GeoPRISMS – EarthScope Eastern North America Workshop (ENAM) Workshop
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Student Field Trip Guidebook

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Introduction

The tectonic and surficial processes that give birth to the world's great orogens are written in the rocks of the mountains and their forelands. In learning how to read the rock record, geologists provide the Earth surface boundary conditions that inform geophysical and geodynamic models at the plate tectonic scale. The goal of this field trip is to visit a small part of the foreland of the Appalachian mountains to observe the detritus produced by orogenic processes and learn how to correctly deduce the tectonic, depositional environment, and paleoclimatic setting. The trip is designed to reinforce in the early-career geoscientist the key observational skills and outcrop-scale features that are necessary to correctly read the rock record. The trip incorporates an introduction to using portable electronic media such as I-Pads in locating and describing outcrops.

List of stops and stop goals

STOP 1. Iacocca Hall observation tower, Lehigh University. Overview of greater Lehigh valley geology and major topographic/physiographic features.

STOP 2. Eastern Industries, Omrod Quarry, Whitehall,PA. Lower Paleozoic carbonates, the transition from a passive margin to an active margin. Beginning of the Taconic orogeny.

STOP 3. Penn Big Bed quarry, Slatedale, PA. Taconic orogeny Martinsburg Formation flysch here metamorphosed to slate. Appalachian cleavage and folds.

STOP 4. Lehigh Gap, Appalachian Trail trailhead. Taconic unconformity, contact between the Martinsburg and Shawangunk formations. First major pulse of Appalachian orogenesis with the collision of an island arc.

STOP 5. Palmerton, PA. Taconic orogeny molasse. Bloomsburg and upper Shawangunk formations.

STOP 6. Stony Ridge, Palmerton, PA. Middle Devonian marine deposits, transformation of the foreland basin for late Paleozoic collision.

Appalachian Geology in the context of the Eastern North American Passive Margin

Eastern North America encompasses the Appalachian Mountains and the archetype Atlantic passive margin and as a result is a source of formative thinking related to continental assembly, orogenic evolution, continental rifting, (reviewed in Sheridan and Grow, 1988; Faill, 1997a,b) and post-rift geodynamic evolution. Key paradigms such as the Wilson cycle (Wilson, 1966; Oliver et al., 1983) and Cenozoic eustasy (Haq et al., 1987; Miller et al., 2008) are based on data and research on this margin. Heterogeneity of the Atlantic passive margin lithosphere is both the result and consequence of the diverse tectonic events that it has experienced over the past billion years (Figures I-1, I-2). These events include various arrangements of subduction polarity during Grenville and Appalachian compressive orogenesis (Faill, 1997a,b), continental margin segmentation, rifting and breakup, leading to the opening of the Atlantic Ocean (Withjack et al., 2011, Schlische et al., 2002), massive igneous activity associated with the Central Atlantic Magmatic Province (CAMP), the post-rift evolution (Hutchinson, 2005), and unsteady Cenozoic epeirogeny (Pazzaglia and Brandon, 1996). The passive margin geodynamic evolution is superposed on a body of lithosphere that marks the transition from fully continental Precambrian Grenville basement in the west, to fully oceanic Jurassic Atlantic sea floor in the east.
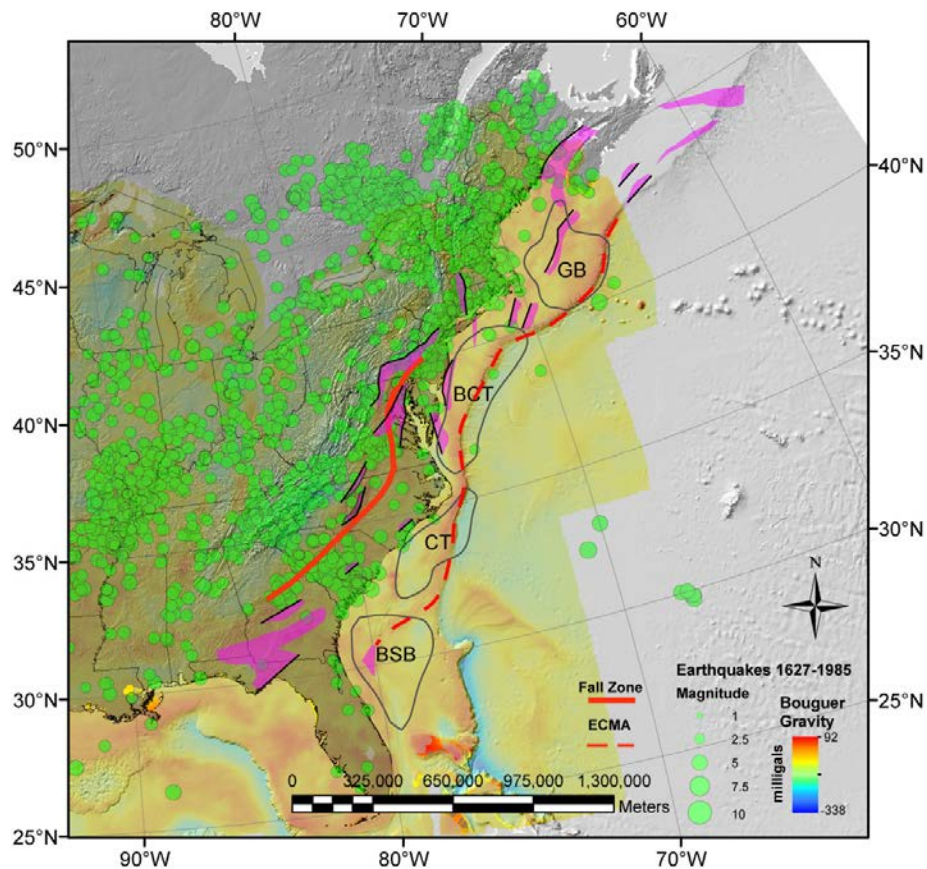
Figure I-1. *Map of ENAM showing the Bouguer gravity anomaly draped on Appalachian topography and Atlantic Ocean bathymetry. Green circles are earthquake locations. Purple polygons are syn-rift basins with border faults in black. Black-outlined polygons are approximate boundaries of shelf-slope basins; GB = Georges Bank basin, BCT = Baltimore Canyon trough, CT = Carolina Trough, BSB = Blake Spur Basin. Topographic, bathymetric, and geophysical data are all from online USGS GIS data repositories.*
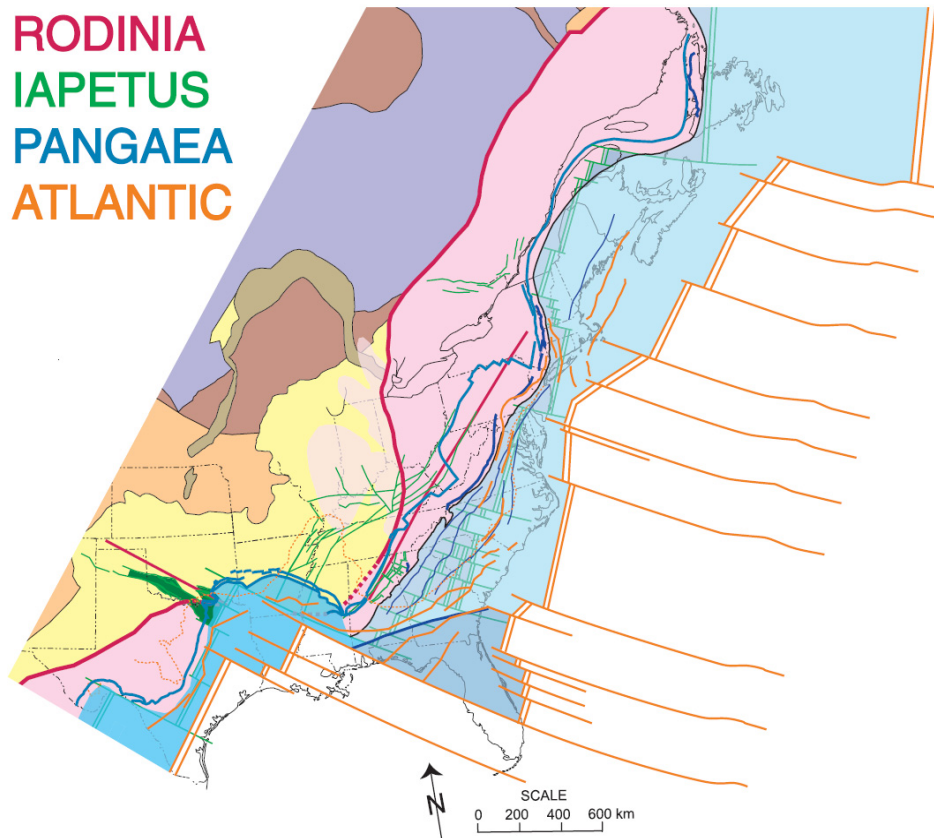
Figure I-2. *ENAM rift margins from the late Proterozoic to the present. (Thomas, 1996).*

Much of the ENAM lithosphere was formed during the late Proterozoic Grenville orogeny during assembly of the Rodinia supercontinent and crust of this age constitutes the basement of the modern passive margin. A latest Proterozoic-early Cambrian passive margin formed by rifting of Rodinia and the opening of the Iapetus Ocean. Large segments of Grenville crust attenuated and separated from North America during this rifting would later be involved in Appalachian orogenesis. Opening of Iapetus also resulted in two continental rifts, the Catoctin rift and Rome trough that ultimately subsided and were covered by a thick wedge of passive margin siliciclastics and carbonates. Low-magnitude, but persistent seismicity remains concentrated in these rifts.

The Appalachians were constructed on top of this Rodinian rift system and passive margin following a protracted period of collisional tectonics during the Paleozoic and closing of the Iapetus Ocean, culminating in the Permian with the Alleghenian orogeny. The traditional interpretation holds that the three great clastic wedges preserved in the Appalachian foreland are related to three pulsed of orogensis during the Paleozoic (Figures I-3, I-4). A passive margin existed across eastern North America at the opening of the Cambrian Period. This passive margin collected a thick sequence of siliciclastic and carbonate deposits including the Cambrian shallow marine facies of the Sauk transgression, represented in Pennsylvania as the Hardyston, Liethsville, and Allentown formations. Late Cambrian to middle Ordovician time saw only carbonate deposition on a shallow marine shelf while east-vergent subduction, growth of an island arc, and closure of Iapetus ensue to the east. Collision of this arc with North America

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occurred in the late Ordovician and is called the Taconic Orogeny. It destroyed the passive margin, forming a foredeep-foreland along the margin that extended west onto the craton. Detritus from the uplifted Taconic highlands were shed west into this foredeep as a flysch-molasse sequence called the Queenston clastic wedge. Once the Taconic highlands were reduced by erosion, the Appalachian foreland was transformed back to shallow marine conditions accumulating sediment with both margin and cratonic provenance through the middle Devonian. The pattern of collision, uplift, and quiescence repeated two more times before the close of the Paleozoic. In the Devonian, the microcontinent Avalonia collided with North America causing the Acadian orogeny and the shedding of a thick clastic wedge westward into the foreland called the Catskill wedge. Lastly in the late Carboniferous, Iapetus closed completely with the collision of Africa and Europe with North America driving the Alleghenian orogeny.
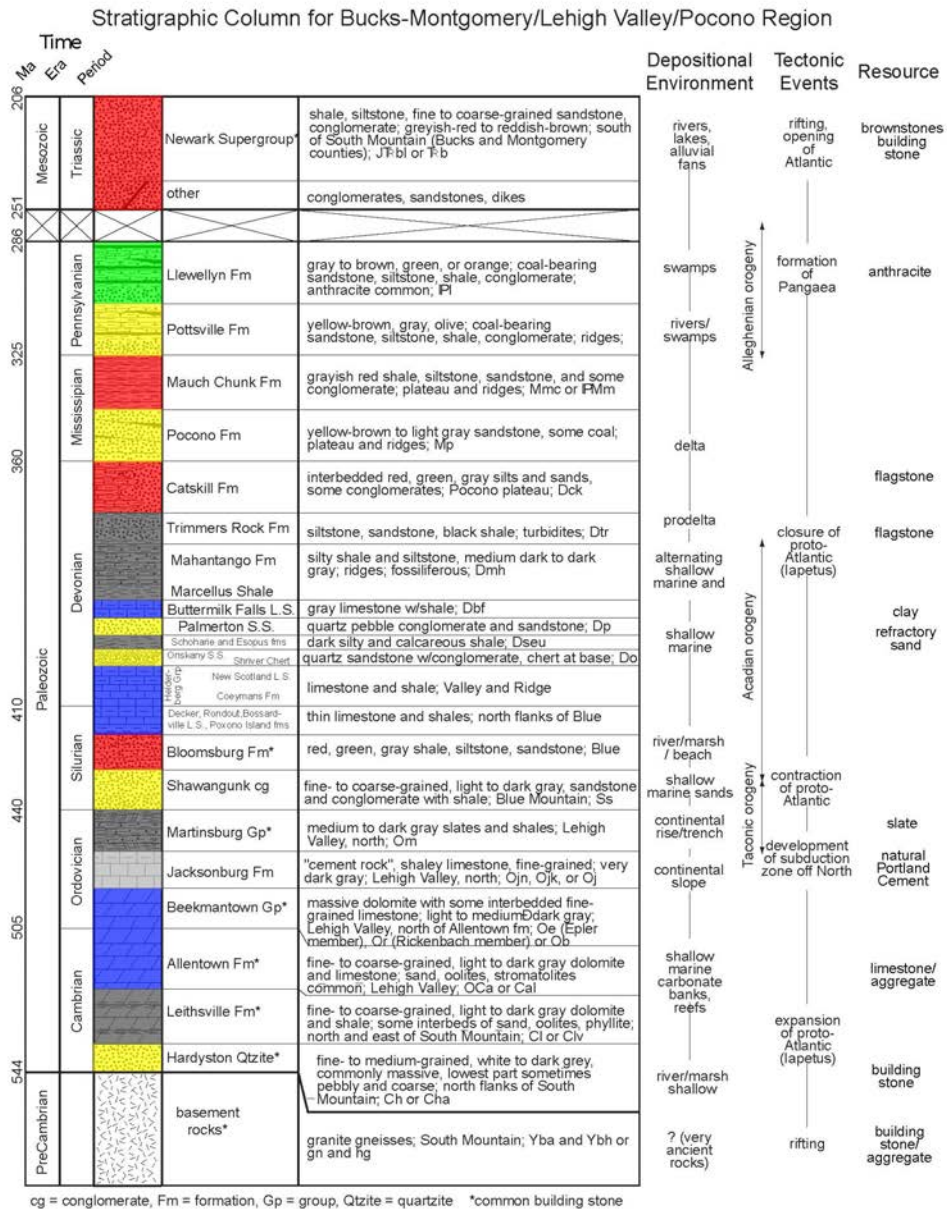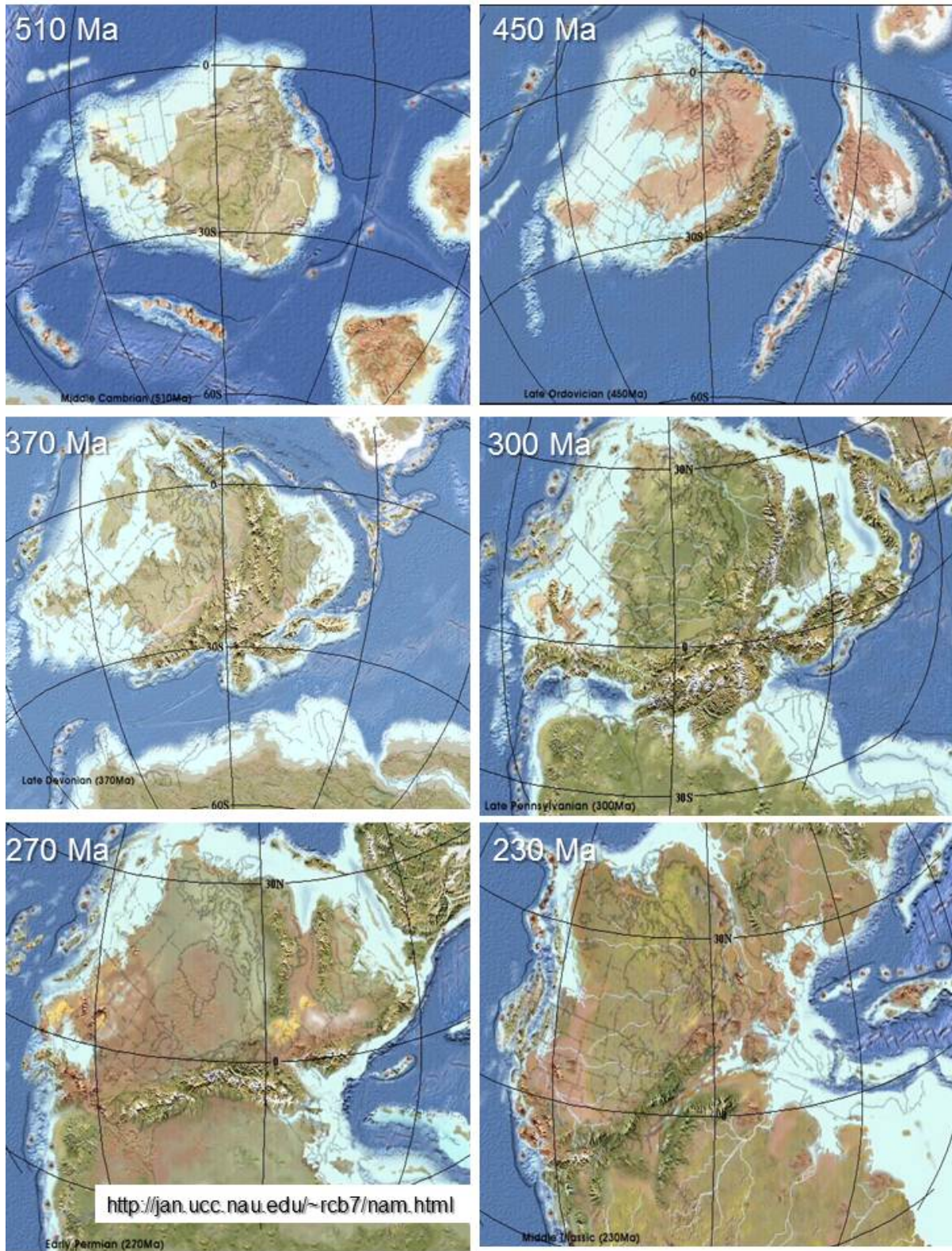
Stratigraphic Column for Bucks-Montgomery/Lehigh Valley/Pocono Region

Time (Ma / Era / Period)	Formation	Description	Depositional Environment	Tectonic Events	Resource
206 — Mesozoic / Triassic	Newark Supergroup*	shale, siltstone, fine to coarse-grained sandstone, conglomerate; greyish-red to reddish-brown; south of South Mountain (Bucks and Montgomery counties); JTrbl or Trb	rivers, lakes, alluvial fans	rifting, opening of Atlantic	brownstones building stone
251	other	conglomerates, sandstones, dikes			
286					
325 — Pennsylvanian	Llewellyn Fm	gray to brown, green, or orange; coal-bearing sandstone, siltstone, shale, conglomerate; anthracite common; Pl	swamps	formation of Pangaea	anthracite
	Pottsville Fm	yellow-brown, gray, olive; coal-bearing sandstone, siltstone, shale, conglomerate; ridges;	rivers/swamps	(Alleghenian orogeny)	
360 — Mississippian	Mauch Chunk Fm	grayish red shale, siltstone, sandstone, and some conglomerate; plateau and ridges; Mmc or PMm			
	Pocono Fm	yellow-brown to light gray sandstone, some coal; plateau and ridges; Mp	delta		
— Devonian	Catskill Fm	interbedded red, green, gray silts and sands, some conglomerates; Pocono plateau; Dck	prodelta	closure of proto-Atlantic (Iapetus)	flagstone
	Trimmers Rock Fm	siltstone, sandstone, black shale; turbidites; Dtr	prodelta		flagstone
	Mahantango Fm	silty shale and siltstone, medium dark to dark gray; ridges; fossiliferous; Dmh	alternating shallow marine and	(Acadian orogeny)	
	Marcellus Shale				
	Buttermilk Falls L.S.	gray limestone w/shale; Dbf			clay
	Palmerton S.S.	quartz pebble conglomerate and sandstone; Dp	shallow marine		refractory sand
	Schoharie and Esopus frms	dark silty and calcareous shale; Dseu			
	Onskany S.S. — Shriver Chert	quartz sandstone w/conglomerate, chert at base; Do			
410	New Scotland L.S.	limestone and shale; Valley and Ridge			
	Coeymans Fm (Helder-berg Gp)				
	Decker, Rondout, Bossard-ville L.S., Poxono Island frms	thin limestone and shales; north flanks of Blue			
— Silurian	Bloomsburg Fm*	red, green, gray shale, siltstone, sandstone; Blue	river/marsh / beach	contraction of proto-Atlantic	
440	Shawangunk cg	fine- to coarse-grained, light to dark gray, sandstone and conglomerate with shale; Blue Mountain; Ss	shallow marine sands	(Taconic orogeny)	
— Ordovician	Martinsburg Gp*	medium to dark gray slates and shales; Lehigh Valley, north; Om	continental rise/trench		slate
	Jacksonburg Fm	"cement rock", shaley limestone, fine-grained; very dark gray; Lehigh Valley, north; Ojn, Ojk, or Oj	continental slope	development of subduction zone off North	natural Portland Cement
505	Beekmantown Gp*	massive dolomite with some interbedded fine-grained limestone; light to mediumdark gray; Lehigh Valley, north of Allentown fm; Oe (Epler member), Or (Rickenbach member) or Ob			
— Cambrian	Allentown Fm*	fine- to coarse-grained, light to dark gray dolomite and limestone; sand, oolites, stromatolites common; Lehigh Valley; OCa or Cal	shallow marine carbonate banks, reefs		limestone/aggregate
	Leithsville Fm*	fine- to coarse-grained, light to dark gray dolomite and shale; some interbeds of sand, oolites, phyllite; north and east of South Mountain; Cl or Clv		expansion of proto-Atlantic (Iapetus)	
544	Hardyston Qtzite*	fine- to medium-grained, white to dark grey, commonly massive, lowest part sometimes pebbly and coarse; north flanks of South Mountain; Ch or Cha	river/marsh shallow		building stone
— PreCambrian	basement rocks*	granite gneisses; South Mountain; Yba and Ybh or gn and hg	? (very ancient rocks)	rifting	building stone/ aggregate

cg = conglomerate, Fm = formation, Gp = group, Qtzite = quartzite   *common building stone

Figure I-3. Stratigraphic column for eastern Pennsylvania.

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Fig. I-4. *Paleogeographic reconstructions of the closing of Iapetus and building of the Appalachians throughout the Paleozoic. (Modified from Blakey; http://www2.nau.edu/rcb7/globaltext2.html)*

The Early Permian (~280 Ma) Appalachians were a lofty mountain chain modeled to be similar in mean elevation, relief, and width to the modern central Andes (Slingerland and Furlong, 1989). Deformation during this orogeny propagated far westward into the foreland, imbricating much of the former foreland basin, and shedding a thick molassic wedge west across the craton. That wedge was responsible for up to 11 km of burial in the anthracite fields of eastern Pennsylvania (Levine, 1986), 4 km in central West Virginia (Reed et al., 2005), and up to 2 km of burial in the mid-continent (Hegarty, 2007). Deep erosional exhumation of the Appalachian core during and after the culmination of crustal thickening first overfilled, and then unroofed the Appalachian foreland with the detritus being transported westward to the mid-continent and beyond (Riggs et al., 1996; Rahl et al., 2003; Hegarty et al., 2007). Erosion reduced much of Appalachian topography to several hundred meters or less of local relief when rifting began in the late Triassic.

Extension during the Late Triassic to Early Jurassic reactivated many of the pre-existing Grenvillian and Appalachian structures, producing a series of wide, deep fault-bounded rift basins from northern Florida to the Grand Banks of Canada (Withjack et al., 2011; Withjack et al., 1998; Withjack and Schlische, 2005; Faill, 2003; Figure I-5). The remnants of these basins, exposed on the margin today, provide a wealth of geologic information about synrift and post-rift depositional and deformational processes (Olsen et al., 1996; Withjack et al., 1998). Rifting began in an apparently distributed fashion, often reactivating sutures of Paleozoic accreted terranes, then localized to the present margin location, leaving behind a number of abandoned Triassic/Jurassic rift basins adjacent to the successfully rifted margin. Most aspects of this localization, including the role of sutures, however, remain unclear. Rift localization off the east coast of the US and its conjugate was roughly coincident with one of the most voluminous but short-lived volcanic events in Earth's history (i.e., the Central Atlantic Magmatic Province (CAMP)), and much of the rifting along the margin was correspondingly volcanic. In contrast, the northernmost portion of this margin offshore Canada is distinctly magma-poor. Here, rifting has left behind wide tracks of highly thinned continental crust and exposed, serpentinized mantle along the margin. Not only does the style of rifting change substantially between these magmatic end-members, variations in magmatism and deformation are also seen on smaller scales between adjacent segments. Segmentation is apparent across the margin from abandoned rift basins onshore to oceanic crust offshore, but many questions remain about the development and evolution of segmentation through time. This margin and its conjugate are particularly well preserved and uncomplicated by subsequent tectonic events, making it an excellent setting in which to examine the deformation, magmatism and segmentation that led to continental breakup.

After rifting, the rift basins underwent significant erosion (locally > 5 kilometers). Much of this erosion occurred soon after breakup, producing a pronounced unconformity between the syn- and post-rift rocks. Additionally, significant deformation occurred after rifting, folding and tilting the synrift strata. Like their post-Rodinian predecessors, low-magnitude, but persistent, seismicity is located along the flanks of the rift basins today (Seeber and Armbruster, 1988; Wheeler, 2006). Rifting rejuvenated the topography and opened up new basins to the east of the foreland which initiated a reversal of Appalachian drainage from formerly towards the foreland (west) to one that was split between the old west-flowing rivers and the newly formed Atlantic slope drainages (Judson, 1975). The formerly low-standing Appalachian basin became a relatively high-standing region and portions of the foreland and Blue Ridge experienced a new

pulse of erosion during the Late Jurassic and Early Cretaceous (~140-150 Ma), also recorded by AFT cooling ages (Miller and Duddy, 1989; Roden and Miller, 1989) and delivery of siliciclastic detritus to Atlantic shelf-slope basins (Poag, 1985, 1992; Poag and Sevon, 1989).

Figure I-5. *Tectonic elements of the eastern North American margin. The southern, central, and northern segments exhibit progressively younger ages for the end of rifting and presumably the onset of seafloor spreading. The East Coast magnetic anomaly approximates the extent of seaward-dipping reflectors at the continent-ocean boundary. The Blake Spur magnetic anomaly may be related to a ridge jump. M-25 is the oldest dated magnetic anomaly; thus, the age of older oceanic crust depends on the inferred spreading rate. Inset shows configuration of the supercontinent Pangea during the LateTriassic (Olsen, 1997), and highlights the rift zone between eastern North America and NW Africa and Iberia. Regional transect through southern segment of margin highlights Paleozoic prerift structures, Triassic-Jurassic rift structures, and Mesozoic/Cenozoic post-rift basins. Modified from Withjack & Schlische (2005).*

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The syn- and post-rift geologic, tectonic, and geodynamic development of ENAM is preserved as a sedimentologic and stratigraphic archive in several shelf-slope basins (Fig. I-1). The long-term depositional and subsidence history of the 400 km long, 100 km wide, and up to 18 km deep BCT has been particularly well studied (Karner and Watts, 1982; Poag, 1985, 1992; Poag and Sevon, 1989; Steckler et al., 1988, 1999). Collectively, the BCT contains siliciclastic sediment equivalent to about 4 km of rock (Hulver, 1997) removed from an area spanning the modern central and New England Appalachian Atlantic slope. These sediments store a rich record of passive margin forcing mechanisms, such as lithospheric flexure, lower crustal flow, source terrane uplift, basin subsidence, paleoclimate and eustatic sea level changes. Patterns of erosion, transport and deposition evolve through time in response to diverse physical and chemical processes. Gravity-driven sediment transport (e.g., landslides and turbidity flows) destabilize the slope and carry sediment to the deep sea where it may be redistributed by oceanographic processes. The sedimentary section can also be altered chemically via diagenesis, methanogenesis and other processes that are associated with venting of carbon-rich fluids and gasses. Several aspects of the sedimentary wedge make the ENAM ideally suited for passive margin studies. First, because the ENAM is 'salt-free' along most of its length, many of the processes recorded in the sedimentary wedge can be imaged without limitations posed by diapiric evaporite bodies common to many other passive margins. Second, sedimentation was nearly continuous and rates were relatively high along the margin providing a robust record of sedimentary environments ranging from glacial-dominated to carbonate.

ENAM Geophysical background

Seismological properties of the eastern North American lithosphere have been investigated by numerous researchers, with primary methods being tomographic imaging with different wave types (on regional and global scales), active source studies (COCORP and LITHOPROBE campaigns), studies utilizing shapes of teleseismic body waves (shear-wave birefringence, receiver-function analysis), and investigations using regional seismic activity.

Continent-scale tomographic studies consistently show the lithosphere to be thickest (~300 km) around the Hudson Bay (e.g., Nettles and Dziewonski, 2008; Grand, 1994; van der Lee 2001; van der Lee and Frederiksen, 2005, Darbyshire et al., 2007), and to thin progressively towards the coast (Figure I-6). On a smaller scale, however, this gradual change from continental interior outward is complicated by considerable variability, which is especially pronounced beneath the Appalachian orogen. This variability is further illustrated in contrasting tomographic imaging efforts (van der Lee and Frederiksen, 2005; Nettles and Dziewonski, 2008).

Whereas the intensity of the features varies with technique, there is general agreement on regions of reduced seismic wavespeed beneath the coastal plain, likely extending across the entire Appalachian orogen, and also eastward under the ocean. Menke & Levin (2001) used surface waves propagating from the Mid-Atlantic ridge to the coast to show that within the low-speed zone enclosing Cape Cod (referred to as a "divot" by Fouch et al., 2000) upper mantle rocks are ~3% slower than in the area further south.
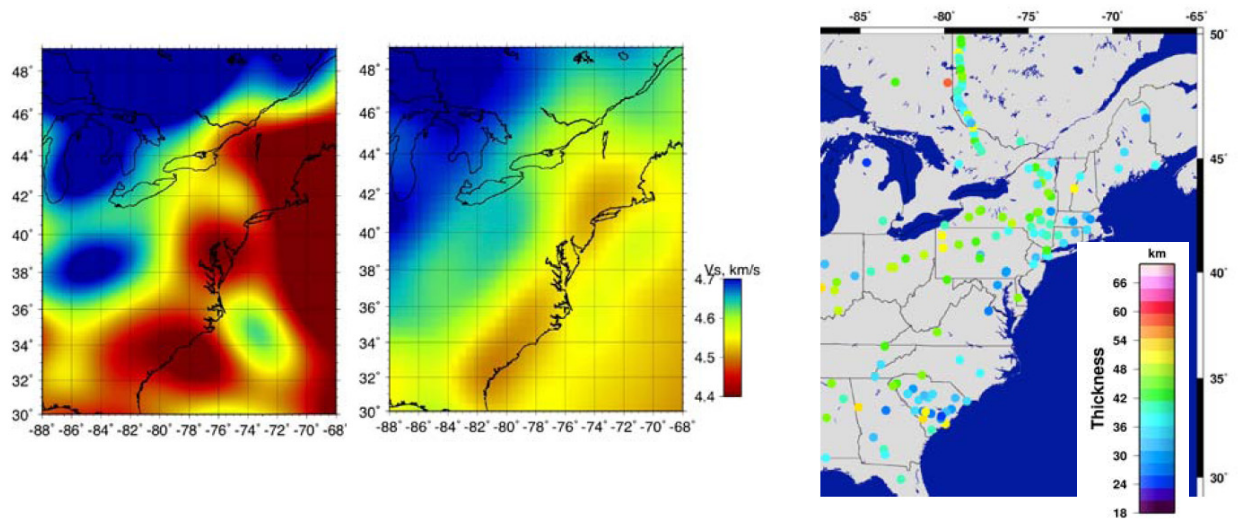
Figure I-6. (a) Left, Horizontal slices at ~100 km through tomographic models by van der Lee and Frederiksen (2005) (left) and Nettles and Dziewonski (2008) (right) show areas of relatively low seismic wavespeed along the Atlantic passive margin of the North American continent that cut across the strike of the Appalachianorogen. Particularly notable is an area between Cape Cod and the Great Lakes. (b) Right, Estimates of crustal thickness using reverberations of teleseismic P-to-S converted waves in the crust (from ears.iris.washington.edu).

Low seismic wave speed in the upper mantle is commonly associated with excess temperature. It is however unclear why, given their largely uniform tectonic history, some regions beneath the Atlantic margin should be considerably warmer than others.

Attempts to determine lithospheric thickness beneath the Appalachians yielded a range of outcomes, not all of them compatible. Surface wave tomography (van der Lee, 2002) suggests relatively thin lithosphere (80 km) beneath the Appalachians, although the author noted a difficulty of defining the exact depth where the lithosphere ended. This estimate agrees to a degree with studies of converted-mode body waves by Rychert et al., (2005, 2007), which identified sharp seismic impedance contrasts at depths of 90-110 km, and interpreted them as the base of the lithosphere. On the other hand, compressional-wave tomographic imaging of a small region at the junction of the Grenville and Appalachian terranes (Levin et al., 1995) identified a significant change in the degree of lateral heterogeneity of the upper mantle at ~300 km, which was taken by the authors to represent the transition from the lithosphere to the asthenosphere.

Numerous studies of seismic anisotropy in the region (see Fouch and Rondenay, (2006), for review) found evidence for significant levels of it throughout the region. However, the relations of the observed anisotropic texture to the present plate motion, asthenospheric processes and the history of tectonic events in the region are not fully worked out. Various authors explained the observations in terms of texture remnant from the time of continental accretion (e.g., Barruol et al. 1997), asthenospheric flow modulated by lithosphere shape (Fouch et al., 2000; Forte et al., 2010), and a combination of both resulting in at least two layers of texture (Levin et al., 1999).

Crustal thickness beneath the Appalachians, determined by means of active source seismic surveys as well as with teleseismic body wave reverberations, varies in the 30-45 km range. A recent study using ambient noise imaging (Bensen et al. 2009) presents uniform maps of crustal

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thickness throughout the North American continent. A notable feature of this map is a difference of at least 5 km in average crustal thicknesses of northern and southern Appalachians. On the other hand, automated computation of crustal thickness from receiver functions (ears.iris.washington.edu) does not show such a clear difference between these regions.

The crust of Eastern North America is surprisingly seismically active (Fig. I-1). There are also some fairly tight concentrations of seismicity, e.g. in the Montreal-Ottawa area, NYC area, St. Lawrence Valley. Reactivated features from past tectonic events (e.g. a Ramapo fault system in NJ and NY states) clearly play a role in where earthquakes take place (e.g. Sykes et al., 2008). In some places (e.g. Adirondacks) occasional earthquakes take place at 30+ km, which is very unusual for the continental crust. (Sbar and Sykes, 1977).

Bouguer and isostatic residual gravity maps of the mid-Atlantic margin (Simpson et al., 1986; Fig. 1) indicate a major gravity low in southeastern Pennsylvania interpreted as a particularly deep sedimentary basin above basement (Shanmugam and Lash, 1982). This basin is not evident from surface geology alone and has not been imaged seismically. It represents one of potentially many such Appalachian basins that formed as a result of interactions with non-uniform Grenville basement and were subsequently covered by allochthonous thrust sheets.

Collectively, the geomorphic, geologic, and geophysical observables are direct evidence for unsteady ENAM epeirogenic deformation which includes uplift and erosion of the Appalachians and its foreland, and non-uniform subsidence of the passive margin basins. There are several possible causes of this epeirogeny of which isostatic (Fisher, 2002), flexural isostatic (Pazzaglia and Gardner, 1994), and dynamic (Moucha et al., 2008) mechanisms have already been proposed and modeled. Not tested, but of equal potential importance are effects, both proximal and distal, of the now well-documented Chesapeake impact structure, the subsidence history of which is known to be both long-lived and unsteady (Hayden et al., 2008). In summary all of these geodynamic processes have profound implications for interpretations of eustasy and sequence stratigraphy (Miller et al., 2008). More importantly, ENAM geodynamic research opens the door for exploration of surface processes-lithospheric dynamic interactions that can be tested against geologic and stratigraphic archives.

TRAVEL AND FIELD RULES:

Safety First: Buckle up in vans, be careful getting in and out, when on road cuts, stay off travel lanes, cross traffic carefully, and please watch out for one another. Be careful when hammering and protect your eyes. When near highwalls, watch for falling rocks. Hard hats and sturdy shoes are required to visit active quarries and construction sites. Practice your skills as a field geologist, take notes and sketch each outcrop, be engaged.

START. STEPS building, Lehigh University. *Proceed east on Packer Ave. Turn right on Ryan Street, then quickly left onto Hillside Ave. Proceed to Hayes St, turn right and continue up South Mountain on Mountain Drive N. At the first triangle, bear left, you have the right of way. At the second triangle stay straight. Turn Right into the parking lot in front of Iacocca Hall and park in a visitor's lot parking space.*

STOP 1. Iacocca Hall Observation Tower. Panoramic view of the Reading Hills, Great Valley, and Kittatinny Ridge from Lehigh campus, Iacocca Hall Tower. On a clear day you can identify points of interest beyond 20 miles distance (Fig. RL-1, RL-2).

The Blue Ridge province in Pennsylvania consists of ridges of Precambrian gneiss and small intervening valleys of Paleozoic sedimentary cover known as the Reading Prong. Early geologists (e.g. Rogers, 1858) interpreted the basement outcrops as anticlinal structures. An overthrust interpretation of the Reading Prong, whereby Precambrian crystalline rocks were thrust over the Great Valley sequence (Figs. RL-3, 4) was first advocated by Stose and Jonas, 1936, though it would be many years before the thick skinned interpretation was abandoned by all (e.g. Fraser, D.M. 1940, Miller 1944). The thinned skin, basement thrust sheet interpretation of the Reading Prong has since been confirmed by field geological Drake et al. (1967), potential field studies (e.g. Bromery, 1960), and well and seismic interpretations (Ratliff et al. 1986). The Precambrian rocks of the Reading Prong are mainly high-grade quartzo-felspathic metaasedimentry and metavolcanic rocks with lesser amounts of amphibolite, marble, and granitic lithologies deformed and metamorphosed during the Grenville orogeny (1.1-1.2 Ga). Basement exposures on Lehigh's campus are referred to as the Byram gneiss.

Looking to the north, the break in slope at the base of Lehigh's Asa Packer campus is approximately the location of the Blue Mountain thrust, which is buried by a thick colluvial wedge covering the lower slope beneath the observation tower. Further north, outcrops of the Cambrian Allentown Fm and overlying Beekmantown Group carbonates [Stop 2], produce a very flat valley (e.g. Lehigh Valley airport). Beyond the middle of the valley the topography is dominated by rolling hills underlain by the Ordovician Martinsburg Fm. [Stop 3]. Separating these carbonate and clastic units is the Ordovician Jacksonburg Fm., [Stop 2] a natural cement mix and the locus of the modern cement plants distributed along strike visible by their smokestacks. David Saylor at Coplay, PA first manufactured Portland cement in the U.S.A. in 1892 (Fig. RL-5). Separating Kittatinney Ridge from the Great Valley sequence is the Taconic unconformity [Stop 4]. The ridge is held up by Silurian clastics of the Shawngunk Fm. Look to the northeast to observe Camel's Hump, an outlier of Precambrian basement thrusted into the Great Valley sequence (Fig. RL-3).

Look to the south to see Lehigh's Goodman campus, Saucon Valley, a syncline underlain by Lower Paleozoic clastics and carbonates, followed by the remainder of the Blue Ridge highlands. The Triassic Border fault of the Newark Basin [Saturday trip] is just beyond the skyline. The Lehigh Valley contains many sinkholes and caves. The karst topography is most developed in the Cambrian Leithsville and Allentown Fms.

Fig. RL-1. Geographic and cultural points of interest visible from Iacocca Tower.
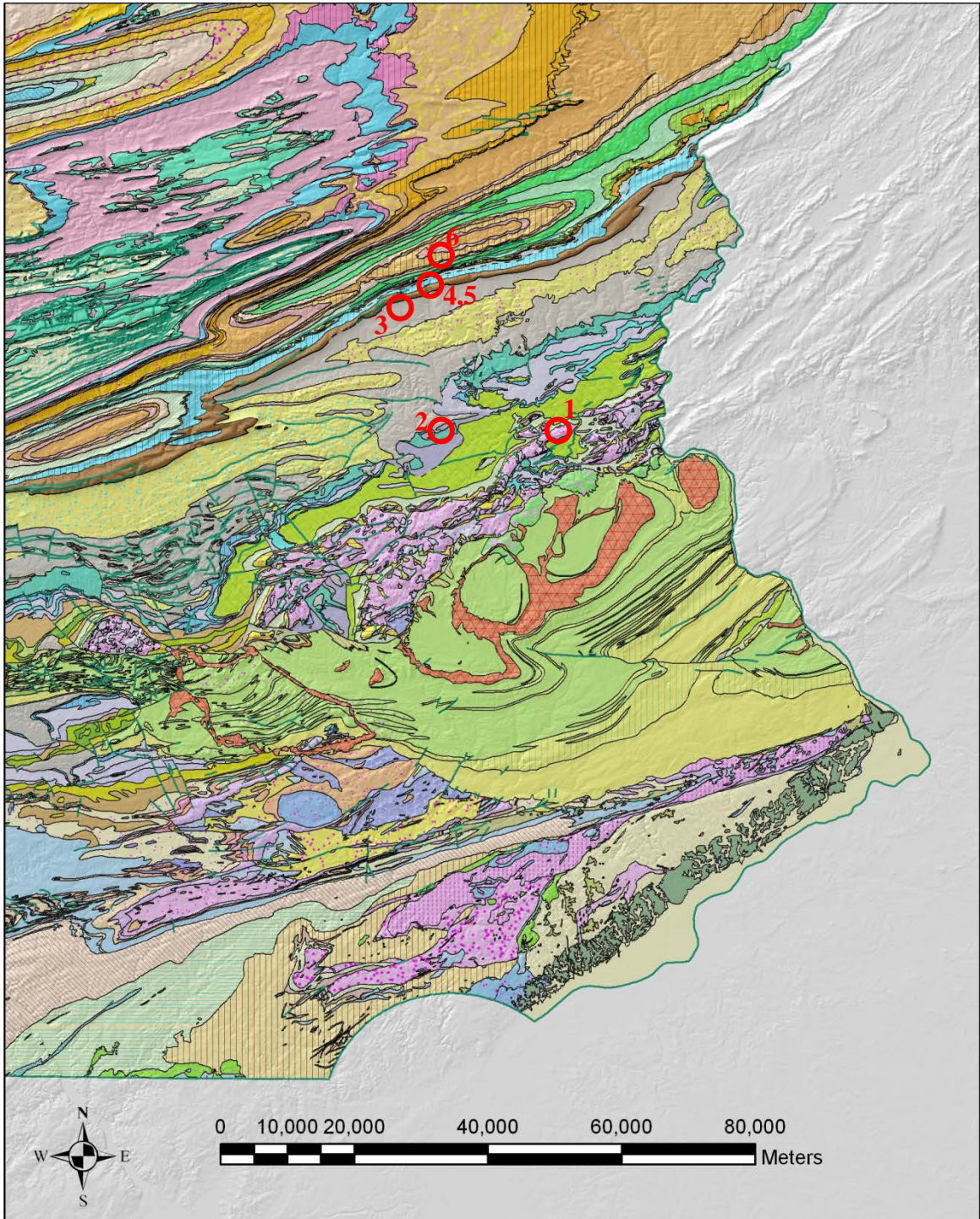
Fig RL-2. *Portion of the Geologic shaded relief map of Pennsylvania showing field trip stops. The purple colors in the center of the map are Precambrian Blue Ridge rocks. The greens and reds to the south are redbeds and intrusions, respectively of the Triassic-Jurassic rift basin. The yellows, browns, grays, and blues to the north are the Paleozoic carbonates and siliciclastics of the Lehigh Valley and Ridge and Valley.*

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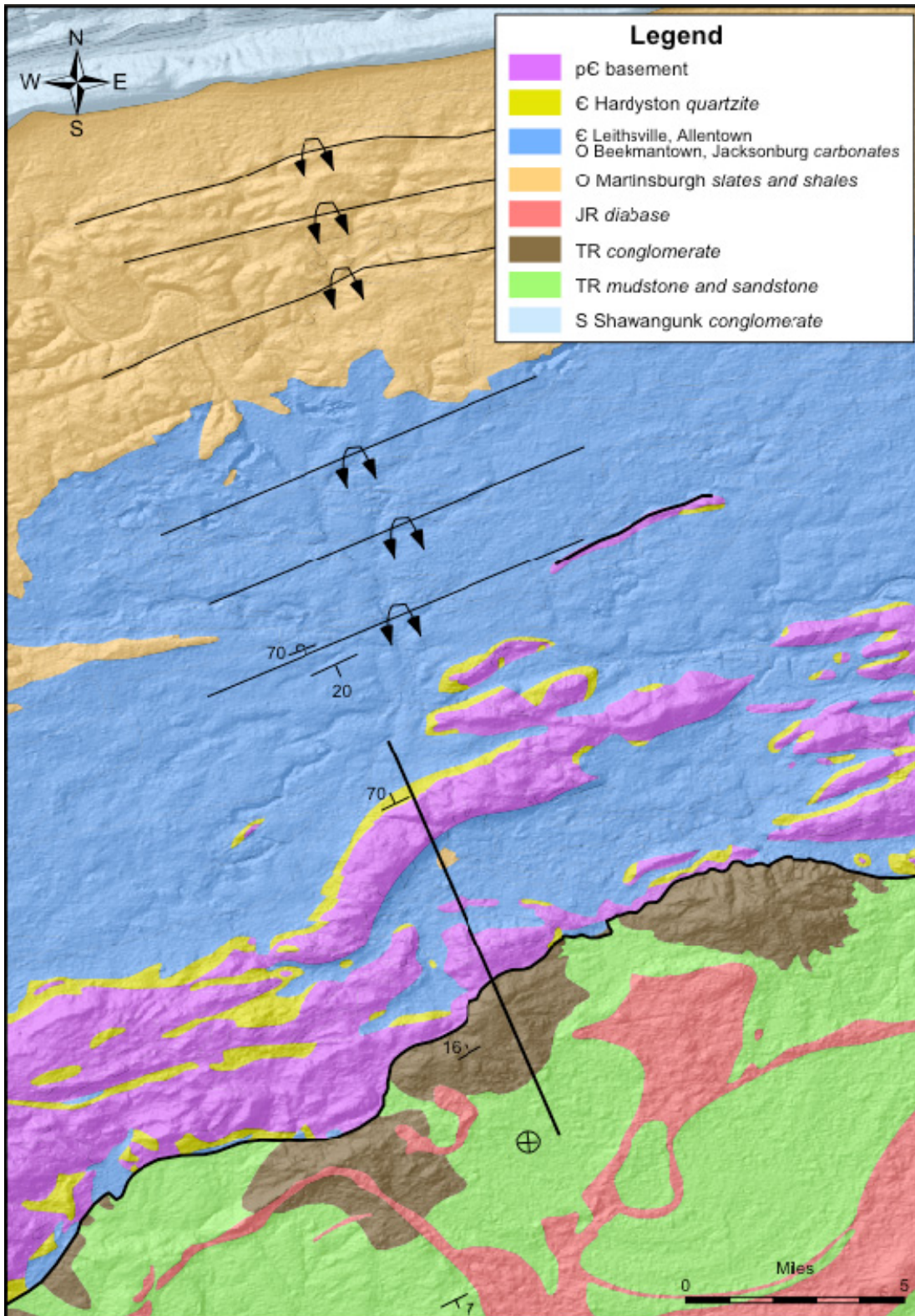
Fig. RL-3. *Geologic map of the central Lehigh Valley modified from the Geologic Shaded Relief Map of Pennsylvania. Camel's Hump is one of several basement outliers (purple color) in an otherwise sea of blue carbonates.*

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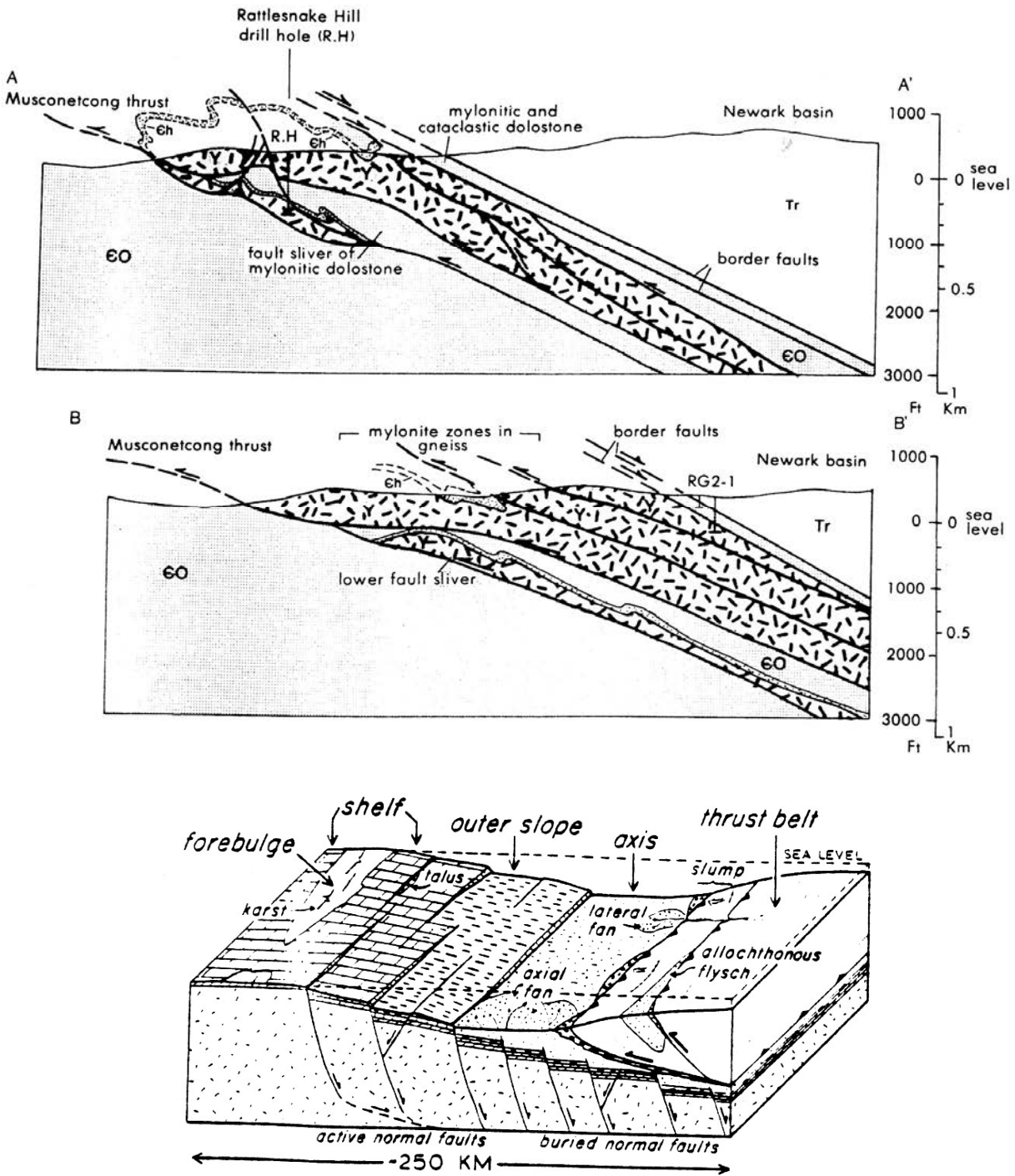
Fig. RL-4. (above) Cross-section generally following line in Fig RL-2 illustrating the nature of the Blue Ridge thrust sheet. (Below) Schematic diagram of a collisional foredeep showing the distribution of facies and basin geometry. Both modified from Radcliff et al., (1986).

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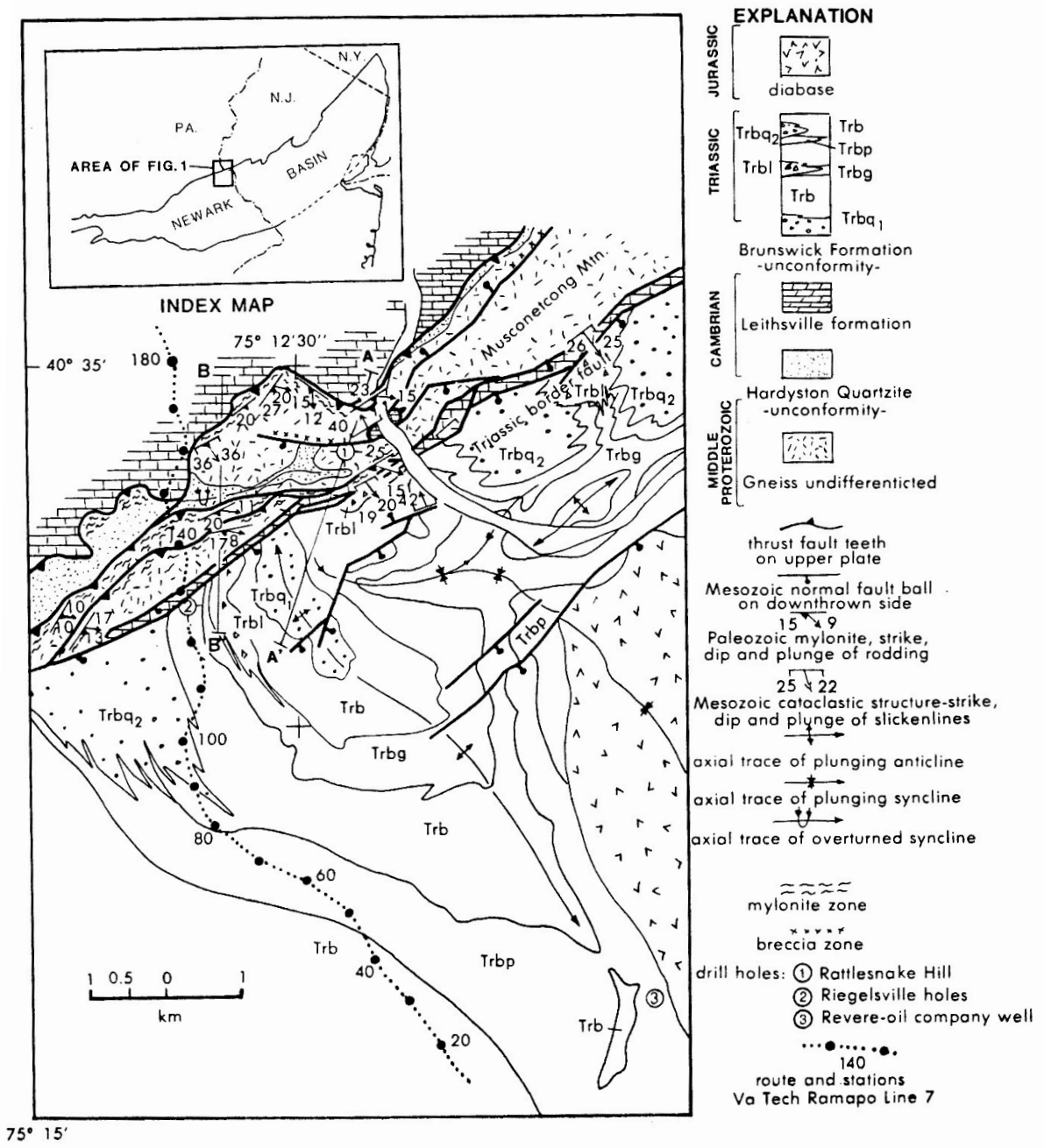
Fig. RL-4 continued. The Blue Ridge thrust in SE PA (Ratcliff et al., 1986).

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Depart Iaccoca Hall parking lot and proceed west on Mountain Drive West. The the first triangle, stay straight, at the second triangle, stay left. Proceed straight to the stoplight on Rt 378. Turn right on Rt 378 and continue straight, across the Lehigh River, and north through Bethlehem to Rt. 22. Exit Rt 378 for Rt 22 west and continue to Rt 145, MacArthur Blvd. Take MacArthur Blvd north. Turn left on S. Church Street and proceed past the Whitehall Quarry to Ruchsville Road. Turn left onto Ruchsville Road – Williow Street. In ~approximately 1 km, turn right into the Omrod Quarry.

Fig. RL-5. *Cement furnaces at Coplay, PA*

Stop 2. Ormrod Quarry, Eastern Industries, Inc. This active quarry, south of Egypt PA is mainly in the Beekmantown Group carbonates (Fig. RL-6). The interbedded argillaceous and cleaner carbonates are use for aggregate stone. Here you will see upright and recumbent, concentric flexural and more complex folds and cleavage that first developed during the Taconic orogeny, but were subsequently modified and further translated foreland during the Alleghanian orogeny. At the southwest end of the quarry you can observe the Jacksonburg Fm, a natural cement rock outcropping beneath the southdipping overturned contact with stratigraphically lower Beekmantown Fm. Greater fold disharmony occurs near the Beekmantown – Jacksonburg contact.

Fig. RL-6 *(left) Photo of a fold in the Whitehall quarry. (Right) Student sketch of a fold in the Omrod Quarry.*

Exit quarry, turn left on Ruchsville Road, turn left onto S. Church Street and drop into Egypt. Turn right onto Rt 329 (Main Street), and proceed to Rt 145. Turn left on Rt. 145. Parallel, then cross the Lehigh River. Continue north to Walnutport and the stoplight with Main Street. Turn left onto Main Street, cross the Lehigh River again, and continue to Rt. 873 South. Turn Right onto West Church Street. Proceed straight, cross under the PA Turnpike and follow Main Street through the town the Emerald. Stay on Main Street by making a right turn on State Route 4018 and crossing Trout Creek. Enter Slatedale and stay on Main Street. Turn right on to State Route 4017 (Brown Street). Ascend the hill and proceed for ~0.5 km to Penn Big Bed Quarry.

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Stop 3. Penn Big Bed Slate Quarry, Slatington PA.

THE QUARRY SIDES ARE STEP AND HIGH
DO NOT GET DANGEROUSLY CLOSE TO THE EDGE.

The Penn Big Bed slate quarry is one of the few remaining quarries of the hundreds to have mined Martinsburg slate in the Lehigh Valley region during the twentieth century.   The Martinsburg Fm. is divided into three members.   The Penn Argyl member is exposed in the quarry.   It represents turbidite deposition into the Taconic forearc.   The cleavage in the quarry dips south, is axial planar in finer beds and fans somewhat in coarser lithologies.   The cleavage formed in both the Taconic and Allegnanian orogeny under lowest greenschist grade conditions.   Towards the north end of the quarry the slates of the Ordovician Martinsburg Fm. are overlain by Illinoian (?) till (Epstein and Epstein, 1969).   Notice the large, asymmetric, north-vergent, similar fold exposed on the north and south quarry walls (Fig. RL-7).
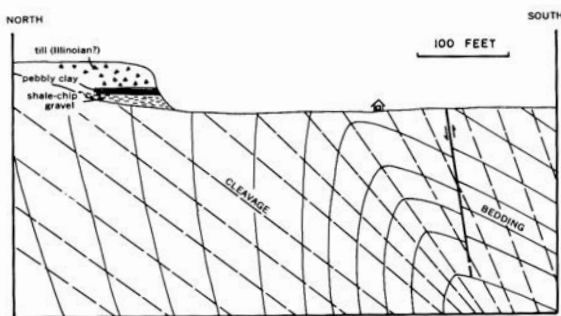
Fig. RL-7. *(left) Photo of the wall in Penn Big Bed Quarry and diagrammatic cross section of the quarry face, looing east, showing cleavage-fold relationship. No horizontal exaggeration. Modified from Epstein and Epstein (1969).*

Exit Quarry and continue north on Brown Street to stop sign on Mountain Road. Turn right onto Mountain Road and continue for ~5 km to the Lehigh River, crossing over the PA Turnpike along the way. Merge with Rt 873 and proceed straight across the Lehigh River. At the stop light, turn right onto Rt 248 and stay left at the next stop light. Approximately 0.2 km after the stop light make a sharp left hand turn and ascend the gravel road to the Appalachian Trail parking area. Use cation making this left hand turn in face of the oncoming traffic.

Stop 4. Lehigh Gap, the Taconic unconformity and structure of Kittatinny Ridge. The boundary between the Valley and Ridge Province and the Great Valley Section in central and eastern Pennsylvania is coincident with the Taconic unconformity, exposed along the southern flank of Blue Mountain (Fig. RL-8).   The contact was identified as the Blue Mountain décollement, a large-displacement, pre-folding, bedding-parallel thrust fault by Epstein et al. 1974 and Lash et al, 1984.   In the PA Turnpike tunnel just to the west of Lehigh gap, the unconformity is overturned with the Silurian Shawngunk Fm. dipping 45° S and the Pen Argyl member of the Martinsburg Fm. dipping 35° S.   There is little evidence of slip along the contact in the tunnel. Anastasio and Myers 1993 show the structure of Blue Mountain as an anticlinally

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folded duplex with a roof thrust the Stoney Ridge-Godfrey Ridge fault, located at the base of the Poxono Island Fm (Gray 1991), and the floor thrust, the Blue Mountain décollement located near the top of the Pen Argyl member stratigraphically below the unconformity. The horses within the duplex are bounded by the Lehigh Furnace Gap fault and an unnamed overlying imbricate which both display ramp and flat geometries (Fig. RL-9). The Stony-Ridge-Godfrey Ridge décollement zone, in addition to serving as the roof thrust to the underlying duplex, floors an overlying disharmonically folded panel of Devonian rocks bounded up-section by the Sweet Arrow fault (Epstein and Sevon 1974).

The abandoned railroad grade at this stop exposes the Taconic unconformity between the Ordovician Martinsburg Fm. and Silurian Shawngunk Fm. The degree of angularity between the beds across the unconformity is ~5° here. Peter Lyttle of the U.S.G.S. notes that when the Taconic unconformity in PA, NJ, and NY states has <10° of angular discordance, the Martinsburg is autochthonous and when the contack is steeper, the Martinsburg Fm. at the contact is allochthonous. The Martinsburg Fm is well-cleaved at the southern end of the outcrop and the intensity of the cleavage diminishes up section towards the unconformity (Fig. RL-10). The north end of the outcrop is made up of shallowly to moderately north-dipping Shawngunk Fm. The formation of cleavage has been extensively studies at Lehigh Gap. Wintsch et al. 1991 used geochemical data to argue of open-system, constant-volume development of slatey cleavage the mudrocks across the mudstone-to-slate transition at Lehigh Gap. Lee et al, 1986 showed that pressure solution and neocrystallization were active deformation mechanisms with the grain shape fabric in quartz grains developing by diffusive mass transfer while the primary bedding parallel phyllosilicates presolved and new chemically distinct phyllosilicates neocrystalized with their basal planes parallel to the flattening plane of the domainal macrocopic cleavage. Epstein and Epstein (1969) argue that the cleavage is Alleghainan in age, based on uniformity of orientation with tectonites developed above the Taconic unconformity, a fact which Wintsch and Kunk (1992) later confirmed by dating cleavage-parallel micas. However, cleaved Martinsburg zenoliths in the Late Ordovician Beemerville intrusive complex in N.J. (Ratcliffe, 1981) and polyphase strain shadows recovered from the Martinsburg Fm. samples orogeny.
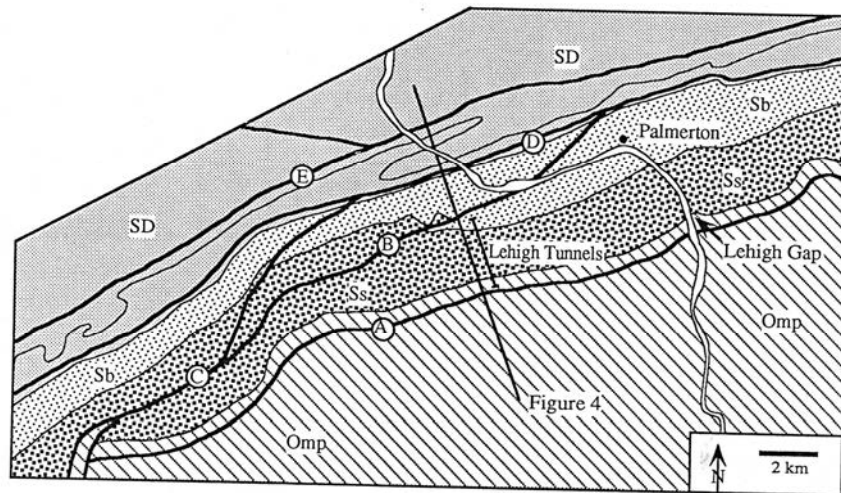
Fig. RL-8. *Simplified geologic map of the Great Valley to Ridge and Valley transition in eastern Pennsylvania (modified from Epstein and others, 1974). A = Blue Mountain decollement, B = Lehigh Furnace Gap fault, C= unnamed thrust, D = Stoney Ridge-Godfrey Gap fault, E=Sweet Arrow decollement, SD = Silurian-Devonian units undivided, Sb = Bloomsburg Fm, Ss=Shawangunk Fm, Om=Martinsburg Fm.*

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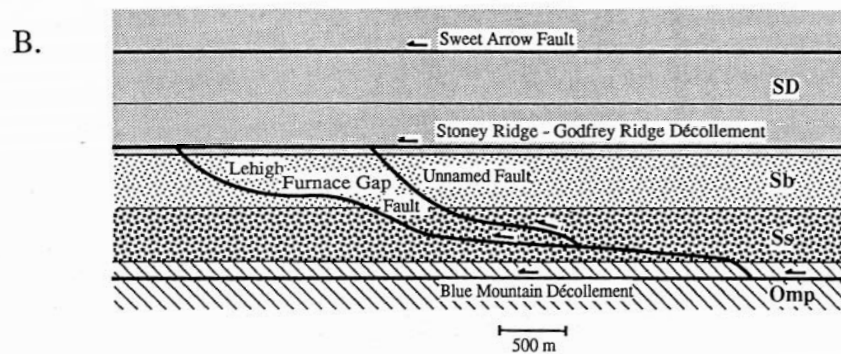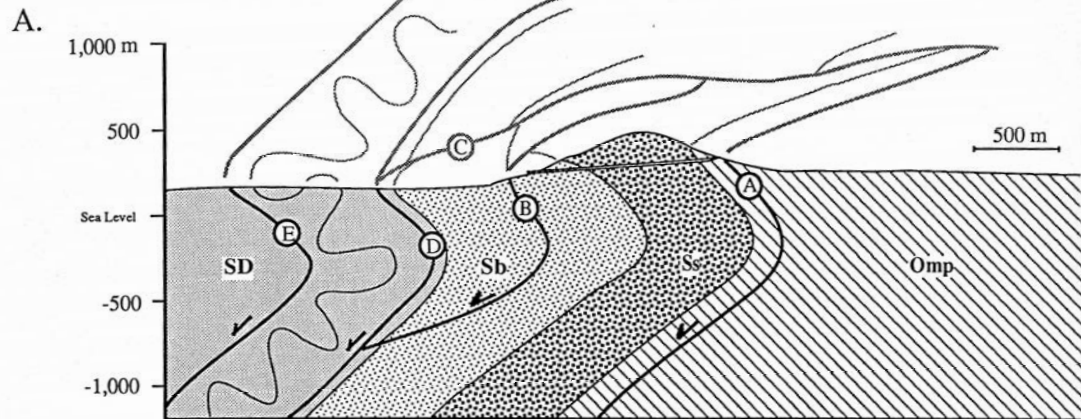
Fig. RL-9. *Interpretive cross section through Blue Mountain at Lehigh Tunnel No. 2. Abbreviations as in Fig. RL-8. (A) Deformed cross section showing the position of the Lehigh tunnels with respect to local structural elements. (B) Balanced and restored cross section through Blue Mountain. (From Epstein and others, 1974).*
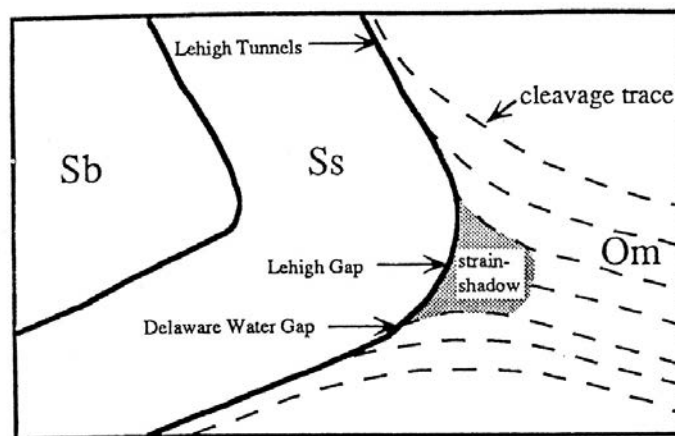
Fig. RL-10. *Diagrammatic sketch of a portion of the Blue Mountain fold to illustrate cleavage geometries and the strain shadow in the Martinsburg Fm near its contact with the Shawangunk Fm at Lehigh Gap. (Modified from Epstein and Epstein, 1969).*

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Of sedimentologic and stratigraphic note at this exposure, there is a 1-meter thick, poorly consolidated conglomerate directly on the unconformity. The unconfomity disappears and the conglomerate horizon thickens into a neritic to brain plain clastic wedge called the Bald Eagle and Juniata Formations in the deeper parts of the foreland further west in Pennsylvania.

Exit the Appalachian Trial parking area and proceed back to Rt 248. Make a right hand turn and continue straight through the next two lights and traverse Lehigh Gap. Bear left off of the highway at the Palmerton exit. Proceed to the stoplight and turn right on Red Hill Drive. Continue for 0.5 km to the large red outcrops. Pull over to right side of road and park.

Stop 5. **Upper Silurian Shawngunk and Bloomsburg Fms., Palmerton, PA.** The outcrops here expose the upper part of the light-brown-colored Shawangunk Fm in contact with the red Bloomsburg Formation. Both of these units are Silurian in age. The contact is obscured by faults, but there is a notable transition in facies from the Shawangunk to Bloomsburg that indicates the change in depositional environment, tectonic, and eustatic setting of the Appalachian foreland at this time. What cannot be seen at the outcrop scale is the provenance of these units. The Shawangunk Fm is almost pure quartz sand with quartz overgrowth cement and almost no matrix whereas the Bloomsburg is approximately 85% quartz sand with 15% lithic fragments and clay matrix. Sedimentologically, fieldtrip participants should focus on bedding, cross-bedding, intercalation of sandstone (quartzite) and darker-colored units in the Shawangunk Fm and on bedding, grainsize change patterns, and white fractures oriented perpendicular to bedding in the Bloomsburg Formation.

In the valley above the transitional contact between the Bloomsburg Fm. red beds and the Lizzard Creek member of the Shawngunk Fm. bedding dips moderately to steeply to the NNW and are in the northwest limb of an overturned anticline. Many beds in the sandstone–siltstone sequence were mechanically active during deformation as evidenced by shear veins and slickenlines. The fanning disjunctive cleavage in siltstone layers is balanced by pre-folding wedge faulting in sandstone layers to accommodate ~20% layer parallel shortening (Fig. RL-11). At the south end of the outcrop, steeply dipping late breaking thrust faults with several centimeter displacements cut the stratigraphy.
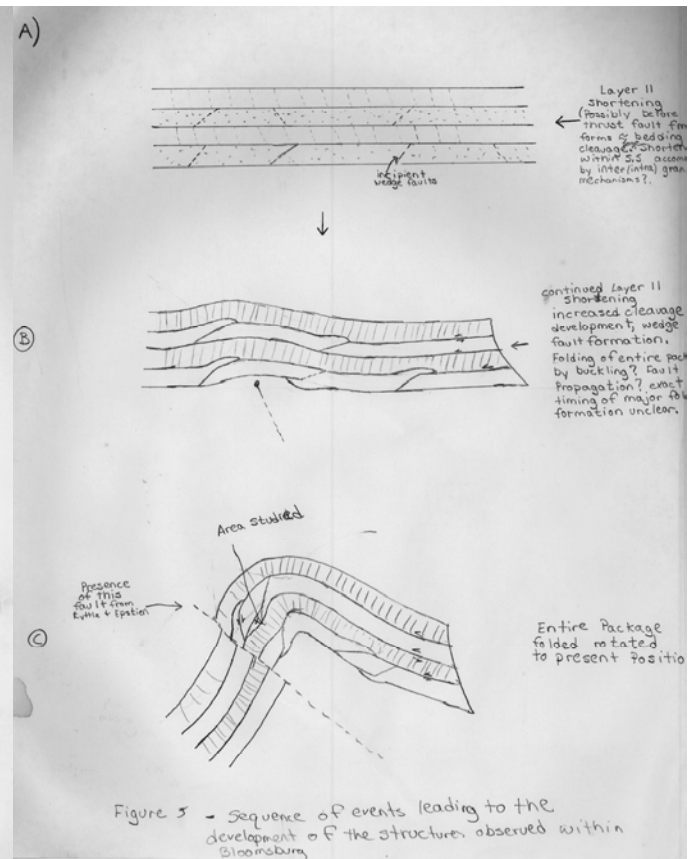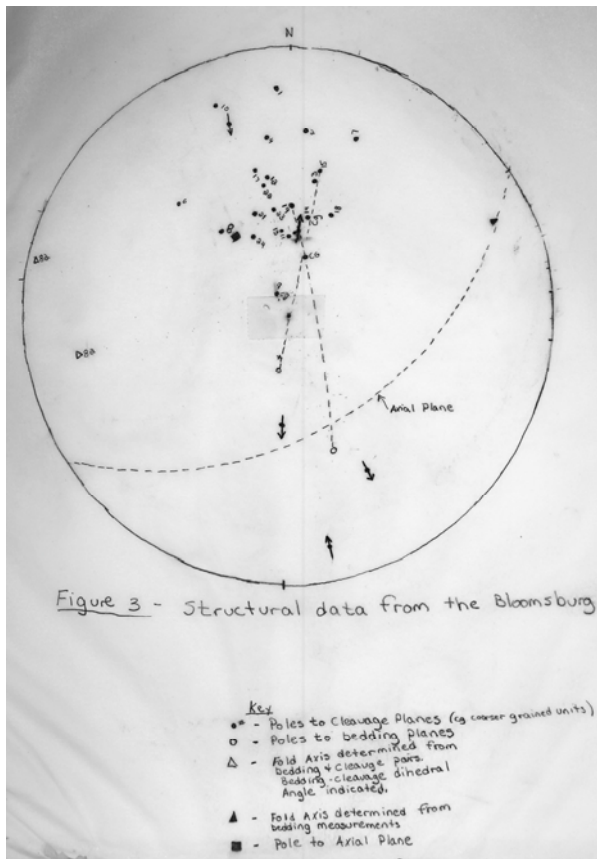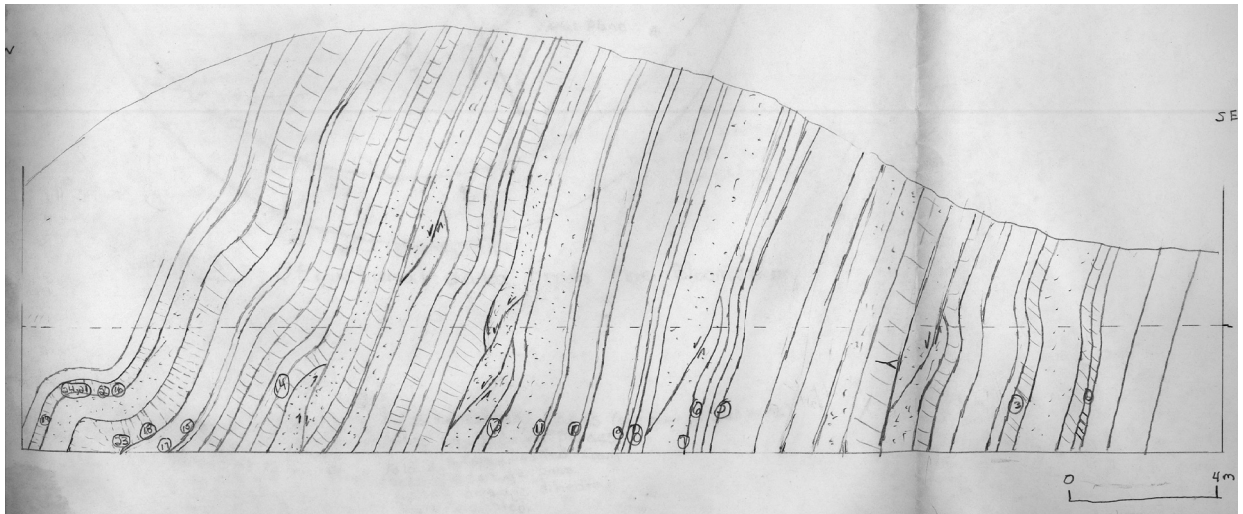
Fig. RL-11. *Student-derived structural measurements from the Bloomsburg Fm at Palmerton, PA. (Top) Sketch fo the outcrop showing numerous small faults that repeat the section. (Bottom left) Stereonet showing poles to bedding planes and cleavage planes. (Bottom right) Sequence of events in developing the bedding plane – cleavage plane relationship.*

STOP 6. **Palmerton Sandstone on Stony Ridge.** The view to the south is of Kittatinny Ridge and its environmentally degraded soils resulting from legacy zinc smelting operations. To the north, the low ridge is underlain by the middle Devonian Marcellus, Mahantango, and Trimmers Rock formations. The latter is a pro-delta deposit that heralds the onset of the Catskill clastic wedge.

The outcrops here expose, in ascending order, the lower to middle Devonian Oriskany, Schohaire-Esopus, and Palmerton formations. They represent the relatively quiet tectonic conditions that persisted following the Taconic orogeny and preceding the Acadian orogeny. The Palmerton and Oriskany formations are coarse grained quartz-pebble conglomerates with the more poorly-exposed calcareous shale and siltstone of the Schoharie-Esopus Formation sandwiched between. Parts of these exposures are particularly fossiliferous. The blocks that define the Stony Ridge spine are corestones, exhumed from a formerly deep chemical weathering profile. At some time in the past, perhaps pre-Quaternary, this ridge was mantled with saprolite and soil derived from these pebbly sandstones. A change in the soil forming environment lead to erosion of the soil and saprolite, exposing the corestones and the former weather fronts that define the edges of the blocks.

The field trip participants need to focus on defining bedding and using all sedimentologic clues, including the fossils, to determine stratigraphic top. When stratigraphic top can be determined, the structural deformation of Stony Ridge can be discussed.

Fig RL-12. (left) Outcrop of the Oriskany Sandstone on Stony Ridge. (right) Bedform-up indicator on Oriskany Sandstone bedding surface.

Field trip end. *Retrace route back to Rt 248, then to Bethlehem via Indian Trail and Shoenersville Road.*

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