known as the Taconic Orogeny. The Taconic arc-continent collision was heralded by submergence of the continental shelf in the submarine trench that formed at the Laurentian margin. This event created additional vertical accommodation space in which dark grey muds (now shale) were deposited in deep, anoxic waters on the trench slope, on top of the formerly shallow shelf carbonates. The transition is commonly marked by a short-lived hiatus in deposition, possibly related to a migrating "forebulge" due to lithospheric flexure at the trench (Fig. 4).

This outcrop is well known for its potholes. Lower Ordovician carbonate rocks of the Beekmantown Group are overlain by carbonate rocks of the Trenton Group. The contact is a rather unimpressive unconformity that is the age and position expected for a forebulge unconformity (stratigraphic time break between two sedimentary layers). A comparable unconformity is seen in the analogous position all the way from Alabama to Newfoundland. Above the unconformity, the Trenton Group records renewed subsidence. The Trenton Group and overlying Utica Shale (seen just upstream at the next stop) form an upward-deepening succession that was deposited on the outer slope of the foredeep.




Courtesy of the Geological Society of America. Used with permission.
Source: Bradley, D. C., and W. S. F. Kidd. "Flexural Extension of the Upper Continental Crust in Collisional Foredeeps." *Geological Society of America Bulletin* 103, no. 11 (1991): 1416-38.

**Fig. 4.** The Taconic orogeny, is recorded stratigraphically in the slope-rise and platform successions (after Bradley and Kidd 1991). On the carbonate platform, the slightly younger event sequence was:
(1) platform uplift and emergence (interpreted as a passage over a forebulge)
(2) renewed carbonate deposition (interpreted as the platform margin of the foredeep), deepening upward into…
(3) black shale deposition as the platform drowned (interpreted as the outer slope of foredeep)
(4) deformation, when the foredeep was overridden by thrusts.

**Stop 2 Exercise:** Learn to measure the strike and dip of a planar feature with a Brunton compass.

*5 min drive to Stop 3.*

**Stop 3. Canajoharie Gorge (42.885354°, -74.562935°): Utica Shale and tephras**

At this stop, the Canajoharie Creek flows through a deep gorge in the Utica Shale. The shale spans the same age range as Trenton Group carbonates farther west (see Stop 3a). Graptolites, trilobites, and other fossils can be found by splitting slabs of shale. A number of tephra horizons can be seen in the cliffs; they are the thin recessed horizons that seep rusty water. The tephras are marine ashfall deposits that presumably were blown into the foredeep from the approaching Shelburne Falls arc during the Taconic collision. Regional correlations using these ash beds as time markers were proposed by Mitchell et al. (1994); correlation was based, in part, on chemical fingerprinting of melt inclusions from quartz phenocrysts (Delano et al., 1994). Zircon and apatite (which can be dated using U/Pb geochronology) are among the useful minerals that can be recovered from these tuffs using a blender and gold pan.

Stop 3 Exercise: Identify and sketch multiple fossils within the Utica Shale (USE YOUR FOSSIL GUIDE).

*90 min drive to Stop 3, including 10 min rest stop.*

**Stop 4. Poestenkill Gorge in Troy: Taconic frontal fault (42.720110°, -73.680387°)**

*Access is from a parking and picnic area on the left side of Linden Ave. on the south side of this roughly east-west gorge that divides Troy.*

At this location we see one of the westernmost thrust faults related to the Taconic thrust system, the Taconic frontal thrust. The hanging wall of the fault is composed of the Cretaceous Bomoseen Formation of the Taconic allochthon, consisting of green arenites and silty wackes and slates. Below the fault is the Ordovician block-rich Cohoes mélange. The original (presumed thrust) fault contact has been cut and displaced by later steep faults.

**Stop 4 Exercise:**

Cite three pieces of evidence that can be used to identify this as a major thrust fault.

*Return to Thompson Lake State Park Campground. 1 hour drive plus refueling stop.*

**October 12**

*Eat breakfast and pack lunches at campground, then break camp. Be ready to depart campground by 8:00 a.m. 1 hour drive to Stop 5.*

**Stop 5. Overlook and rest stop (42.749216°, -73.567627°)**

Here we quickly reflect the main points we saw and discussed yesterday. The Subway nearby has a rest room.

*1 hour drive to Stop 6.*

**Stop 6. Hoosac Schist (42.708989°, -73.062894°)**

*Around Golden Eagle Restaurant.*

The Hoosac Schist protolith was Precambrian to Cambrian sediments deposited along Laurentian continental slope on top of continental basement along with some ocean basalts (Fig. 5). It was metamorphosed and thrust westward during the Taconic orogeny. This summit marks the eastern faulted edge of the great Taconic allochthon whose western edge we saw yesterday at Stop 4.

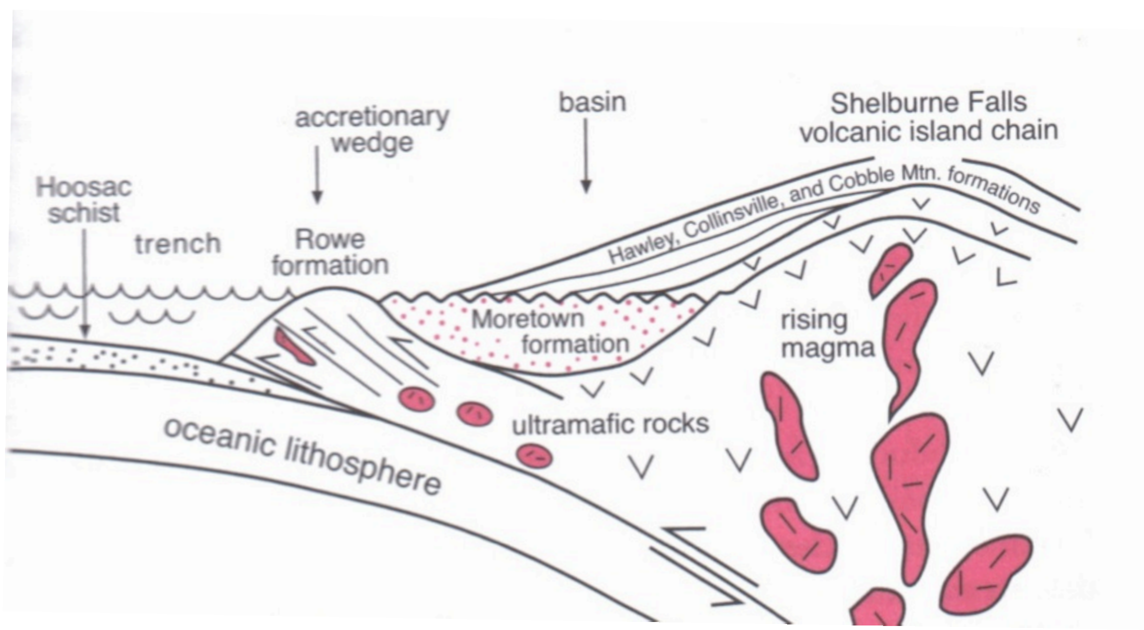



**Fig. 5.** Taconic orogeny, viewed offshore of Laurentia. Starting from left, shown are Laurentian continental slope sediments (Hoosac schist), accretionary wedge (Rowe Formation), forearc basin (Moretown Schist), and island arc itself (Hawley-Collinsville Formation Schist) shown just prior to collision (after Skehan 2001, p. 291).

**Stop 6 Exercise:**

6a. How might you infer that this schist was originally a sediment instead of an igneous rock?

6b. In which direction is the foliation (planar fabric) dipping? Does this make sense given the tectonic context?

*10 min drive to Stop 7.*

**Stop 7. Rowe Schist (42.670782°, -73.006699°)**

The Rowe Schist is the first unit we will see on this trip that originated in the incoming arc terrane. The Rowe Schist consists of Late Cambrian to Ordovician metavolcanic ashes incorporated into the accretionary wedge in front of incoming Shelburne Falls arc (Fig. 5). Associated with the schist are frequent ultramafic talc schists that represent metamorphosed and deformed olivine-rich mantle rocks. The contact between the Rowe and Hoosac schist marks the suture along which the collision between the Shelburne Falls arc and the Laurentian margin occurred.

**Stop 7 Exercise:**

In which direction is the foliation (planar fabric) oriented? Does this make sense given the tectonic context?

*5 min drive to Stop 8.*

**Stop 8. Serpentinite Boulders in Suture Zone (42.665372°, -72.989675°)**

*Park at designated area and walk back uphill for ~ 50m and than turn left into a forest road. Walk further uphill for ~ 100m and climb down into the small creek to the left. Look at the boulders in the creek.*

Within the Rowe schist numerous lenses of ultramafic rocks are exposed that are part of a narrow belt that trends roughly north-south from Newfoundland to Connecticut, known as the Red Indian Line. The ultramafic rocks are now dominantly serpentine ($Mg_3Si_2O_5(OH)_4$) and talc ($Mg_3Si_4O_{10}(OH)_2$) but originally were mantle peridotites that were involved in the suturing process between Laurentia and the Shelburne falls arc. During suturing the peridotites (mainly composed of olivine ($Mg_2SiO_4$)) reacted with water to serpentine. Subsequent regional metamorphism during the Acadian orogeny heated up the rocks and serpentine reacted to talc.

.

*30 min drive to Stop 9.*

[Time permitting] **Stop 9. Pillow basalts in the Hawley-Collinsville Formation (42.604964°, -72.912124°)**

*45 min. Continue east along Rt. 2 and then turn right on Rt. 8A south. Follow winding Rt. 8A for 3 miles south to sharp right bend in 8A. Turn left at bend onto Pudding Hollow Rd. Go 0.1 mile and take immediate turn left onto Middle Rd. Park by bridge. Outcrops are down by the brook.*

Finally we have arrived at the remnants of the island arc itself that caused the Taconic orogeny: the Hawley-Collinsville Formation. This formation was formed in the Middle Ordovician when the Shelburne Falls arc was thrust unconformably over the Moretown schist during the Taconic Orogeny. Here you see direct evidence for the volcanism associated with the Shelburne Falls arc: pillow basalts.

**Stop 9 Exercise:**

Sketch the pillow basalts. What do these structures tell you about the environment in which the volcanism occurred?

*20 min drive to lunch stop.*

**Lunch Stop (42.602653°, -72.739301°)**

We will stop for 45 minutes to eat lunch in view of the river.

*5 min drive to Stop 10.*

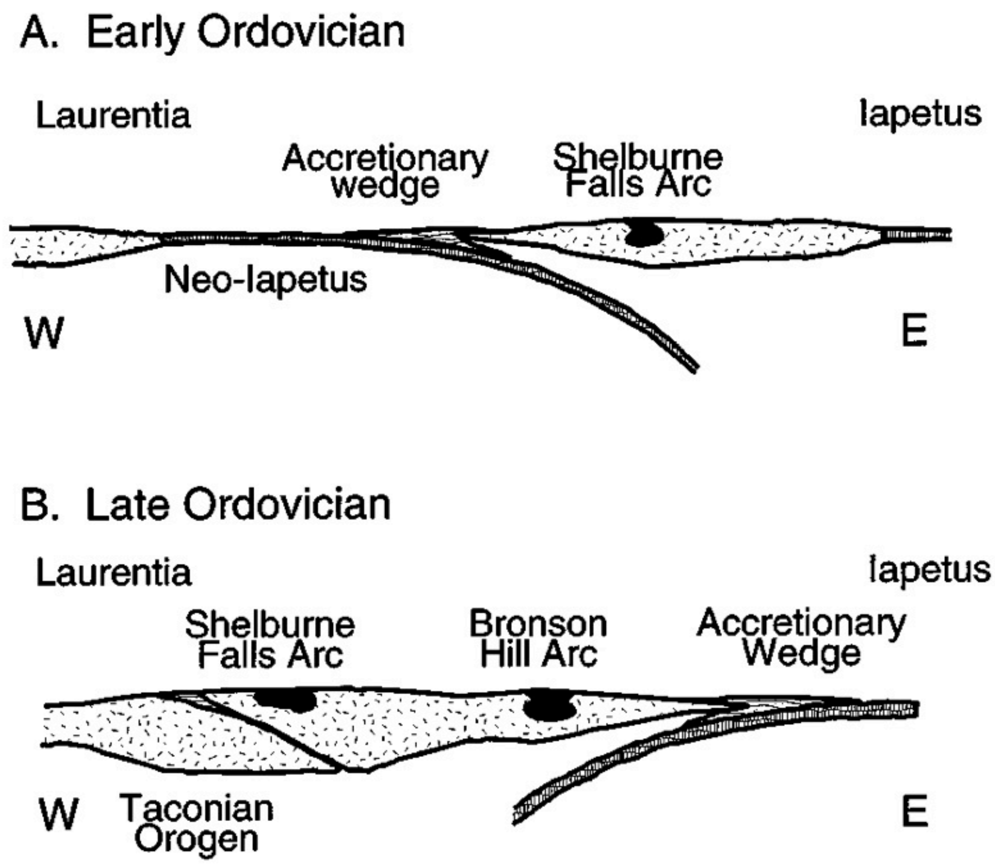
**Stop 10. Shelburne Falls Dome (42.590917°, -72.730317°)**

*From Shelburne Falls turn left on South St./Shelburne Falls Rd. and then left again at Gardner Falls Rd.*

The Shelburne Falls arc in Massachusetts and Vermont formed above an east-dipping subduction zone (present coordinates) and is equivalent to the Penobscot and Victoria arcs in Newfoundland. In both Newfoundland and the northeastern United States, rocks of the former passive margin are now flanked to the east by Ordovician volcanic and plutonic rocks; arc magmatism in both areas spanned pre-, syn-, and immediately post-collisional times (Karabinos et al., 1998; van Staal et al., 2007).

The Shelburne Falls arc consists of metamorphosed intermediate to felsic rocks with geochemistry consistent with formation in an arc environment. The felsic rocks are commonly intruded by mafic rocks that may have formed in backarc or forearc extension. Zircons in the felsic rocks have been dated using U/Pb to between 485 and 470 Ma (Karabinos et al., 1998). To the south, the correlative Hollackville Pond Gneiss intrudes the Moretown Formation, not only providing a minimum age constraint on the Moretown Formation, but also demonstrating that it and equivalent plutons near Shelburne Falls formed on the Ganderian margin. The Hollackville Pond Pluton was previously dated with U/Pb zircon evaporation at 479±8 Ma (Karabinos et al., 1998), and geologists from Harvard have recently re-dated zircon from this outcrop with U/Pb chemical abrasion isotope dilution thermal ionization mass spectrometry, producing an age of 474.97±0.16 Ma (Macdonald et al., 2013).

**Exercise 10:** Draw cross-cutting relationships between the mafic and felsic components of the Shelburne Falls rocks. What is the relative age between the different intrusions and the metamorphism? How can you determine a relative age? Are there any recurring orientations to either the intrusions or the metamorphic fabrics? If so, measure them.





Source: Karabinos, Paul, Scott D. Samson, et al. "Taconian Orogeny in the New England Appalachians: Collision between Laurentia and the Shelburne Falls Arc." *Geology* 26, no. 3 (1998): 215-18.

**Fig. 6.** Subduction reversal in Early Devonian following Taconic orogeny. (a) In the Early Ordovician, the subduction zone dipped eastward under the Shelburne Falls arc as it approached Laurentia. (b) Accretion of the Shelburne Falls arc occurred in the Late Ordovician, leading to the Taconic orogeny and deformation of Laurentia. Then, subduction polarity reversed to a westward dipping configuration. This led to further arc volcanism on the eastern margin of the accreted terrane (Bronson Hill Arc). After Karabinos et al. 1998.

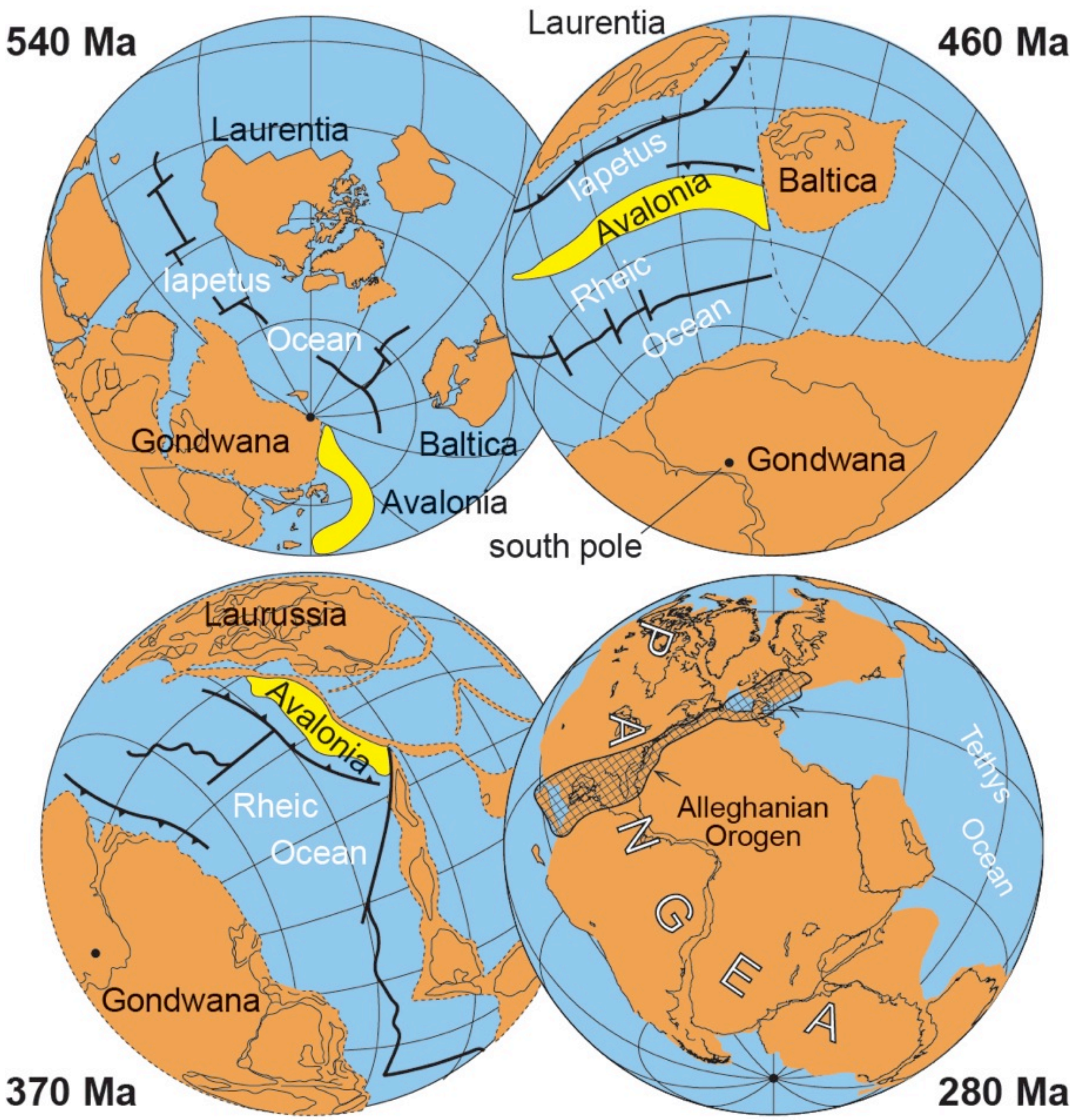



**Fig. 7.** Accretion of Avalonia (Acadian orogeny) and subsequent assembly of supercontinent Pangea (after Nance, 2008).

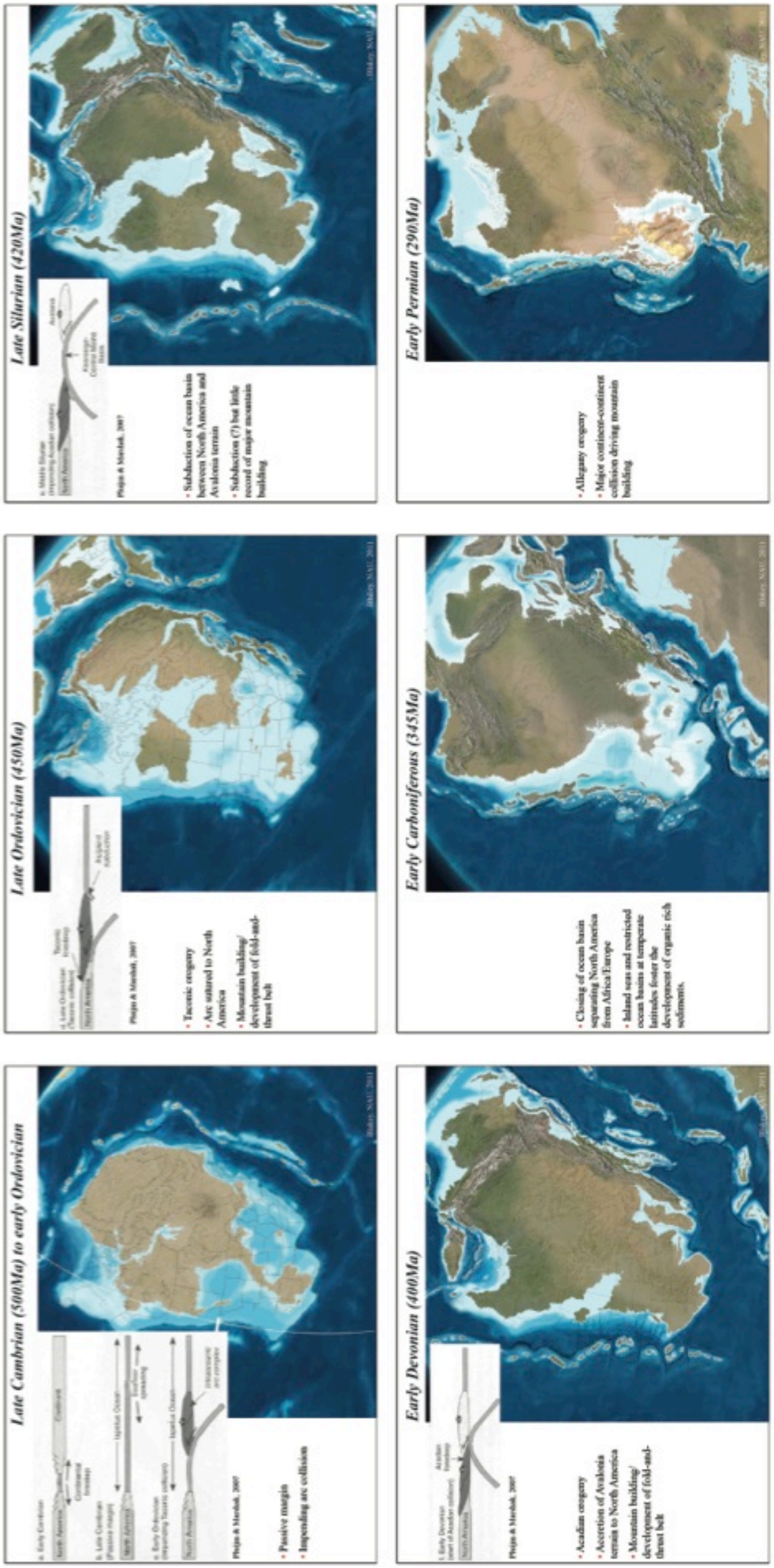



**Fig. 8.** Summary of Taconic and Acadian Orogenies.

*45 min drive to Stop 11.*

**Stop 11. Dinosaur tracks (42.241609°, -72.623584°)**

*Continue east on Rt. 2 and then head south for 45 min. on I-91. Stop at park with pull-out on east side of the road north of Holyoke, MA, walk straight along the path, across the railroad tracks.*

Following the Acadian orogeny, Laurentia began to assemble with the other major continental masses (including the supercontinent Gondwana). By the Late Permian, the supercontinent Pangea had formed during what is known as the Alleghenian orogeny (Figs. 7 and 8). Pangea then began to break up in the Early Triassic (Fig. 9), leading to the opening of the Atlantic Ocean. We will not see any evidence for the Alleghenian orogeny on this trip but will see evidence for the subsequent breakup of Pangea in the form of the rift-related volcanic and sedimentary rocks in the Deerfield basin (Figs. 9-11). These sediments contain some of the finest fossil dinosaur footprints known anywhere in the world.

The dinosaur footprints in the Deerfield basin were formed in the Early Jurassic when dinosaurs walked along a wet, muddy surface. The footprints were buried, lithified, and then re-exhumed by Quaternary erosion. A young boy discovered these tracks in 1802 in South Hadley, MA, marking the first discovery of dinosaur fossils in North America (this was before dinosaurs themselves had even been recognized or named). In 1854, Dr. J.C. Warren of Harvard University used a photograph to illustrate some of the footprints—the first time a photograph appeared in an American scientific publication.

**Stop 11 Exercise:**

11a. Sketch a few of the dinosaur footprints. Include a scale. Make a rough estimate of these dinosaurs' height and weight. State your assumptions.

11b. Follow the path across the railroad tracks down the river. Examine and describe the exposed volcanic rocks. What environment did they form in (i.e. sub-areal or sub-aqueous)? How can you tell?

11c. What was the origin of the sediments in which the dinosaur tracks were made? Explain in terms of the Wilson cycle framework and paleoenvironmental setting.

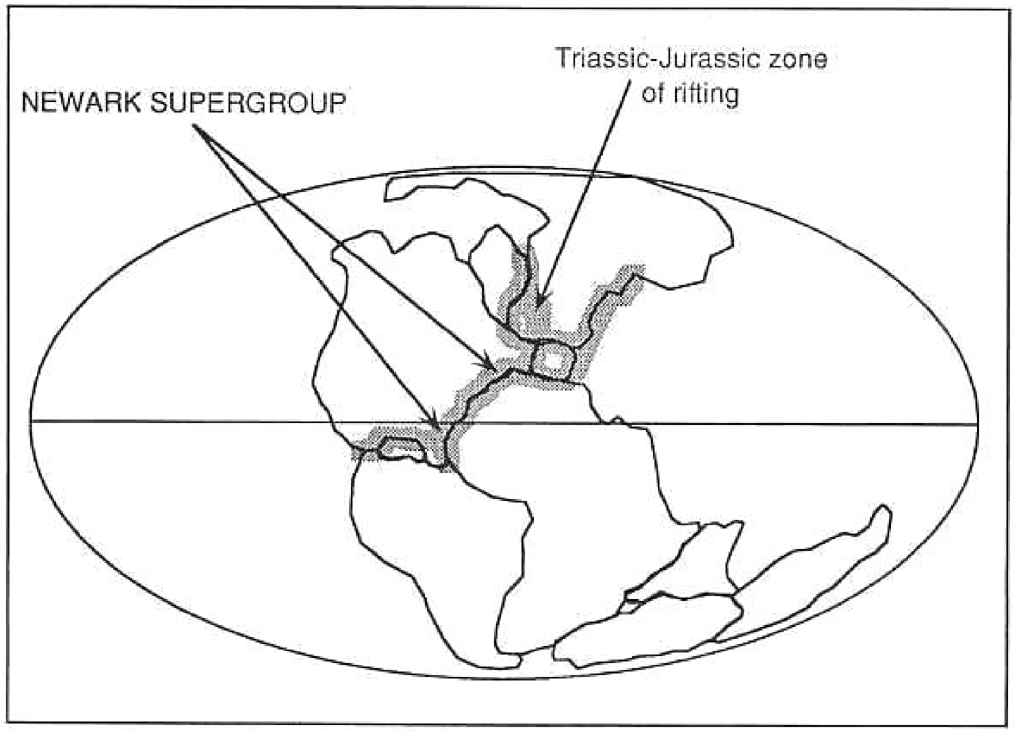



**Fig. 9.** Pangea during the Late Triassic (225 Ma), during the initial phase of rifting.


Source: Olsen, P. E., N. G. McDonald, et al. "Stratigraphy and Paleoecology of the Deerfield Rift Basin (Triassic–Jurassic, Newark Supergroup), Massachusetts." *Guidebook for Field Trips in the Connecticut Valley Region of Massachusetts and Adjacent States* 2 (1992): 488-535.

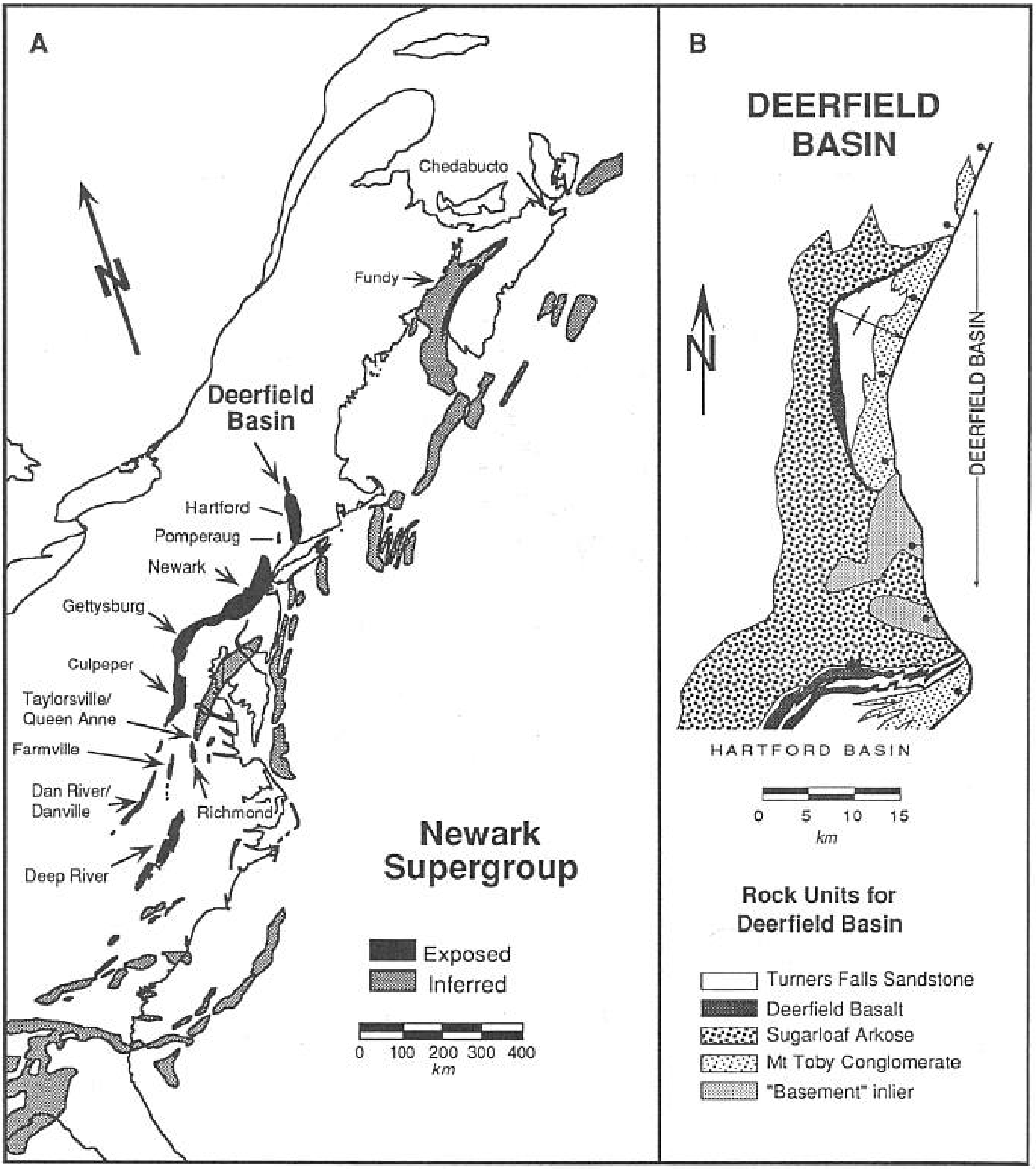



**Fig. 10.** Simplified geologic map of Mesozoic rift-related deposits associated with breakup of Pangea. (a) Overview of eastern margin of U.S. (b) Deerfield basin, showing rift-related volcanism and sedimentation.


Source: Olsen, P. E., N. G. McDonald, et al. "Stratigraphy and Paleoecology of the Deerfield Rift Basin (Triassic–Jurassic, Newark Supergroup), Massachusetts." *Guidebook for Field Trips in the Connecticut Valley Region of Massachusetts and Adjacent States* 2 (1992): 488-535.

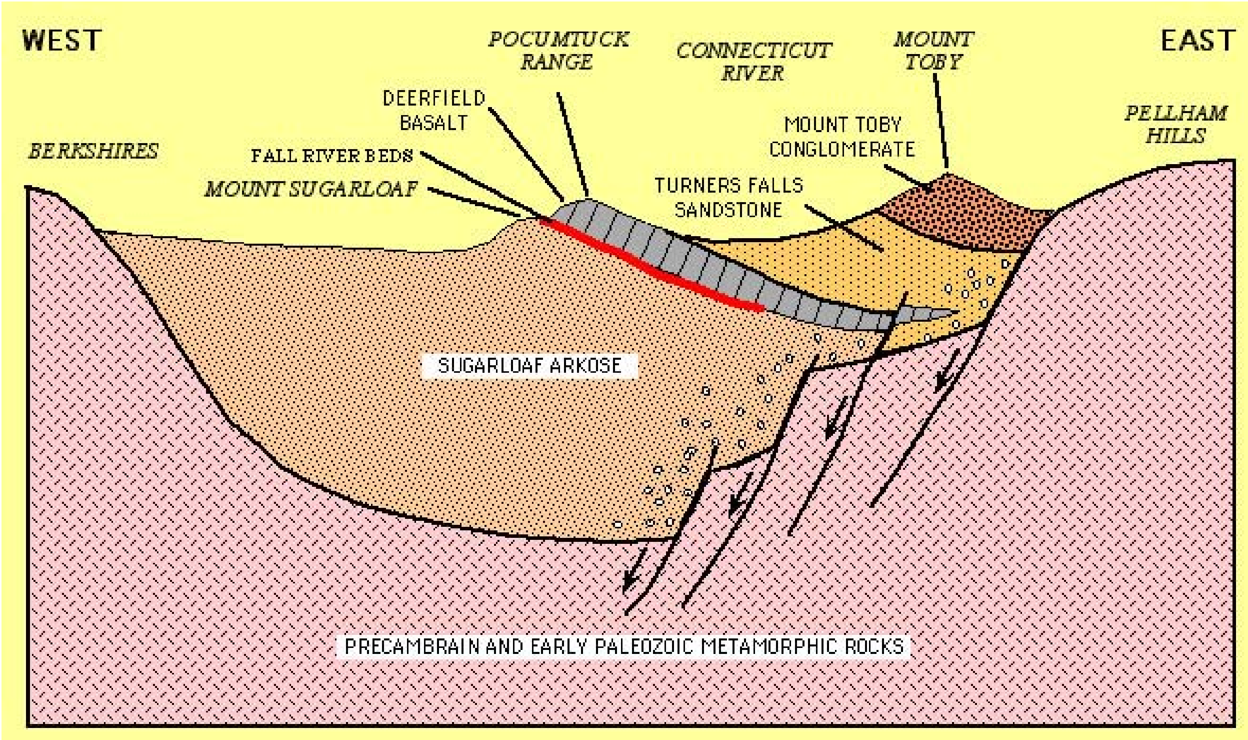



**Fig. 11.** Stratigraphy of the Deerfield Basin (see Fig. 10 for plan view).

*20 min drive to Stop 12.*

**Stop 12: Amherst College Beneski Museum of Natural History (42.371978°, -72.514299°)**

The field trip will conclude with a visit to the Amherst College Beneski Museum of Natural History. Please take time to explore the various exhibits and collections (including the mineral collections in the hallway). You'll need to visit the trackway room in the basement to complete these exercises.

**Stop 12 Exercise:**

12a. Choose an exhibit showing sedimentary features, sketch them, and explain how they formed.

12b. Choose an exhibit showing dinosaur tracks, sketch them, and explain what they reveal about dinosaur locomotion.

*Drive back to MIT campus, about 2 hr.*

**NOTES**

## NOTES

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## Glossary of Terms

Acadian orogeny – a mountain building event caused by the collision of the Avalonian **terrane** (now New England) with **Laurentia**, representing further closure of the **Iapetus Ocean**. Further northeast, Baltica (now Europe) was colliding with Laurentia in the Caledonian orogeny.

Accretion – typically refers to the joining of fragments of crust on the margins of continents

Accretionary wedge – a prism of sediments formed at a subduction zone from the scraping of sediments off the top of the subducting oceanic crust, with a minor contribution of sediment from the continent on the overriding plate.

Active margin – a margin between two plates, forming a linear concentration of earthquakes and typically volcanoes (c.f. **passive margin**).

Alleghenian orogeny – an **orogeny** following the **Acadian orogeny**, in which **Laurentia** + Avalonia collided with **Gondwanaland** (containing what is now Africa). This orogeny is largely responsible for the building of the Appalachian mountains and so is sometimes called the Appalachian orogeny. This marked the complete closure of the **Iapetus Ocean**.

Allochthon - a large block of rock that has been moved, typically by thrust faulting, far from its original position.

Anticline – a fold, generally convex-upward, whose core contains the **stratigraphically** older rocks (c.f. **syncline**).

Anticlinorium – a complex anticlinal structure of regional extent composed of lesser folds.

Arc – a linear region of volcanoes formed at a subduction zone.

Arenite – a sandstone containing less than 15% **matrix**

Arkose – a sandstone containing more than 25% feldspar.

Autochthon – the rocks that underlie a **thrust fault** along which an **allochthon** is pushed.

Basement – a general term for the **igneous** and **metamorphic rocks** that underlie **sedimentary rocks**.

Bedding – the formation of parallel layers of sediment as particles settle to the bottom of a sea, river or land surface.

Black shale – **shale** that is black in color because it contains a significant amount of organic material, typically indicating anoxic conditions during deposition.

Breccia – a coarse-grained rock consisting of larger angular fragments of minerals or other rocks in a fine-grained **matrix**.

Carbonate – strictly speaking, a mineral with a $CO_3$ group in its formula. However, *rocks* that are made almost entirely of carbonates are colloquially also called carbonates. These include limestone (made almost entirely of calcite), dolostone (made almost entirely of dolomite) and marble (metamorphosed carbonate rock).

Carbonate platform – an extensive flat, shallow marine area where both biological and nonbiological carbonates are deposited.

Conglomerate – a sedimentary rock composed of larger rounded fragments (c.f. **breccia**) of minerals or other rocks in a fine-grained **matrix**.

Continental shelf – the underwater continuation of continents, extending up to hundreds of km from the shoreline. It is relatively flat and shallow (typically less than 200 m water depth), and is at its most extensive at **passive margins**.

Continental slope – the steeper slope that separates the comparatively flatter **continental shelf** (shallower) and continental rise (deeper).

Craton – a very stable portion of continental crust, typically very old (>2 billion years).

Cross-bedding – a sedimentary structure defined by thin beds inclined at an angle to larger-scale **bedding** structures, cross-bedding forms when sediment is deposited in the presence of a directional flow of air (e.g. sand dunes) or water (ripples).

Dip – the angle of greatest tilting of a rock layer as defined by its **beds**. The direction of dip is perpendicular to that of its **strike**.

Dolostone – a carbonate rock composed largely of dolomite ($CaMg(CO_3)_2$), typically formed by replacement of Ca in calcite ($CaCO_3$) by Mg from percolating fluids during burial and **lithification**.

Dike – a planar (appears linear on the surface of the Earth) **igneous** intrusion, often associated with large-scale magmatic activity in an area. Dikes are commonly found in swarms when associated with large magma chambers or the **rifting** of continents.

Equant – referring to a mineral's shape – a crystal with all sides of a similar length.

Fault – a fracture or zone of fractures along which there has been displacement

Foliation – a general term for a planar arrangement of textural or structural features in any rock type. Often used to describe planar features caused by mineral alignment during **metamorphism**.

Forearc (basin) – at a subduction zone, the region between the **arc** and the **trench**. The basin is caused by downwarping of the overriding plate due to subduction of the underriding plate.

Foreland basin – a basin formed either in front of or behind a large mountain belt or **arc**, caused by downwarping of the plate due to the large mass of the mountain belt. The lithosphere behaves elastically and so flexes downward, creating space adjacent to the mountain belt that can accommodate an accumulation of sediment.

Forebulge – in a **foreland basin**, the forebulge is the upward flexure of the plate some distance from and in response to the downward flexure caused by the loading of the plate by the mountains.

Foredeep – in a **foreland basin** the foredeep is the region between the **forebulge** and a **thrust** belt that is adjacent to the topographic load (mountains). This thrust belt is caused by the collision of the two plates. The foredeep represents a submerged topographic low between the thrust belt (often above sea level or in shallow water) and the forebulge (shallow water), and as a result receives sediment from both sides, although sediments from the thrust belt and the **orogen** typically dominate.

Gneiss – a foliated rock formed by regional **metamorphism**, in which bands of granular minerals alternate with bands of platy or elongate minerals.

Gondwana – a former **supercontinent** that collided with **Laurentia** to form **Pangaea** approximately 300 Ma.

Grenville orogeny – one of the major **orogenies** that formed the **supercontinent Rodinia** approx. 1.3-1.0 Ga, it affected the southern and eastern margins of **Laurentia**, which now form a belt running from Labrador to Mexico.

Groundmass – finely crystalline or glassy material that surrounds larger crystals (**phenocrysts**) in **igneous rocks**.

Iapetus Ocean – a large ocean that existed from roughly 600 to 400 Ma. Although the continents have shifted somewhat since, the basic positioning of the Iapetus ocean relative to the continents is similar to that of the present-day Atlantic. It separated **Laurentia** (North America) from Baltica (Europe) and **Gondwanaland** (containing what is now Africa). Its nature as precursor to the Atlantic gave rise to its name, the Iapetus Ocean. Iapetus was a titan and the father of Atlas, for whom the Atlantic Ocean was named.

Igneous rock – any rock formed by the cooling and crystallization of magma/lava.

Inlier – an area of older rocks surrounded by younger rocks. Can be caused simply by preferential erosion of young material to reveal an exposure of older material, or by folding/faulting.

Isostasy – the idea that the lithosphere (elastic, rigid upper portion of the Earth, up to 200 km thick) and the asthenosphere (lower-viscosity, ductile-deforming portion of the Earth directly below the lithosphere) tend toward gravitational equilibrium over long time scales. The idea of isostasy is used to understand the stability of topographically high mountain belts (the mass excess is compensated for by a "mass deficiency" – i.e. lower density – in the mantle beneath the mountain belt), as well as the depression of the lithosphere by topographic loads and the resurgence of lithosphere that has had such a load removed (e.g. by erosion or **tectonic denudation**). This applies to ice, too – for example, regions of the Earth that were loaded by ice during the last ice age are still experiencing uplift, in some places at more than 1 cm per year. This is called isostatic readjustment.

Lamination – bedding in which the beds (called laminae) are very thin. They are common in **shales** and are commonly laterally discontinuous or easily disturbed / contorted. Laminations are also found in **stromatolites** and chemical precipitates.

Laurentia – once a separate continent, Laurentia now forms most of North America East of the Rockies.

Lithification – simply the formation of rocks from sediments by compaction and cementation.

Matrix – in **sedimentary rocks**, this refers to silty-muddy material surrounding larger material (sand, pebbles, boulders). In **igneous rocks** this refers to fine-grained material between **phenocrysts**, often also called **groundmass**.

Melange – a heterogeneous mixture of rocks caught up in a collision between a continent and an oceanic plate.

Melt inclusion – these are found in some igneous minerals when the mineral grows around and encapsulates a small amount of melt. When the rock cools, this inclusion will crystallize into minerals or form a glass.

Meta - when used as a prefix in a rock name, this refers to the metamorphosed equivalent of that rock type (e.g. metasediment, metavolcanic, meta-sandstone).

Metamorphic rock – any rock derived from pre-existing rocks by mineralogical, chemical and/or structural changes in the solid state, in response to changes in temperature and pressure.

Moho – a seismic discontinuity that marks the transition between the crust and the underlying mantle.

Normal fault – a fault on which the overriding block moves downward. Formed by tension.

Orogen – a mountain belt. Orogenesis is the formation of mountain belts, typically by the collision of two plates.

Outlier – an area of younger rocks surrounded by older rocks. Typically formed by erosion of surrounding rocks, often around a particularly resistant rock type, until the resistant younger rock is completely surrounded by older rocks.

Pangaea – a **supercontinent** formed ~300 Ma during a series of **orogenies** including the **Alleghenian** orogeny, and **rifted** apart beginning ~ 175 Ma as the Atlantic Ocean began to open.

Passive margin – a margin between continental and oceanic crust that is not marked by a plate margin/boundary and so has very little volcanic or seismic activity (e.g. the Eastern seaboard of the US). C.f. **active margin**.

Phenocryst – a larger crystal in igneous rocks that have a bimodal crystal size distribution. The fine crystals surrounding phenocrysts are called **groundmass**.

Protolith – the original **sedimentary**, **igneous** or even **metamorphic rock** that existed prior to a metamorphic event.

Rifting – refers to any tensional behavior in the Earth's crust that manifests as **normal faulting** and crustal extension. Large-scale rifting is a major feature of continental breakup.

Rodinia – a **supercontinent** that existed between 1100 and 750 Ma. It formed in a series of orogenies including the **Grenville orogeny**.
Schist – a strongly **foliated** crystalline rock caused by **metamorphism**, in which visible crystals are aligned.

Sedimentary basin – a region of considerable extent (thousands of square km) where the combination of deposition and subsidence has formed a thick accumulation of sediment.

Sedimentary rock – any rock made up of fragments of other rocks and/or chemical and/or biochemical precipitates.

Shale – a **sedimentary rock** made of mud (i.e. a mudstone) defined by its very thin bedding. This thin bedding is often called **lamination**.

Slate – a metamorphic rock caused by the minor metamorphism of mudstone. Looks and feels like a hard **shale**.

Stratum – bed or rock unit. Plural = strata.

Stratigraphy – the study of **strata** (rock layers) and their relationships to one another, as well as the correlation of strata on regional and global scales. The word "stratigraphy" is also used to refer to the nature of the rock layering and structure in an area, e.g. "the stratigraphy suggests that this area was once a delta".

Strike – for an inclined bed, the strike is the compass direction of the horizontal line that can be drawn on it. Its direction is perpendicular to that of the **dip**.

Stromatolite – **laminated** sedimentary accumulations formed by the trapping of sediment by algal mats or columns. These are typically colonies of cyanobacteria that trap a sediment layer and then grow over that layer, to progressively grow upward at a very slow rate. They represent some of the oldest life on Earth, with postulated stromatolites found in rocks more than 3 billion years old.

Supercontinent – a large landmass comprising more than one **craton**. Past examples include **Rodinia** and **Pangaea**. Today, Eurasia-Africa may be thought of as a supercontinent.

Suture – after a continental collision, the suture, typically a major **fault** or fault zone, marks the boundary between what used to be two separate landmasses.

Syncline – a fold, generally concave upward, whose core contains the **stratigraphically** younger rocks (c.f. **anticline**).

Taconic orogeny – the earliest of the three **orogenies** we will talk about on this trip. Sediments deposited on the **Laurentian** coast of the **Iapetus ocean** in the Cambrian and early Ordovician (prior to 470 Ma) were ultimately caught up during the collision of Laurentia with the Shelburne Falls **arc** in the middle Ordovician. This collision is called the Taconic orogeny.

Tectonic denudation – gravitational collapse of **orogens** due to the lateral spreading of the topographic load along deep, low-angle / almost-flat **normal faults**.

Tephra – volcanic ash, pumice and blocks formed by airfall or ashflow (but not lava) during volcanic eruptions.

Terrane – a **fault**-bounded block of regional extent, characterized by a geologic history different from that of adjacent terranes.

Thrust fault – a **fault** on which the overriding block moves upward. Formed by compression.

Trench – typically refers to the submarine trench that forms at a subduction zone due to the downward-bending of the subducting oceanic plate.

Ultramafic rocks – refers to **igneous** and occasionally **metamorphic rocks** with $<45\%$ $SiO_2$. Mantle rocks are almost all ultramafic.

Unconformity – a surface between two rock layers that were not laid down in an unbroken sequence. An unconformity represents a hiatus in deposition and a time gap in the rock record.

Wacke – pronounced "wacky", a sandstone containing more than 15% **matrix**.

Weathering – the destructive process or group of processes by which earthy and rocky materials are changed *in situ* in color, texture, composition and form. Distinct from erosion, which is the physical or chemical *removal* of material.

Wilson cycle – a general plate tectonic cycle (also known as the **supercontinent** cycle) that comprises 1) **rifting** during the breakup of a **supercontinent**, 2) **passive margin** cooling and sediment accumulation during seafloor spreading and ocean opening, 3) **active margin** volcanism and **terrane accretion** during subduction and ocean closure, and 4) **orogenesis** during continent-continent collision that forms the next supercontinent.

## Timeline of Events Relevant to the Trip

| Time | Era/Period | Event | | |
|---|---|---|---|---|
| 1.3-1.0 Ga | Mesoproterozoic | Formation of Rodinia, including the collision of Laurentia with other continental landmasses in the Grenville Orogeny. Crustal overthickening and metamorphism (Stop 2). | | |
| 800-530 Ma | Neoproterozoic | Rifting and breakup of Rodinia. Uplift and exhumation of deeply buried Grenvillian rocks. In the late Proterozoic, the Laurentian continental slope accumulates ediments, which form the protolith for the Hoosac Schist (Stop 6). | | |
| 510-470 Ma | Late Cambrian to Early Ordovician | LAURENTIA | SHELBURNE FALLS ARC | AVALONIA |
| | | Eastern margin of Laurentia is below sea level. On the shallow continental shelf, stromatolites form (Stop 1) and the Beekmantown group carbonates are deposited on top of the Grenville metasandstone (Stop 2). | The Shelburne Falls Arc Arc produces lava flows, ashes, sediments composed of eroded volcanic material. As the Iapetus Ocean begins to close, the arc approaches Laurentia. | Having recently broken off from Gondwana, the Avalonian arc drifts off Northward. |
| 470-450 Ma | Middle to Late Ordovician | ------------- THE SHELBURNE FALLS ARC COLLIDES WITH LAURENTIA ------------- (THE TACONIC OROGENY) | | |
| | | The Laurentian continental shelf is submerged in the submarine trench that forms at the Laurentian margin. Trenton Group carbonates form on top of the Beekmantown carbonates (Stop 3a). At the same time, the Utica shale is deposited deeper in the foredeep (Stop 3b). Deep burial and metamorphism of sediments from the Laurentian margin formthe Hoosac Schist (Stop 6). | Volcanic ash accumulates in the foredeep and is intercalated with the Utica shale (Stop 3b). Volcanic ash and sediment from the accretionary wedge is deeply buried and metamorphosed, forming the Rowe Schist (Stop 7). Volcaniclastic material from the volcanic forearc forms the Moretown Schist (Stop 8). The core of the Shelburne Falls arc itself contains pillow basalts (Stop 9) and deep-seated schists (Stop 11) in the Hawley- Collinsville Formation. | Avalonia begins to collide with Baltica along its Eastern margin. The Western Iapetus has now closed due to the collision of Laurentia and the Shelburne Falls Arc. The Eastern Iapetus Ocean continues to close as Avalonia approaches Laurentia and its accreted arc (Shelburne Falls). |
| | | Shelburne Falls Arc | becomes | part of Laurentia |
| 440-410 Ma | Silurian to Early Devonian | Subduction begins behind the Shelburne Falls Arc, forming a new arc on the Shelburne Falls margin of Laurentia, called the Bronson Hill Arc. Magmatism associated with this can be seen in Western Connecticut and Central Massachusetts (Early to Middle Silurian). Downwarping of the Laurentian continent near its margin due to subduction creates accommodation space in which sediments accumulate in the Silurian to Early Devonian (Stops 10 & 12). | | With the development of a new subduction zone on the Laurentian margin of the Iapetus Ocean, Avalonia continues to approach Laurentia as the Iapetus continues to close. |

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12.001 Introduction to Geology
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