The Taconic foredeep in upstate New York

Field trip for Harvard and Bucknell Universities, April 2011
led by Dwight Bradley (USGS, Anchorage) and Bill Kidd (The University at Albany)

Introduction. This two-day field trip will visit outcrops along a 100-km transect through the Ordovician Taconic foredeep in Upstate New York's Mohawk Valley (Figs. 1 and 2, maps). The foredeep formed during the Taconic orogeny, which was the collision between the eastern (present coordinates) passive margin of Laurentia and an extensional magmatic arc above an east-dipping subduction zone (Fig. 3, plate model). The Mohawk Valley is a classic area for several reasons:

- This is the best transect through the Taconic foredeep, a basin that can be traced some 3300 km from Alabma to Newfoundland. Everywhere to the south, the foredeep was messed up by later Paleozoic deformation (that is, Alleghanian and/or Acadian thrust faulting and associated folding). This is not a problem to the north because Taconic deformation advanced as far or farther onto the craton than did younger deformations. The problem to the north is that parts or all of the foredeep are underwater or buried by Quaternary sediments.

- The Mohawk Valley lies on the south flank of the Adirondack Mountains, a Neogene dome, exhuming the foredeep in an outcrop band between Mesoproterozoic basement on the north and Silurian-Devonian cover on the south. Because of the regional southward plunge, the map view is like a cross section.

- Ordovician carbonates and shales in the Taconic foredeep are rich in age-diagnostic fossils—especially graptolites. This is the best possible age and paleolatitude for a foredeep.

- Prevailing winds blew volcanic ash from the approaching magmatic arc into the foredeep. Thirteen of these ashes serve as time markers that make it possible to establish aspects of the paleogeography at particular instances.

Cambrian-Ordovician Appalachian margin of Laurentia. The Cambrian-Ordovician margin of eastern Laurentia formed at about 540 Ma and was deformed during the Taconic collision starting about 465 Ma (age controls summarized by Bradley, 2008). At the latitude of the Mohawk Valley, the rift and drift stages of passive margin evolution are not as well expressed as along other sectors of the margin, so many key parts of the story are borrowed from the north and south.

- **Basement:** Granulite-facies metamorphic rocks and plutonic rocks of the 1.3 to 1.0-Ga Grenville Province (e.g., in the Adirondacks).

- **Rift-related rocks**: To the north and south, Neoproterozoic rift-related sedimentary and igneous rocks are recognized at many places, and are attributed to rifting on the basis of sedimentary facies, age, igneous components, and chemistry (Rankin et al., 1989;

Williams et al., 1995). In Newfoundland, rift-related igneous rocks are as young as 550.5+3/-2 Ma (Cawood et al., 2001).

- **Passive-margin platform**: The succeeding Cambrian to Ordovician platformal sequence is one of the world's classic miogeoclinal prisms. The platformal strata thicken to the east, deepen to the east, and blanket slightly older rift-related rocks—all pointing toward a passive-margin setting. Where best preserved and exposed (in Newfoundland), the lower part of the sequence consists of sandstone, siltstone, shale, and limestone, and the upper part is limestone and dolomite. Being gradual, the transition from extension-driven to thermally driven subsidence is hard to pinpoint, but clearly it had taken place by late Early Cambrian (ca. 520 Ma). In light of the bracketing ages of 550 and 520 Ma, the rift-drift transition is picked at ca. 540 Ma.

- **Slope and rise deposits of the Taconic Allochthon:** Paired with the shallow-water platform was an area of coeval, deep-water (slope-rise) deposition. Paleogeographically, the deep-water rocks are important because they establish that the platform faced deep water for many tens of millions of years. The deep-water rocks occur in thrust sheets that were transported cratonward up and over age-equivalent platformal strata. This regional-scale pattern is commonly seen in ancient arc-passive margin collisions.

Demise of the passive margin during the Taconic orogeny. The collisional demise of the passive margin during the Taconic (or "Taconian") orogeny, is recorded stratigraphically in the slope-rise and platform successions. In the deep-water belt, impending collision was signaled by an influx of outboard-derived siliciclastic turbidites (Rowley and Kidd, 1981). 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) deposition of easterly-derived turbidites, which were shed from a submarine thrust belt that advanced from the east (interpreted as the foredeep axis)
(5) deformation, when the foredeep was overridden by thrusts.

Figure 4 shows the diachronous nature of facies belts and the corresponding numbered events within the Taconic foreland in the Mohawk Valley. Figure 5 shows stratigraphic revisions by Mitchell et al. (1994) in light of new correlations between ash beds.

The thrust allochthons that overrode the passive margin carried rift-, passive margin-, and foreland basin deposits, all of them native to the Laurentian margin. In Canada, the highest thrusts carry ophiolites, which unequivocally record the former existence of an ocean basin (Iapetus) to the east of the Laurentian margin. The ophiolites have yielded U-Pb zircon ages from 508±5 to 484±5 Ma (see Williams et al., 1995 for original sources). Thus the ophiolites are substantially younger than the oldest seafloor (ca. 540 Ma) inferred to have lain immediately offshore as the oceanic part of the Laurentian plate. A more plausible interpretation is that the ophiolites formed by seafloor spreading in a supra-subduction setting (e.g., Jenner et al., 1991). Amphibolites from the metamorphic sole of the Bay of Islands ophiolite in Newfoundland yielded a $^{40}Ar/^{39}Ar$ amphibole ages of 469±5 and 464±9 Ma (see Williams et al., 1995 for original sources); the metamorphic sole is interpreted as a relict of the paleo-subduction zone during or just before emplacement of the ophiolite onto the passive margin. 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; Zagorevski et al., 2006).

The Taconic collision was accompanied by regional metamorphism of both basement and sedimentary cover of the Laurentian margin. In the northeastern United States, Taconic regional metamorphism reached kyanite grade and took place at 465±10 Ma ($^{40}Ar/^{39}Ar$ amphibole; Laird, in Drake et al., 1989). This age is similar to the end date of the passive margin inferred from stratigraphic evidence. Along the Taconic suture, blueschist and eclogites have been discovered (Laird, in Drake et al., 1989), but only in a few small enclaves that would likely have been overlooked in a less thoroughly mapped region. These high-pressure rocks confirm the presence of a subduction zone during the Taconic collision.

Foreland effects of lithospheric flexure

The concept of flexural extension of the continental plate during arc-passive margin collision was developed in two foredeeps: the Arkoma foreland basin of the Ouachita orogen and the Taconic foredeep of New York (Bradley and Kidd, 1991). The Mohawk Valley is one the best and most accessible places to see this phenomenon. The normal faults strike parallel to the orogenic belt and have mostly down-to-east displacements that in places exceed 500 m. Multiple lines of evidence reveal that faulting took place during the same time as the Taconic collision. The simplest of these is the regional map pattern (Fig. 2), which shows that Middle Ordovician formations including the Schenectady, Utica, and Trenton are cut by faults, whereas the youngest Ordovician, Silurian, and Devonian strata bury the faults and are not offset. In addition, local conglomerate beds in the Trenton Group are found next to certain faults (e.g., Noses), and faults that define the Dolgeville graben show evidence of synsedimentary displacement.

Together, the normal faults that cut the Taconic foredeep define a domain of upper-crustal extension more than 100 km wide, parallel to the orogen, and just in front of it. The faults can be visualized as the steps of a stalled downgoing escalator (Fig. 6). The most distal faults are the youngest and have smaller down-to-east displacements, whereas those closer to the orogen are older, had more time to move, and built up larger displacements. The mechanism of upper-crustal extension in collisional foredeeps was explored by Bradley and Kidd (1991). At that time, we argued that what is seen in the Mohawk Valley is *flexural extension*, i.e. the product of plate bending. In this model, while the uppermost crust was extending, the rest of the crust and mantle lithosphere—everything below some neutral surface—was shortened. An alternative model (Schoonmaker et al., 2004) is that foredeep extension is the product of slab pull, acting on the whole plate.

Extensions of Walther's Law to infer the rate of Taconic plate convergence

Taconic foredeep geology is amenable to the application, or extension, of Walther's Law. In its restricted sense, Walther's Law states that the vertical succession of a conformable sequence of facies reflects lateral changes in environment. But this is really a broader concept: geologic extrapolation from two dimensions to a third one, or from three dimensions to a fourth.

- Facies belts in the Taconic foredeep existed because of the collision and they migrated in concert with the advancing orogen. At a given time, the main paleogeographic belts, each with its distinctive geologic regime, were the orogen, the foredeep axis, the normal faulted outer foredeep slope, the forebulge's eastern shelf, and the forebulge. At a given place, a stratigraphic succession records these same events: unconformity above the Beekmantown; upward deepening carbonate deposition (Black River & Trenton); subsidence to below storm base, with normal faulting (Utica); arrival of orogenically derived turbidites (Schenectady); and deformation.
- The same logic can be used near the orogenic front in the Taconic mélange to deduce the sequence of deformations. A west-to-east transect from undeformed into deformed turbidites broadly matches the deformation sequence.
- The rate at which facies belts migrated toward the craton is the rate of plate convergence, or close to it, at the end of collision (Bradley and Kusky, 1986; Bradley, 1989). In the 1980s, available data suggested that the convergence rate in the Mohawk Valley was around 2 cm/year. This number could be much improved with high-precision U-Pb TIMS ages of the 13 ash beds that serve as regional time markers.

Equivalence of features between oceanic subduction zones and arc-passive margin collision zones

Oceanic subduction zone	**Arc-passive margin collisional orogen**
Forebulge, at abyssal depths	Forebulge, near sea level
Outer trench slope, cut by normal faults	Outer foredeep slope, cut by normal faults
Trench axis, smoothed by turbidites fed mostly by ax currents (6-11 km depths)	Foredeep axis, smoothed by turbidites fed mostly by a currents (1-3 km depths)
Submarine accretionary wedge	Submarine thrust belt

Field trip stops

Mileages, where given, are rough estimates from Google Earth.

Stop 1. Moss Island, Little Falls (43.0385°, -74.8461°)

Meet at 11 AM on Saturday, Apr 15 at the parking lot just S of the bridge on NY 169, which is just E of the city of Little Falls and NW of Thruway exit 29A. Moss Island is between the Mohawk River and Erie Canal. Cross the canal on Lock 17.

These exposures are famous for the fantastic potholes that formed when, as the Niagara River is today, the Mohawk River was the outlet of the entire Great Lakes system. The bedrock is deformed syenite, Grenville age (ca. 1 Ga). It is exposed here in a horst between two Ordovician normal faults. The contact with overlying Cambrian passive-margin dolostones is not exposed here but should not be far above the tops of the cliffs.

Stop 2. Inghams Mills (43.0616°,-74.7638°). Black River and Trenton Groups

Drive NW on NY 169 about 0.5 miles to NY 5, then E on NY 5 about 0.5 miles, then fork left on NY 167. Follow this about 2.5 miles to Dockey Rd. (County Rd. 127). In about 1.8 miles, just before crossing East Canada Creek, watch for a left turn that leads to outcrops in the Inghams Mills spillway, just downstream from a dam that impounds Kyser Lake. If the gate is locked and access impossible, we'll proceed to Stop 3. For future reference, the phone number of Brookfield Renewable Power, the hydro plant operator, is 315-413-2700.

The outcrops below the dam expose a deepening upward sequence of carbonates that were deposited on the cratonic flank of the Taconic foreland basin. Two regionally extensive rock units are exposed here: the Black River and Trenton Groups, both Ordovician in age. The Black River consists of a shallow marine dolostones with mudcracks and fenestral fabric, indicating episodic dessication and thus, deposition very close to sea level. The base of the Black River, not exposed here, is an erosion surface on the Beekmantown Group; this is in the right time and position to be a forebulge unconformity to be seen at Canajoharie. The Black River is overlain by the Trenton Group. Note megaripples and limestone conglomerate that contains clasts of Grenville basement. Basement rocks evidently were exposed fairly nearby, possibly along a normal fault scarp or in a broad forebulge arch.

The Black River beds are cut by minor normal faults of probably Ordovician age that roughly parallel map-scale normal faults in the foredeep.

Stop 3. Dolgeville (43.10210°, -74.76840°): Dolgeville facies, transitional from Trenton to Utica

We'll skip this classic stop because of high water. The outcrops are now gated off but access can be arranged by calling Frank Ceneviva, plant operator at the Dolgeville power station, at 315-

429-8538. He's happy to grant access to geologists. To get to Dolgeville from Inghams Mills, return to NY 167 and drive N about 4 miles.

Outcrops below the dam, which are accessed from the west bank of East Canada Creek, are assigned to the Dolgeville Facies of the Trenton Group. These are deep-water carbonates interbedded with black shales. Several tephras are present. The strata exposed here are younger than the youngest beds at Inghams Mills and record continued deepening.

A north-striking normal fault, one of two that define the Dolgeville graben, has been mapped just east of the gorge. The beds in the gorge have been deflected to steep dips near the fault. Detailed measured sections closer to and farther from the inferred fault show systematic thickness differences, indicating that faulting was synsedimentary.

Stop 4. Paradise Road overpass (43.0104°, -74.8638°). Dolgeville passing up into Utica.

Follow NY 167 SW all the way into Little Falls and cross the river. From the bridge, drive about 1.8 miles SW to NY 5S, go E about 0.4 miles, then S on Paradise Road about 0.8 miles to just before where it crosses the NY Thruway on an overpass. This is the west end of a long roadcut along the Thruway. The way to see these rocks is from the Thruway, and with enough time and effort, it now seems to be possible to arrange a work permit to access these roadcuts. Contact info: Guy Hulbert, 315-438-2414.

This stop is a last minute substitute for Stop 3 at Dolgeville.

Deep-water carbonates assigned to the Dolgeville Formation are overlain by Utica Shale. West-directed slump folds record synsedimentary tilting related to normal faulting.

Stop 5. Canajoharie Creek (42.89769°, -74.57070°): forebulge unconformity

Return to NY 5S and drive E about 2.8 miles to the NY Thruway interchange. Get on the Thruway, drive E, and exit at to Canajoharie. On leaving the toll booths you come to NY 5S. Go right (W) about 0.25 miles. Turn L just before crossing Canajoharie Creek on Moyer St., go about 0.4 miles to a right fork at Floral Ave., and proceed about 0.2 miles to its end.

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.

A comparable unconformity is seen in the analogous position all the way from Alabama to Newfoundland. It is diachronous: at any given transect, it is younger toward the craton; along strike, it varies with age, presumably a result of different collision ages at promontories and embayments in the passive margin. In Newfoundland, paleokarst features along this unconformity reach to depths of 120 meters (Knight et al., 1991); this gives some indication of the altitude of the inferred forebulge.

Above the unconformity, the Trenton Group records renewed subsidence. The Trenton and overlying Utica Shale (seen just upstream at Stop 6) form an upward-deepening succession that was deposited on the outer slope of the foredeep.

Stop 6. Canajoharie Gorge (42.89395°, -74.56590°): Utica Shale and tephras

Go back to Moyer St., turn R, go 0.4 miles to Maple Ave, turn R, then go 0.3 miles to a right turn into Wintergreen Park. Walk down into the gorge.

Upsection from Stop 5, Canajoharie Creek flows through a deep gorge in Utica Shale. The shale spans the same age range as Trenton Group carbonates farther west. Graptolites can be readily 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 can be dug out with a knife blade. Zircon, apatite, biotite, and quartz (containing melt inclusions) are among the useful minerals that can be recovered from these tuffs using a blender and gold pan. 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).

Day 2.

Stop 7. Plotter Kill (42.82707°, -74.05228°). Schenectady Fm. turbidites

Plotter Kill is a deep gorge on the north side of NY 159 about 6 miles W of Schenectady. Access is via a maintained trail from a parking lot with signs.

A hiking trail leads down into Plotter Kill gorge and excellent exposures of turbidites of the Schenectady Formation. The Schenectady was deposited along the axis of the Taconic foredeep.

Stop 8. Mohawk River outcrops below Cohoes Falls in Waterford (42.78467°,-73.70300)

Get on I-90 and drive E to I-787. Drive N on it until it ends and joins to NY 32. Cross the Mohawk River and then make three turns in rapid succession: L on Clinton, R on Grand, L on Grace. In another 0.35 turn L on Columbus Ave and park near its end. Walk south from end of street into open ground; angle 45 degrees right and cross main path along cliff top; find path down cliff close to where bushes start [distance to the top of this path from end of pavement on Columbia Street is less than 100m].

This is the best place to see the Taconic mélange and is a Stop 4 of a NYSGA field trip by Kidd et al. (1995), from which the following is paraphrased. The melange occupies a belt along the leading edge of the far-traveled Taconic allochthon, and locally, beneath it. It is characterized by a blocks-in-matrix texture and phacoidal cleavage. In some zones, the mélange appears to be made entirely of Ordovician turbidites, with competent blocks of greywacke in a phacoidally cleaved shaly matrix. The protolith is thought to be something like that seen in the Schenectady

Formation at Stop 5. In other zones, exotic blocks traceable to various units in the Taconic allochthon are present. Several deformation mechanisms were involved in melange formation: (1) bedding disruption (e.g., by boudinage) due to ductility contrasts during tectonic deformation; (2) in-sequence and out-of-sequence thrust juxtaposition of varied rock units; and (3) deformation of olistostromes that accumulated at the toe of the advancing Taconic thrust belt. Most of the deformation has a "hard-rock" as opposed to "soft-rock" origin, as evidenced by polished, phacoidal cleavage surfaces.

Stop 9. Thacher Park and Indian Ladder Trail (42.6549°, -74.0176°)

Reverse directions to I-787 southbound. At I-90 go west and at NY 85 go south about 12 miles (Google Earth estimate) to NY 157. Turn right and drive NW about 3.5 miles to Thacher Park (watch speed limit). Park at overlook; I think this is the 4th parking lot on the right. The Indian Ladder Trail descends the cliff at this point and comes back up farther east. It is still closed for the season but we have permission to do the western half.

The main purpose of this visit to a classic Devonian section is to see evidence for what happened in the aftermath of the Taconic orogeny.

Two successions are exposed in the Helderberg escarpment at Thacher Park: the latest Silurian to earliest Devonian Helderberg Group of shallow-marine carbonates, and below that, the Schenectady Formation of Ordovician turbidites. We will hike down the Indian Ladder Trail through three parts of the Helderberg Group (Coeymans Formation at the top, Manlius Formation below that, and Rondout Formation at the very base). The three Helderberg units exposed here comprise a transgressive sequence. The Helderberg was deposited in the distal foreland of the Acadian orogeny, which involved collision between the Taconic-modified margin of Laurentia and the Avalon terrane, of peri-Gondwanan origin. When the Helderberg Group was being deposited, the Acadian deformation front was located in the Central Maine Basin, several hundred kilometers across strike (Bradley et al., 2000). It is synorogenic, though you'd never know to look at the rocks themselves.

About 20 km to the west in Cherry Valley, a zircon age from an ash from within the Helderberg Group sets the base of the Devonian at about 418 Ma.

The Indian Ladder Trail follows a bench at the base of the cliff, where the recessive, flat-lying Rondout Formation overlies the Schenectady along an angular unconformity. Dips in the Schenectady reach several tens of degrees. Two key observations can be made here: (1) evidence for post-Schenectady, pre-Rondout deformation, i.e. the Taconic orogeny; and (2) evidence that the folded part of the Taconic foredeep was beveled by erosion between ca. 450 and ca. 420 Ma when the Helderberg Group was deposited near sea level. West of the Taconic deformation front, the undeformed part of the Taconic foredeep must also have rebounded to sea level during this same interval—presumably because the Taconic orogenic load was reduced by erosion (and conceivably also by extension).

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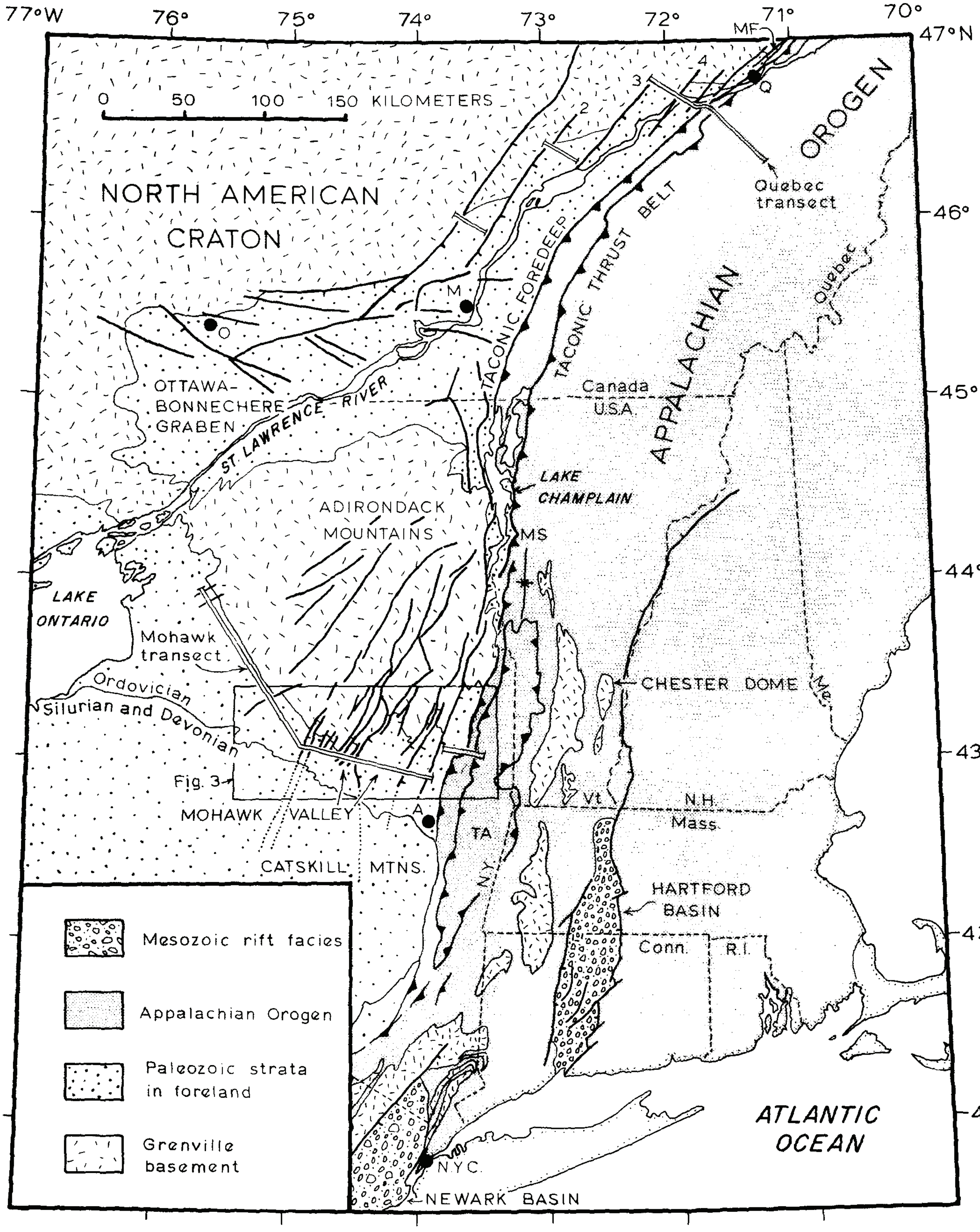
Fig. 1. Generalized geologic map from Bradley & Kidd (1991).



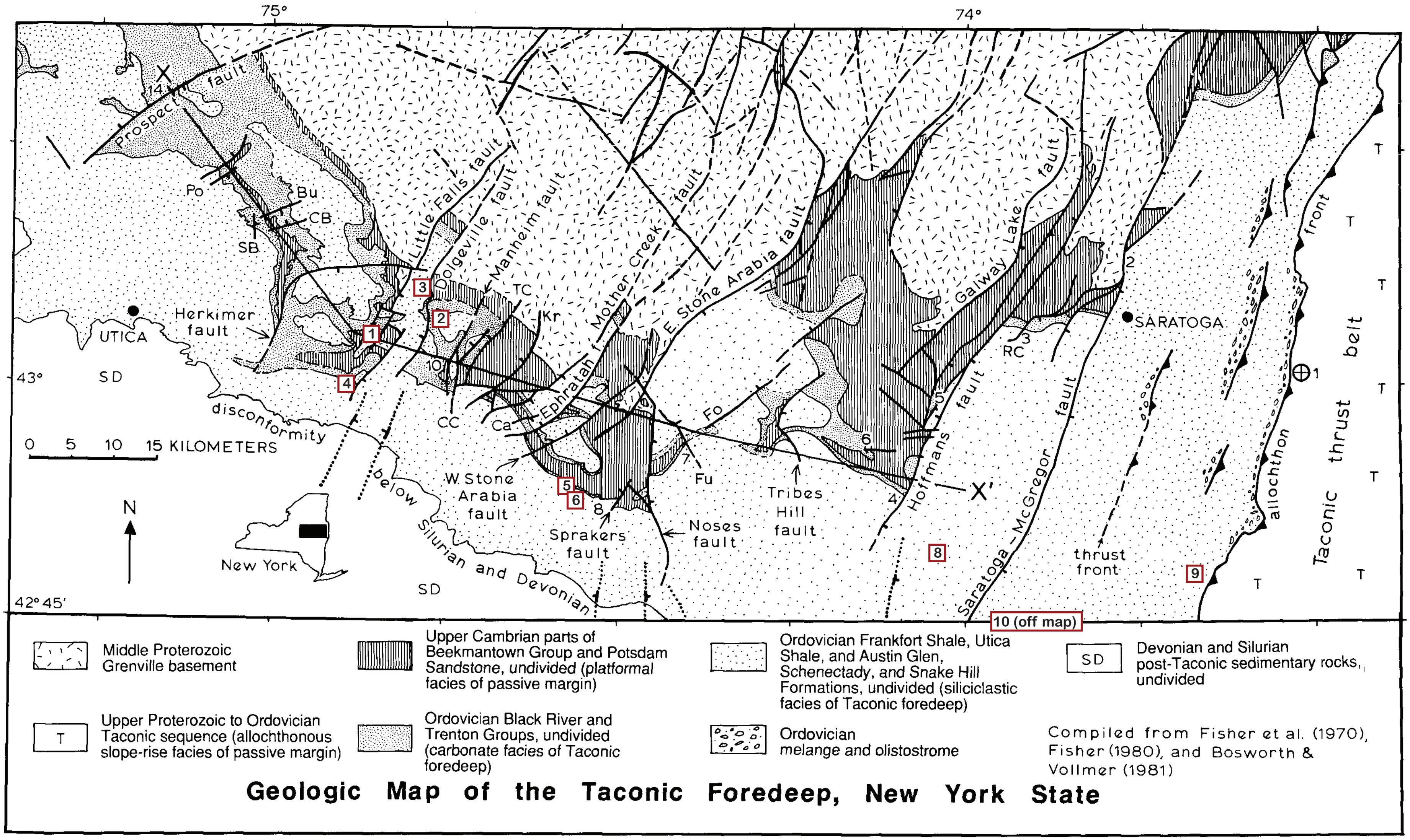
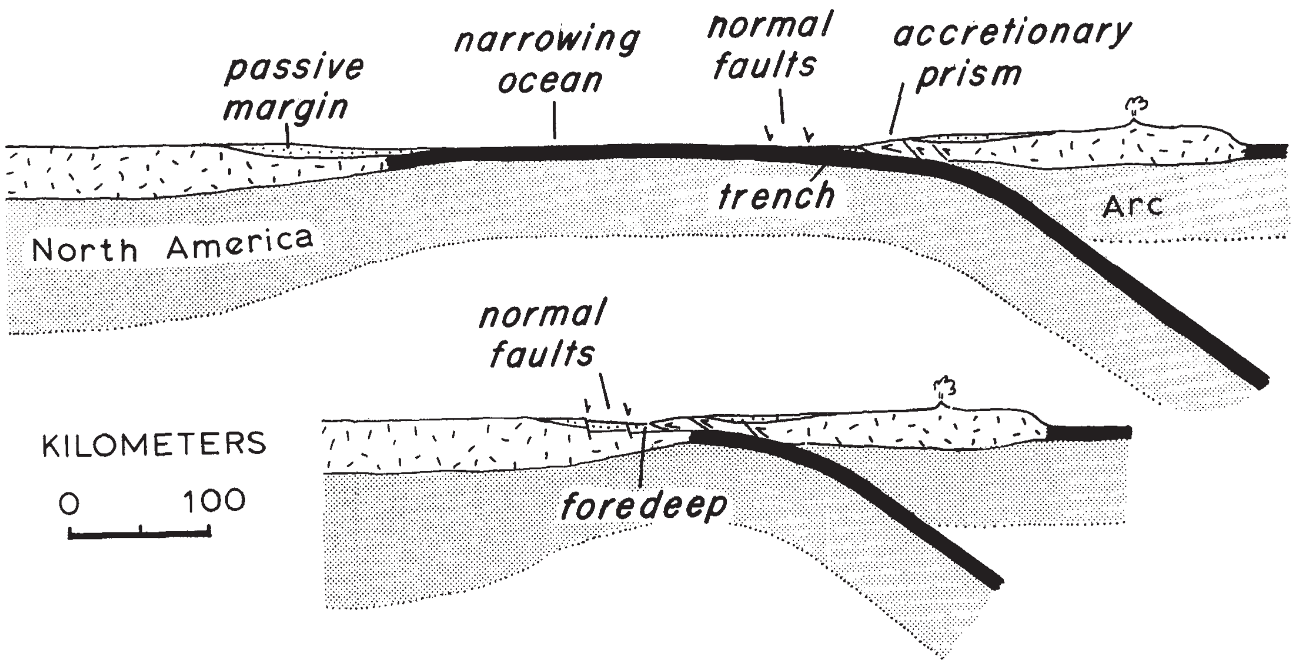


Figure 3. Generalized geologic map of the Taconic foredeep, eastern New York State. Ordovician normal faults are located west of, and strike subparallel with, Ordovician thrusts, which crop out in the eastern part of the map area. Simplified from Fisher and others (1970), with modifications from Fisher (1980) in the area between and including the Manheim and Hoffmans faults; and from Bosworth and Vollmer (1981) for the position of frontal thrusts. The Mohawk Valley approximately follows the line of section X–X′. Abbreviations for minor faults: Po, Poland; SB, Shedd Brook; Bu, Buttermilk Creek; Ca, Caroga Creek; CB, City Brook; CC, Crum Creek; Kr, Kringsbrush; Fu, Fultonville; Fo, Fonda; RC, Rock City Falls.

Figure 2—Mohawk Valley map.

Figure 3. Plate model (from Bradley & Kidd, 1991)



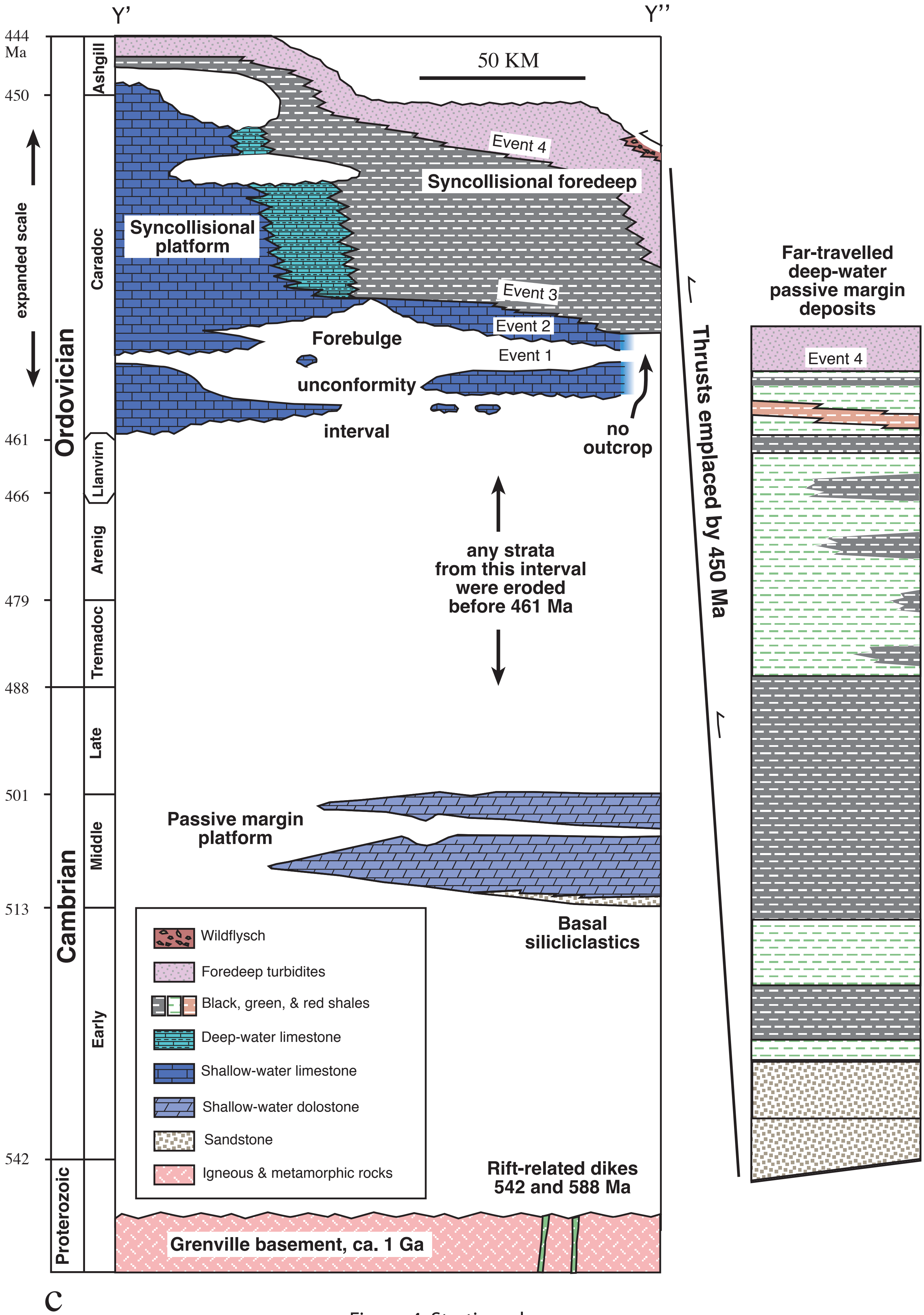


Figure 4, Stratigraphy

Fig. 5. Stratigraphy based on new tephra correlations (Mitchell et al., 1994)

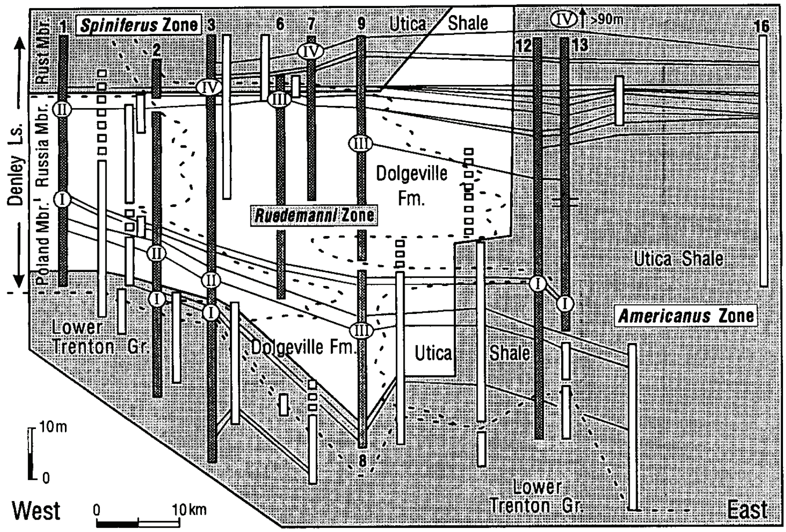


Figure 2. Northwest to southeast lithostratigraphic cross section redrawn from Cisne et al. (1982) showing distribution of facies (dashed lines) and physically traced K-bentonites (thin lines) among sections (vertical bars) in Mohawk Valley. Sections discussed in text are shaded and numbered as in Figure 1. Diagram modified to show distribution of graptolite biozones (white and light shading) and several geochemically correlated K-bentonites (labeled I–IV). Graptolite zonation based on Riva (1969, 1974) and Goldman et al. (1994).

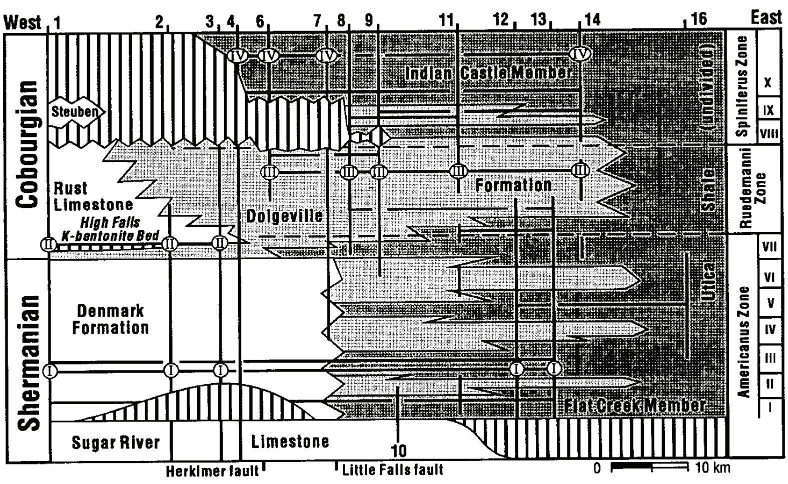


Figure 3. Chronostratigraphic cross section illustrating lithofacies (Trenton Group limestones—white; Dolgeville Formation and similar facies—light shading; Utica Shale—darker shading), biozones (dashed lines), and geochemically correlated K-bentonites (thick horizontal lines). Sections studied (thick vertical lines) numbered as in Figure 1. Vertical ruling represents hiatus. Note contrast in distribution of biozones and K-bentonites labeled I–IV with that shown in Figure 2. Hiatus beneath Denmark Formation at Rathbun Brook and Wolf Hollow Creek is one of several possible interpretations (see text). Correlation of uppermost Rust Limestone is speculative, and assumes that sediment slides in that unit at Trenton Falls are synchronous with those in uppermost Dolgeville Formation to east. Numbered boxes on right correspond to graptolite epiboles discussed in text.

Fig. 6. Block diagram showing regional paleogeography and structure, from Bradley & Kidd (1991).