The Ordovician Exposed:
12th International Symposium on the Ordovician System

Field Trip Guidebook for the Post-Meeting Field Trip:

The Central Appalachians

June 12-16, 2015

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Stonehenge Formation at Bellefonte South measured section, Pennsylvania (Lower Tremadocian)
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Acknowledgments: The field trip leaders and guidebook authors are indebted to a number of landowners who have allowed access to their properties over the years, among them the Fisher, Murphy, and Price families of Bedford County, Pennsylvania and the Dixson family of Axemann, Pennsylvania. The authors thank the National Park Service for a scientific collecting permit to study the exposures within the C&O Canal Historic Park. We greatly appreciate permission from the Pennsylvania Geological Survey to incorporate figures from their virtual field trip to the Union Furnace section in central Pennsylvania in this guidebook. We acknowledge IUP Geology undergraduate Savannah J. Irwin and the accommodating proprietors of Pro-Packet Printing in Indiana, Pennsylvania, for their tireless assistance in assembling the guidebook. Many other colleagues contributed to the content of this guidebook directly or indirectly, including Randy van Scyoc of New Enterprise Stone and Lime and Duff Gold, Emeritus faculty at Pennsylvania State University. D. K. Brezinski, C. B. Cecil and A. P. Schultz provided timely reviews.

Chapter 0.
Introduction.

John F. Taylor

Field trip overview: The lower Paleozoic rocks to be examined on this trip through the central Appalachians represent an extreme range of depositional environments. The lithofacies we will examine range from pelagic radiolarian chert and interbedded mudstone that originated on the deep floor of the Iapetus Ocean, through mud cracked supratidal dolomitic laminites that formed during episodes of emergence of the long-lived Laurentian carbonate platform, to meandering fluvial conglomerate and interstratified overbank mudstone packages deposited in the latest stages of infilling of the Taconic foredeep. In many ways this field trip is about contrasts. The Upper Cambrian (Furongian) and Lower Ordovician deposits of the Sauk megasequence record deposition controlled primarily by eustatic sea level sea level fluctuations that influenced deposition along the passive, southern (Appalachian) margin of the paleocontinent of Laurentia. The only tectonic influence apparent in these passive margin deposits is the expected thickening of the carbonate stack toward the platform margin as compared to the thinner (and typically shallower) facies that formed farther in toward the paleoshoreline. Carbonates overwhelmingly dominate the passive margin succession. Clastic influx was minimal and consisted largely of eastward transport of clean cratonic sands across the platform from the adjacent inner detrital belt to the west during higher order (2^{nd} and 3^{rd} order) regressions.

In contrast, Middle and Upper Ordovician deposits of the Tippecanoe megasequence record the strong influence of tectonics, specifically Iapetus closure. The first signal of this tectonic transformation was the arrival of arc-related ash beds that abound in the active margin carbonates. Subsequent intensification of Taconic orogenesis resulted in the foundering of the carbonate platform under the onslaught of fine siliciclastics arriving from offshore tectonic sources to the east, creating a deep marine flysch basin where graptolitic shale and sandstone turbidites accumulated. The foreland basin thus created would fill with progressively coarser and more shallow/proximal clastic facies through the Upper Ordovician, culminating in deposition of fluvial redbeds that cap the Taconic clastic wedge. Arguably the most controversial rocks within the Tippecanoe Sequence in this area are unusual, Lower Ordovician deep marine facies that are associated with the much younger flysch of the Martinsburg Formation in the Great Valley of eastern Pennsylvania. Long considered the erosional remnants of a Taconic-style thrust sheet, and referred to as the Hamburg Klippe, these deep marine deposits have recently been reinterpreted as olistostromal deposits that were introduced by gravity sliding into the flysch basin contemporaneous with Martinsburg deposition.

Besides their constituent lithofacies, rocks of the Sauk and Tippecanoe megasequences also present a stark contrast in faunas. Cambrian and Lower Ordovician faunas predate the Great Ordovician Biodiversification Event (GOBE), a global event that saw unprecedented diversification within many major invertebrate groups (mollusks, corals, and bryozoans to name a few) that previously were only minor components of the marine fauna. Unfortunately, the much higher diversity of Middle and Upper Ordovician faunas wrought by the GOBE is somewhat muted in this region by the stresses introduced by conversion of the Appalachian shelf into a flysch basin. Another noteworthy difference between the Cambrian and Ordovician biota related to the paleogeographic setting of the rocks to be examined on this trip derives from their evolution in the shallow marine environments of Laurentia. Several shelf-wide extinctions decimated the shallow marine faunas of the Laurentian shelf through the late Cambrian producing stage-level biostratigraphic units known as biomeres. The biomere phenomenon is discussed in this guidebook and a few stops to examine Cambrian faunas and one biomere boundary extinction are included to provide contrast with stage boundary extinctions that occurred later, in the Ordovician, that lack the defining attributes of the biomere boundary extinctions. Again, it's all about contrast.

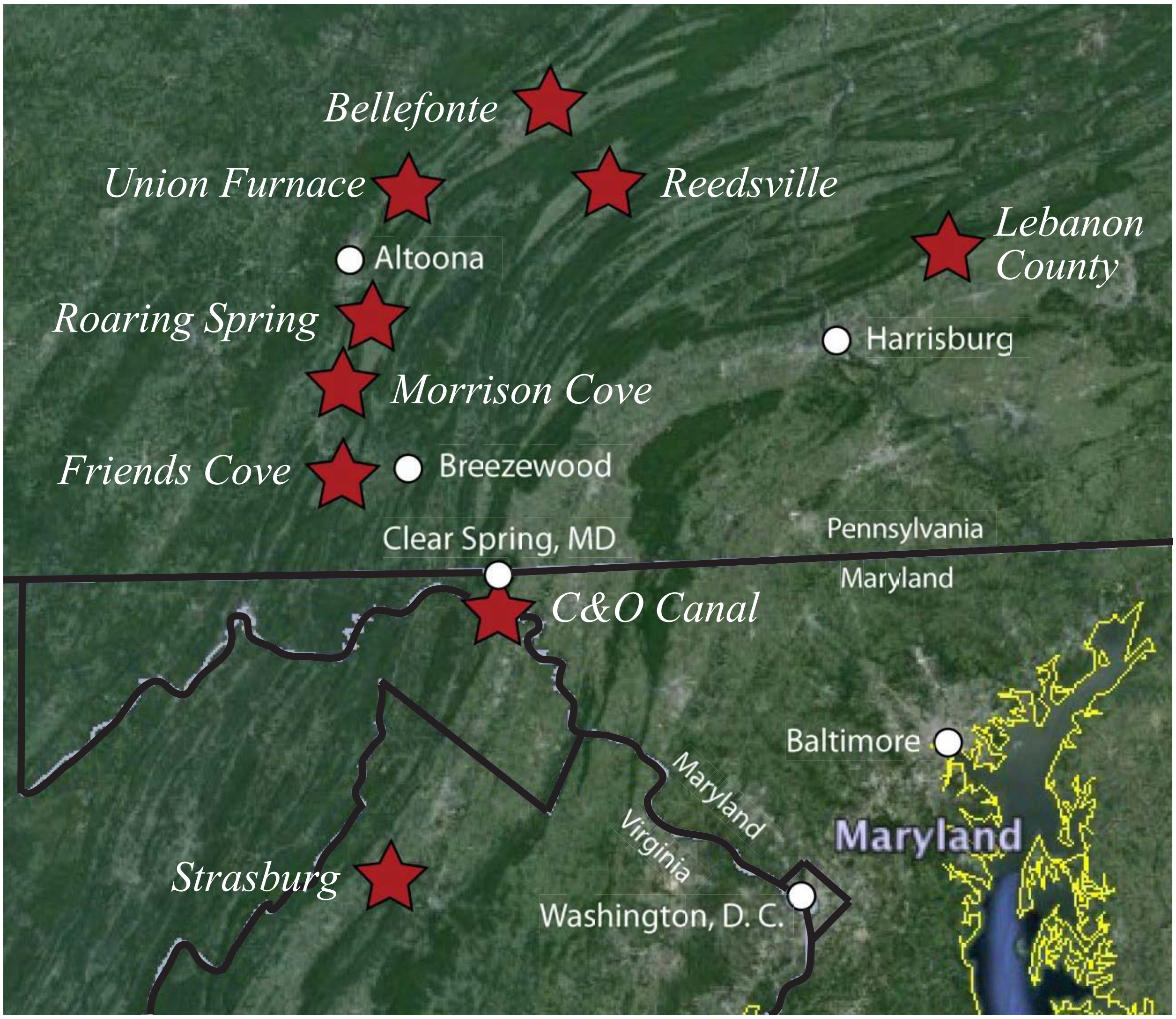


Figure 0-1: Modified Google Earth image the Central Appalachians showing areas (stars) to be visited on the field trip.

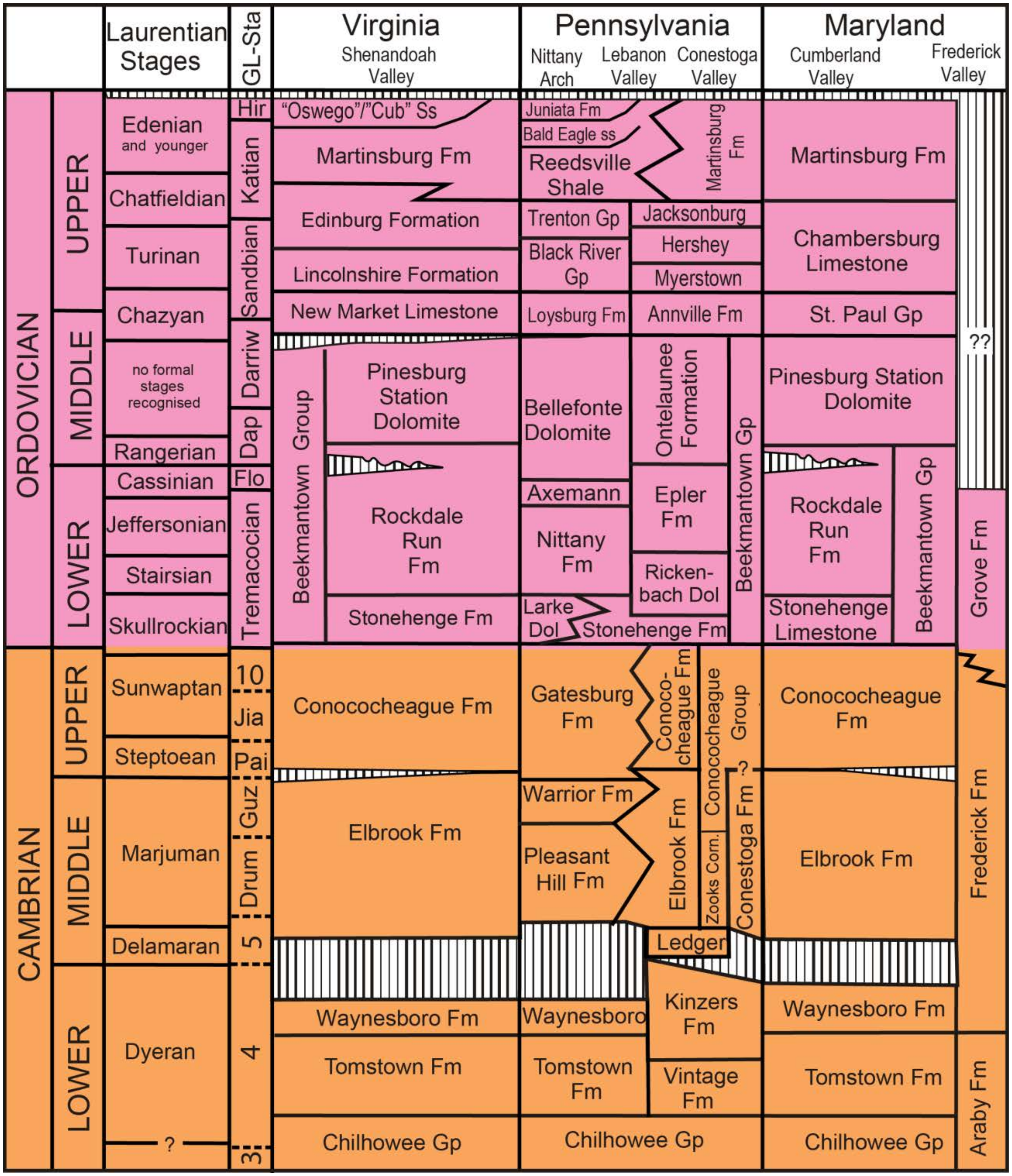


Figure 0-2: Lithostratigraphic units recognized in the central Appalachian region and their positions within both Laurentian and global chronostratigraphy. Vertical lines indicate unconformities including the prominent Knox Unconformity at the top of the diagram. After Brezinski *et al.* (2012). Abbreviations: Dap - Dapingian, Darriw - Darriwilian, Flo - Floian, Guz – Guzhangian, Hir - Hirnantian, Jia - Jiangshanian, Pai – Paibian.

Figure 0-3: Delegate photograph for the 12th International Symposium on the Ordovician System Post-meeting field trip at Dam 5 on the Chesapeake and Ohio (C&O) canal with Conococheague Formation in the background. Symposium and trip leaders: A – Steve Leslie, B- John Taylor, C – John Repetski, D – Bob Ganis, and E – Chuck Mitchell. Photograph contributor: F – Adrian Popp. June 13, 2015.

Reference

Brezinski, D.K., Taylor, J.F., and Repetski, J.E., 2012, Sequential development of platform to off-platform facies of the great American carbonate bank in the central Appalachians, p. 383–420. *In* Derby, J. R., Fritz, R. D., Longacre, S. A., Morgan, W. A, and Sternbach, C. A., eds., The Great American Carbonate Bank: The Geology and Economic Resources of the Cambrian –Ordovician Sauk Megasequence of Laurentia. American Association of Petroleum Geologists Memoir 98.

Chapter 1: Furongian and Ordovician units of the Shenandoah Valley, Virginia

John F. Taylor, Charles E. Mitchell, Randall C. Orndorff, and John E. Repetski

Introduction

The first day of the field trip (Figure 1-1) will be spent primarily examining active margin, Middle and Upper Ordovician carbonates and the fine-grained clastics that were deposited on top of them as the Taconic orogeny converted the region from shallow marine platform to deep marine flysch basin. However, one stop (Stop 1-2) will allow participants to see some well-developed peritidal cycles in the Furongian Conococheague Formation, which was deposited near the seaward edge of the Appalachian carbonate shelf while it was still a passive margin setting. Stop 1-1 is the well studied Tumbling Run section just south of Strasburg, Virginia, where the entire Middle and Upper Ordovician carbonate succession is exposed from its sharp basal contact with dolomite at the top of the underlying Beekmantown Group to its intercalated boundary with the calcareous Stickley Run Member at the base of the overlying Martinsburg Formation. Stop 1-3 at the type section of the Oranda Formation in the outskirts of Strasburg will afford an opportunity to closely examine this package of inter- fine-grained (but highly fossiliferous) limestone and black shale that directly overlies the Edinburg Formation. Significant new information on the age and correlation of these rocks provided by tephrochronology and geochemical analysis of the numerous bentonite beds in this interval will be discussed at that last stop of the day.

Stop 1-1: Tumbling Run measured section of Middle and Upper Ordovician active margin carbonates of the New Market, Lincolnshire, and Edinburg formations. Co-ordinates: Latitude 38° 58' 53" N; Longitude 78° 23' 34" W.

This outcrop is among the sites most frequently visited by geology classes in eastern North America, in part, because it was described in splendid detail by Fichter and Diecchio (1986) as Locality 16 in volume 6 of the Centennial Field Guide series prepared as part of the of the Geological Society of America's Decade of North American Geology (DNAG). Two of their figures are included here as Figures 1-2 and 1-4. The former presents not only the stratigraphic units represented at the Tumbling Run section, but also equivalent units to the west at Brock's Gap at the western edge of the Great Valley thrust sheet and to the east in sections deposited in deeper environments farther into the Martinsburg shale basin. The latter (Figure 1-4) is a detailed field sketch of the outcrop with formation boundaries and other significant features (e.g. K-bentonite beds) identified to facilitate a self-guided tour of the outcrop. The detailed lithologic information provided for each unit not only enables the reader to discriminate the three formations exposed here in their entirely; it also is used to relate the lithofacies exposed here to the environments that succeeded one another over time, as progressively deeper environments along the carbonate ramp advanced westward to occupy the area that is now the Shenandoah Valley. A second, informative color figure of the outcrop and inferred environments along the carbonate ramp and proximal portions of the shale basin was prepared for the trip by R. C. Orndorff and is included here as Figure 1-3.

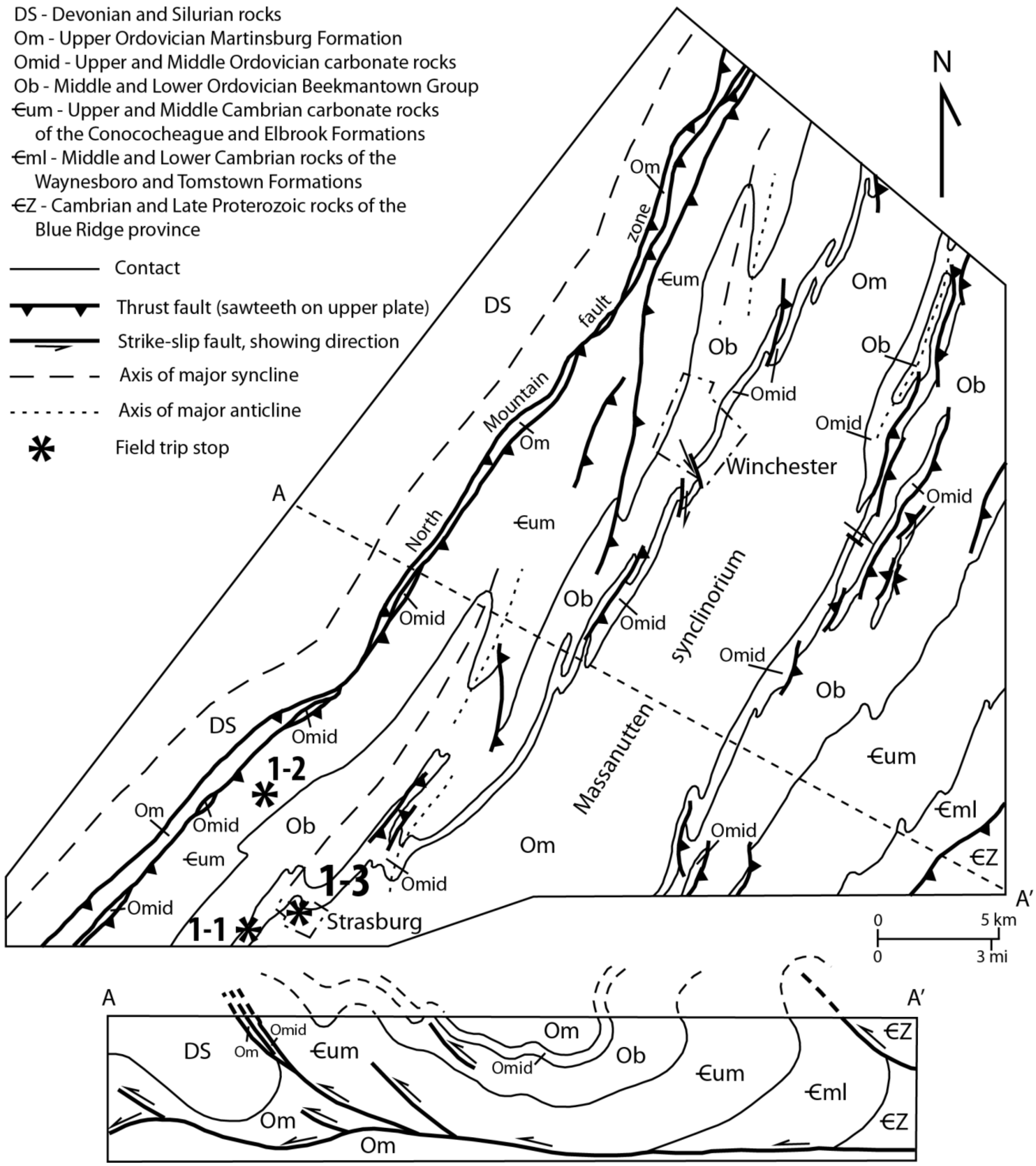


Figure 1-1: Portion of 1:100,000 geological map of the northern Valley and Ridge region in Virginia showing the location of sites discussed in the text. Modified from Rader (1996).

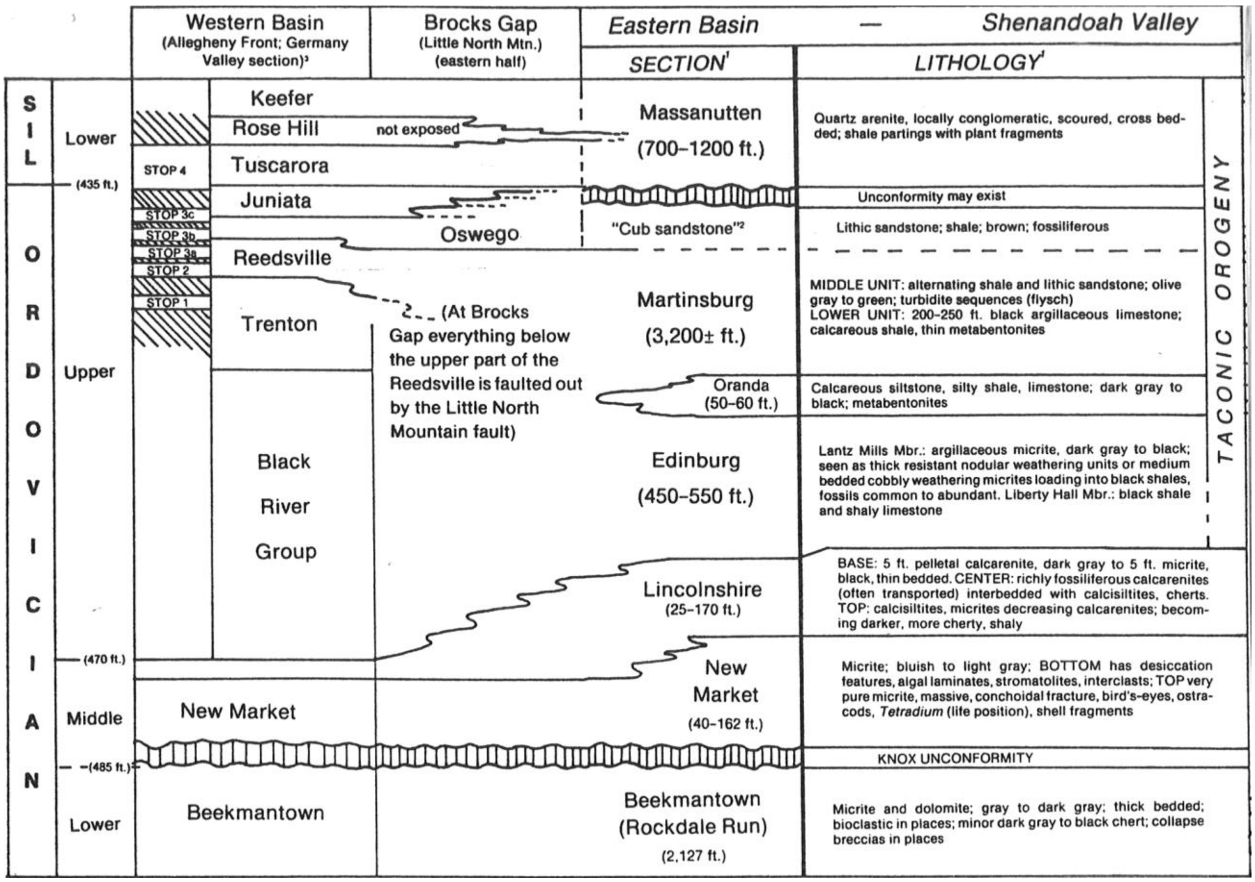


Figure 1-2: Correlation chart from Fichter and Diecchio (1986, fig.2) showing the stratigraphic relations among the Ordovician and basal Silurian lithostratigraphic units across the Shenandoah Valley.

With these figures in hand, one should have little difficulty recognizing the massive, pure limestone of the New Market Limestone just east of the bridge over Tumbling Run, the chert-rich and darker Lincolnshire Formation above it, and the superjacent Edinburg Formation by its distinctive cobbly weathering, a feature produced by soft-sediment deformation induced by the considerable amount of siliciclastic clay that was being fed into the basin from the east as the Taconic orogeny got well underway. The Edinburg is famous for its silicified trilobite fauna (Whittington and Evitt, 1954) and a few silicified sclerites might still be found on loose blocks found in the talus at this stop. The sharp contact between the New Market Limestone and underlying Beekmantown Group dolomites is near stream level below the bridge on the north side of the road.

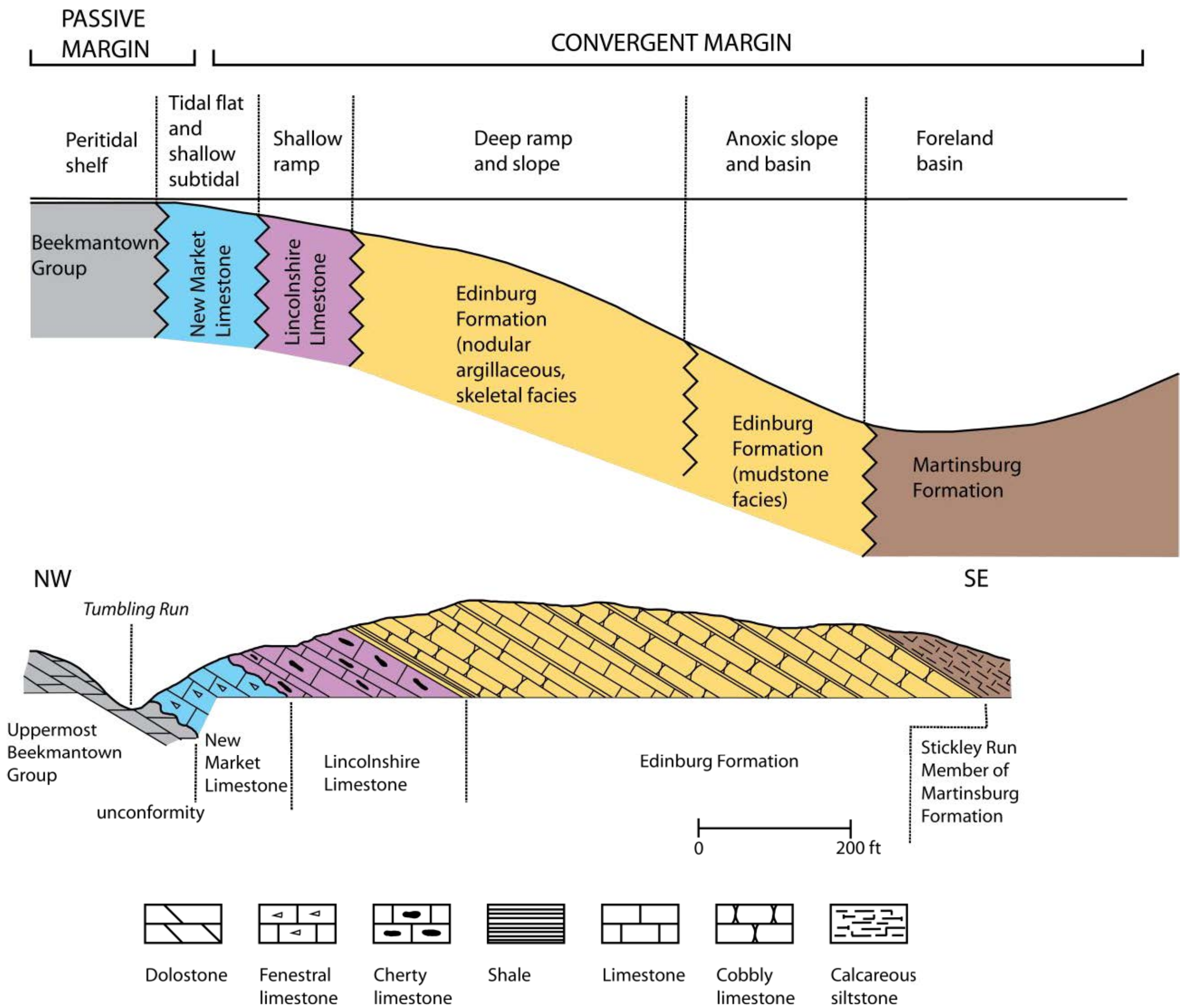
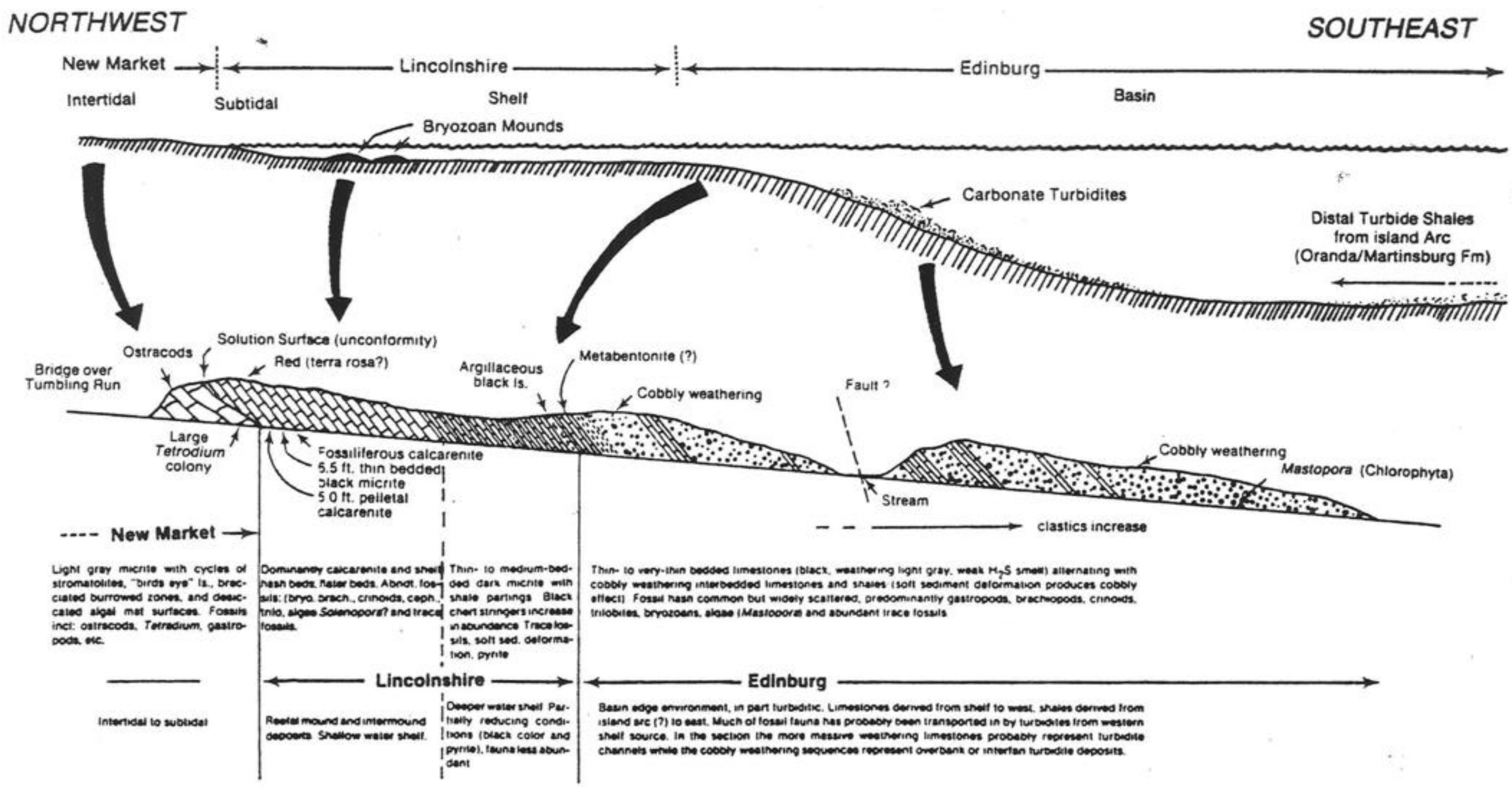


Figure 1-3: Simplified profile of the units exposed at Tumbling Run (Stop 1-1) and interpreted environmental settings in which they originated (prepared by R.C. Orndorff).

Facing page:

Figure 1-4: Detailed sketch of the outcrop at Tumbling Run (Stop 1-1) showing the Middle and Upper Ordovician units exposed there and their inferred positions on the carbonate ramp that bordered the Martinsburg basin. From Fichter and Diecchio (1986, fig. 5).



NORTHWEST
SOUTHEAST
New Market
Lincolnshire
Edinburg
Intertidal
Subtidal
Shelf
Basin
Bryozoan Mounds
Carbonate Turbidites
Distal Turbide Shales from island Arc (Oranda/Martinsburg Fm)
Bridge over Tumbling Run
Ostracods
Solution Surface (unconformity)
Red (terra rosa?)
Argillaceous black ls.
Metabentonite (?)
Cobbly weathering
Fault ?
Large Tetrodium colony
Fossiliferous calcarenite
5.5 ft. thin bedded black micrite
5.0 ft. pelletal calcarenite
Stream
Cobbly weathering
Mastopora (Chlorophyta)
clastics increase
New Market
Light gray micrite with cycles of stromatolites, "birds eye" ls., brecciated burrowed zones, and desiccated algal mat surfaces. Fossils incl: ostracods, Tetradium, gastropods, etc.
Dominantly calcarenite and shell hash beds, flaser beds. Abndt. fossils: (bryo. brach., crinoids, ceph., trilo, algae Solenopora? and trace fossils.
Thin- to medium-bedded dark micrite with shale partings. Black chert stringers increase in abundance. Trace fossils, soft sed. deformation, pyrite
Thin- to very-thin bedded limestones (black, weathering light gray, weak H2S smell) alternating with cobbly weathering interbedded limestones and shales (soft sediment deformation produces cobbly effect). Fossil hash common but widely scattered, predominantly gastropods, brachiopods, crinoids, trilobites, bryozoans, algae (Mastopora) and abundant trace fossils
Lincolnshire
Edinburg
Intertidal to subtidal
Reefal mound and intermound deposits. Shallow water shelf.
Deeper water shelf. Partially reducing conditions (black color and pyrite), fauna less abundant
Basin edge environment, in part turbiditic. Limestones derived from shelf to west, shales derived from island arc (?) to east. Much of fossil fauna has probably been transported in by turbidites from western shelf source. In the section the more massive weathering limestones probably represent turbidite channels while the cobbly weathering sequences represent overbank or interfan turbidite deposits.

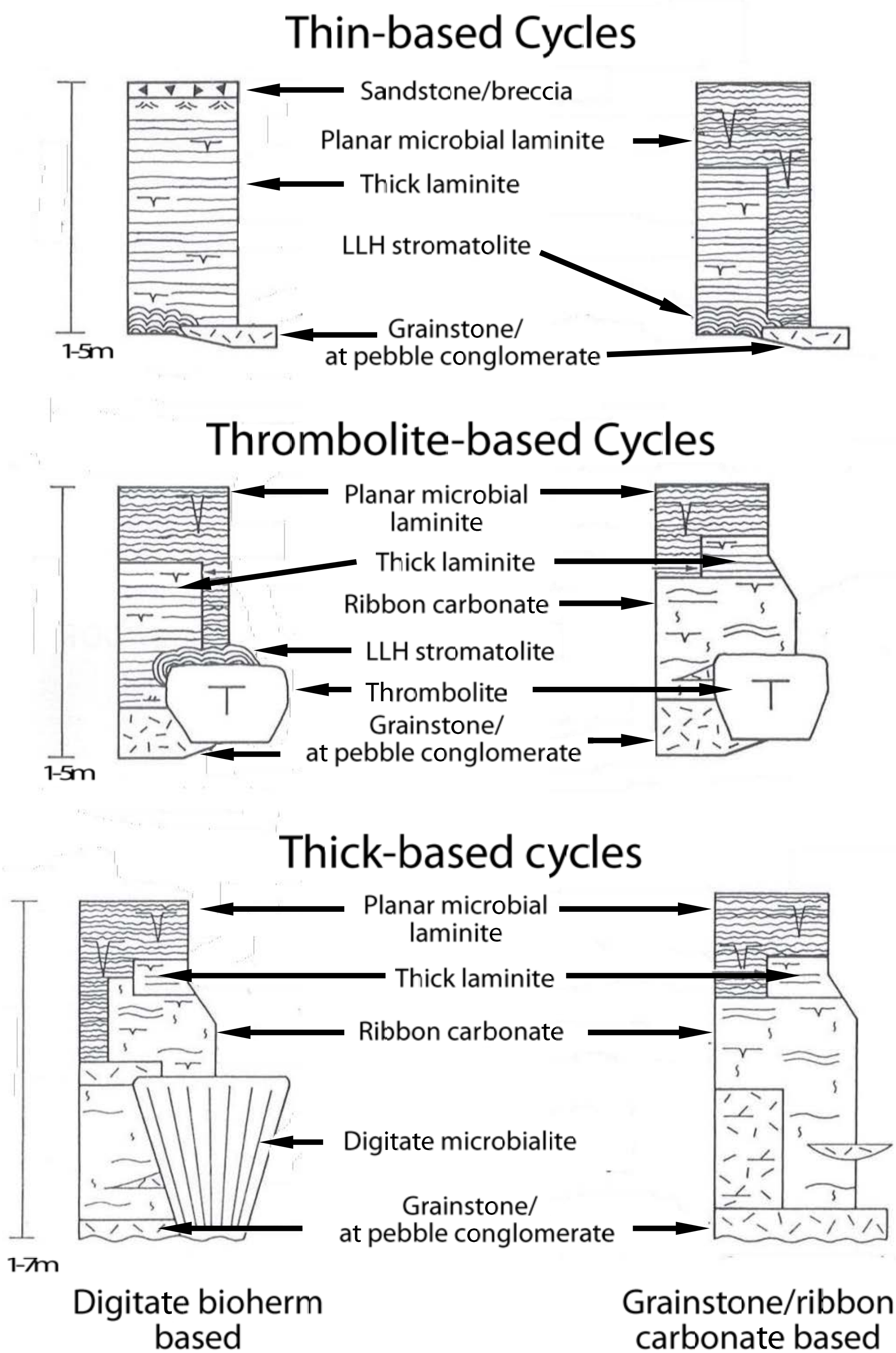


Figure 1-5: Anatomy of upward-shoaling, meter-scale cycles in the Conococheague Formation (modified from Koerschner and Read, 1989).

Stop 1-2: Virginia Route-55 outcrop of cyclic peritidal carbonates of the Furongian Conococheague Formation.
Co-ordinates: Latitude 39° 2' 11" N; Longitude 78° 22' 58" W.

Sea level oscillations of varying magnitude left their record in early Paleozoic carbonates deposited in settings sufficiently shallow to bundle shallow subtidal, intertidal, and supratidal facies in upward shoaling cycles. The broad rim that persisted at the outer margin of the Appalachian shelf through the Furongian was such a setting and the conspicuously cyclic rocks of the Conococheague Formation have been the focus of numerous studies in cyclostratigraphy (e.g. Koerschner and Read, 1989; Osleger, 1991a, 1991b). The vast majority of the Conococheague cycles are capped by supratidal planar microbial laminite. However, the 5th order (meter-scale) cycles that abound in this formation vary considerably in thickness, composition, and architecture that all depended on where within the larger/longer term (4th and 3rd order) cycles they were deposited. Figure 1-5, modified from a figure in an exceptionally thorough and grounded treatment of sedimentary cycles by Koerschner and Read (1989), shows some of that variation. The cycles seen here at Stop 1-2 are "thick-based" cycles as described in that paper with thrombolitic reefs at the base and prominent ribbon carbonate (thinly interbedded limestone and dolomite) in the middle of the cycle.

The position of this exposure within the stratigraphically lower part of the outcrop band of the Conococheague suggests that these strata are lower Furongian, but poor exposure of the carbonates in the Shenandoah Valley coupled with faults that often are concealed by cover makes that a risky interpretation. Virtually identical cyclic strata occur at many levels within the thick (500-700 m) Conococheague Formation, making it that much more difficult for mappers to establish the accurate position within the formation for isolated outcrops. Fortunately, the trilobites that inhabited the outer shelf environments where the Conococheague formed evolved rapidly through the Furongian, rendering their remains useful for discriminating different parts of the formation (Taylor *et al*., 2009; Brezinski *et al.,* 2012). The genus *Plethopeltis*, in particular, is represented by a series of different, fairly short ranging species that record rapid evolution in the outer shelf microbial reefs that they inhabited in this region (Figure 1-6). There are at least four intervals in the Conococheague where increased accommodation, provided by 3rd order transgressions that also left their mark in other sedimentary basins, produced thick thrombolitic reef complexes. These reef-rich packages have been numbered from bottom to top and referred to as Thrombolite I through Thrombolite IV and each has its own unique trilobite fauna. This will be discussed in greater length on Day 2 in the Cumberland Valley in Maryland.

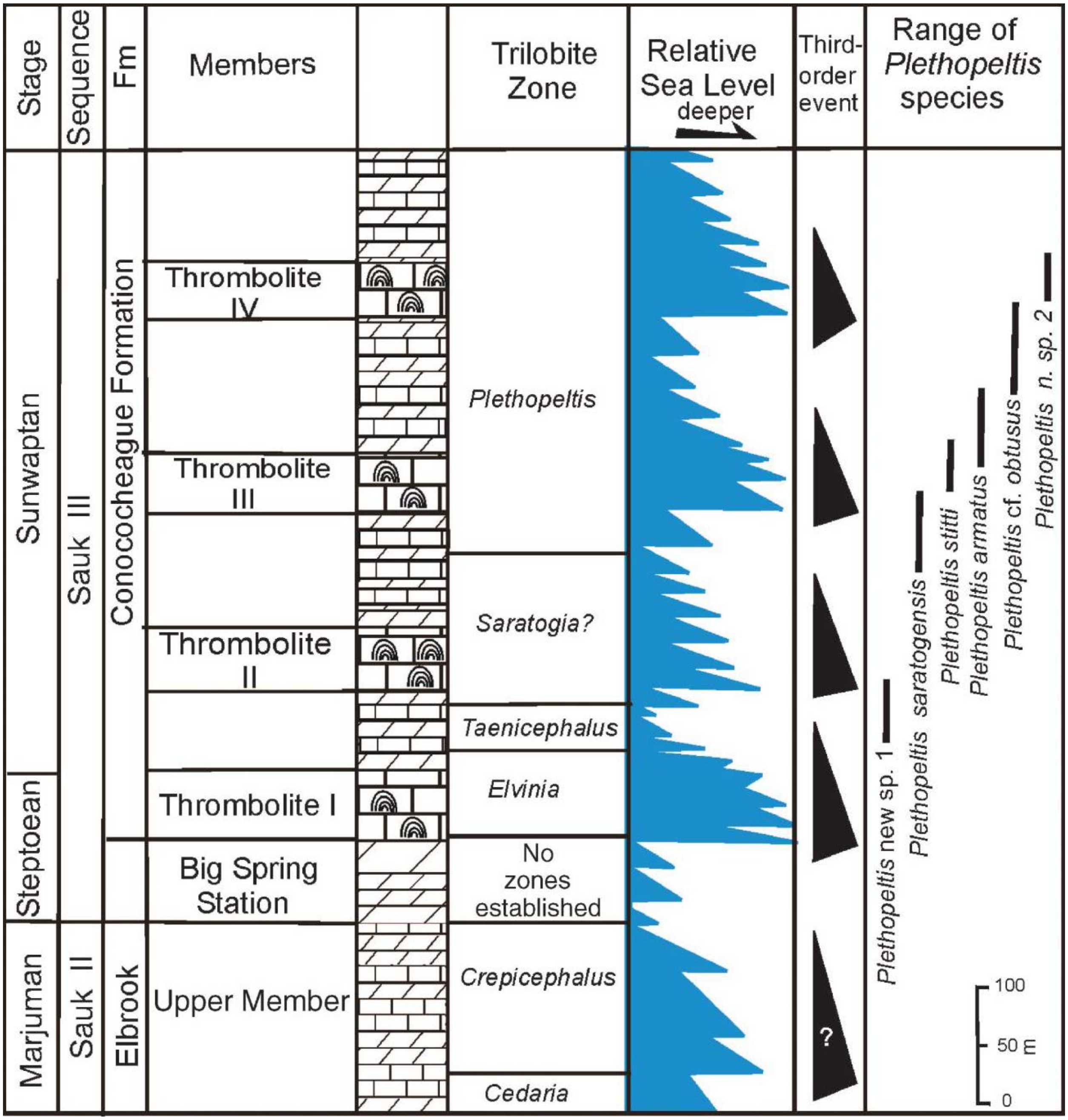


Figure 1-6: Thrombolitic reef packages and 3rd order cycles in the Conococheague Formation in relation to stratigraphic ranges for *Plethopeltis* species (Brezinski *et al.*, 2012).

Stop 1-3 Oranda Formation type section, Virginia Route-55, west edge of Strasburg, Virginia.
Co-ordinates: Latitude 38° 58’ 53” N; Longitude 78° 23’ 34 W.

Charles E. Mitchell, Bryan Sell, Stephen A. Leslie, and Daniel Goldman.

Route-55 section. The hillsides and road cuts around Strasburg in the northern end of the Shenandoah Valley of northeast Virginia provide a number of exposures of the early Late Ordovician succession in this region (Figure 1-1).

The main outcrop forms a small bluff that extends for ~120 m along the north side of the Route-55 between Colley Block Road and Frontier Fort Lane. An additional ~ 100 m long section of intermittently exposed greywackes and calcareous shales crops out east of Frontier Fort Lane (Figure 1-2). This section spans a late Sandbian, upward-deepening, active margin carbonate succession (Edinburg and Oranda Formations) that was smothered by black shales and turbidite-dominated, basin fill (Martinsburg Formation). The succession records the expansion of the Taconic foreland basin and the local arrival of sediments from the accreted terranes of the Taconic orogenic belt to the east. The carbonates bear a succession of diverse shelly and sparse conodont faunas, whereas graptolites are the main fossils that occur in the Martinsburg Formation. Numerous K-bentonites occur within these units as well.

The strata maintain a northeast strike within the section. Beds within the Oranda Formation are steeply overturned, but dips in the overlying, relatively plastic Martinsburg Formation range from steeply easterly to vertical or steeply westward in most of the exposure. Cleavage is well developed at this locality, particularly in the shaly rocks, and generally strikes north-northeast and dips consistently westward at 35-60°. The resulting intersection with bedding makes large slabs nearly impossible to collect here and the rocks split poorly. Macrofossils are significantly deformed.

Lithostratigraphy. The upper part of **Edinburg Formation** (St. Luke Limestone Member) forms the base of the section at the western (uphill) end of the exposure. These strata are about 15 m thick and strike N45°E, are overturned, and dip steeply to the east. The Edinburg Formation is more completely exposed along the Tumbling Run section (Stop 1-1) and is not described here in detail. The St. Luke Limestone Member at the present site consists mainly of wackestone and fenestral lime-mudstone (dismicrite) that most likely represent deposition in protected shelf to mud-flat environments (Rader and Read, 1989). The unit bears two K-bentonites (each ~ 8 cm thick) near the top of the formation, at 13.7 and 14.6 m above the base of the exposure (Figure 1-7).

The **Oranda Formation** (Cooper and Cooper, 1946) overlies the Edinburg Formation and marks a strong deepening accompanied by an influx of clastic sediments. The Oranda Formation here is 18.3 meters thick and is mainly an interbedded succession of black, argillaceous wackestone and lime-mudstone with thin, black to dark gray, calcareous shale and siltstone with minor packstone and fine grainstone (calcisiltite). The wackestone is commonly irregularly bedded to nodular and all but the calcisiltite and siltstone bear common benthic macrofossils. Brachiopods are common (e.g., *Christiania, Bimuria, Leptaena, Orthambonites, Oxolecia, Resserella, Reuschella, Sowerbyella*) and are frequently accompanied by bryozoans (esp. *Prasopora*) and trilobites (e.g., *Cryptolithus, Bumastus, Illaenus, Encrinurus* [Cooper and Cooper, 1946; Craig, 1949]). Articulated *Echinosphaerites* specimens, as well as echinoderm debris, are common at some levels in this unit.

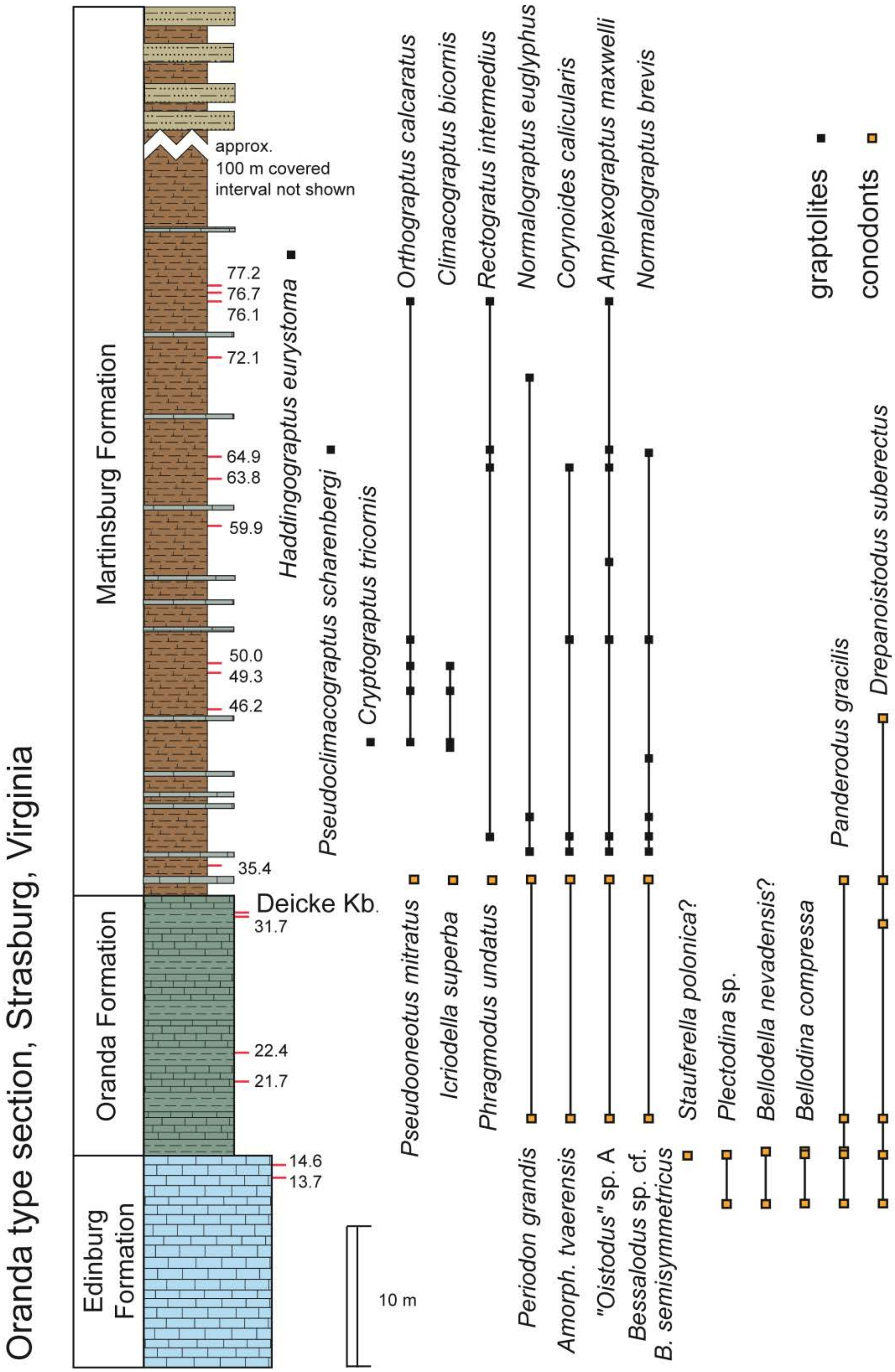


Figure 1-7: Oranda Formation type section along Virginia Route-55. Columnar diagram showing location of lithological units, K-bentonites, and biostratigraphic samples, including graptolite and conodont species ranges.

The Oranda Formation at this locality also includes four prominent K-bentonites. Two approximately 15 cm-thick beds occur about 0.5 m apart at 6.7 and 7.4 meters above the base of the unit (Figure 1-8). The second pair occurs at 1.3 and 1.6 m below the top of the formation. Geochemical analysis of phenocrysts confirms that the highest of these, which forms a prominent 30 cm-wide reentrant, is the widespread **Deicke K-bentonite** (Adhya, 2009; Kolata *et al*., 1996; Sell *et al*., 2015). Sediments beneath these altered volcanic ash beds are heavily silicified, presumably from silica liberated from the glassy ash as it underwent alteration to illite-smectite clays.

The contact with the overlying Martinsburg Formation is gradational and is picked at 33.3 m in the measured section of Rader and Read (1989). Epstein *et al.* (1995) emphasized this gradational feature and the regional differences in the facies expression of the unit and recommended including most of the Oranda Formation within their newly proposed Stickley Run Member of the Martinsburg Formation. They transferred the lower part of the unit to the underlying Edinburg Formation and drew the base and the top of the Stickley Run Member at the lowest siltstones and the highest limestone of 1 inch or greater thickness, respectively. Rader *et al.* (1996) adopted this recommendation on their 1:100,000 scale map of the region.

The **Martinsburg Formation** is typically a very thick unit (following the usage of Cooper and Cooper, 1946). Only the lower 50 m are exposed in this section. The true depositional thickness of the Martinsburg Formation is poorly constrained because the unit invariably contains the roof-thrust zone of the main Alleghanian duplex thrust belt. While Rader and Read (1989) estimated a thickness of 850 m, Epstein *et al.* (1995) estimated that the present thickness might approach 2000 m based on their regional mapping observations.

In general terms the Martinsburg Formation, as recognized in northern Virginia, consists of three divisions:

1) a lower, calcareous, black shale and interbedded carbonate turbidite unit of perhaps 90 m in thickness (essentially the Stickley Run Member of Epstein *et al.* [1995] minus the rocks included above in the Oranda Formation);

2) a vast middle division that is an interbedded succession of greywacke turbidites and silty mudstone with minor limestone turbidites; and

3) an upper division (known informally as the "Cub sandstone") that is dominantly medium to thick-bedded greywacke with common hummocky cross-stratification and fossiliferous brown mudstone (Fichter and Diecchio, 1986).

The middle turbiditic unit is commonly considered to have been deposited as part of a submarine fan system that eventually filled the available accommodation space in the Taconic foreland basin (Diecchio, 1993). Both upsection and laterally these strata pass into storm-dominated, clastic shelf environs that rimmed the basin. To the north and northwest in Pennsylvania the laterally equivalent shelf clastics are referred to as the Reedsville Formation and to the west and southwest in Virginia and Tennessee the laterally equivalent shelf strata are referred to as the Dolly Ridge Formation or Martinsburg Formation (Diecchio, 1985; Kreisa, 1981; Kreisa and Springer, 1987). The Oswego and Juniata Formations in Pennsylvania are the lateral equivalent of the sand-dominated "Cub sandstone" of northern Virginia and West Virginia (Fichter and Diecchio, 1986).

The highly argillaceous carbonates that form the transitional boundary between the upper Oranda beds and the dominantly laminated black shale of the lower Martinsburg are especially rich in the trilobites *Cryptolithus* and *Isotelus* along with abundant *Sinuites*. Brachiopods, in contrast, are essentially absent. Graptolites are common in the black shales where they are accompanied by phylocarid debris, orthoconic cephalopods, and rare scattered shelly material. Although fossils are rare in the turbiditic middle member, sandstone beds of the upper part of the middle unit and the "Cub sandstone" commonly contain transported shelly material including a fauna suggestive of correlation with the widespread *Orthorhychula* Zone of the Reedsville Formation (Diecchio, 1985).

Bedded limestone within the calcareous shale succession is generally thin, graded calcisiltite to calcareous mudstone. Small scale, soft sediment slump structures are common in these units and suggest transport toward the north-northeast (Epstein *et al*., 1995) roughly parallel to the Martinsburg basin axis.

As noted above, the lower Martinsburg Formation in this section is strongly cleaved and is also somewhat weathered, but in-place material, including a series of at least eleven K-bentonites, can be excavated with modest effort from the main road cut section. The lower part of the middle, turbiditic member crops out farther down hill along the road, east of Frontier Fort Lane.

Biostratigraphy. The Edinburg and Oranda carbonates produce few conodonts (Figure 1-7). Leslie (1995) recovered sparse faunas indicative of the North Atlantic *Amorphognathus tvaerensis* Zone and the Laurentian Mid-continent *Phragmodus undatus* to *Plectodina tenuis* zonal interval. This assemblage is also present in a thin grainstone bed at approximately two meters above the Deicke K-bentonite, within the lowermost part of the Martinsburg Formation as traditionally defined.

A low diversity graptolite fauna dominated by *Normalograptus brevis* and *Amplexograptus maxwelli* appears near the base of the Martinsburg Formation, above the ~ 40 cm-thick K-bentonite denoted as Bed 22 in the measured section by Rader and Read (1989). *Climacograptus bicornis* occurs rarely in the lower part of the Martinsburg Formation at this site together with several other species consistent with assignment of this interval to the late Sandbian *C. bicornis* Zone. Finney *et al.* (1996) reported a similar fauna in which they also reported the presence of *Corynoides americanus*, which perhaps led Kolata *et al.* (1996) to refer this interval to the lower Katian *C. americanus* Zone. No other taxa in this assemblage support that assignment and the species that occurs here is *C. calicularis* rather than the younger species.

K-bentonite tephrochronology. Numerous altered volcanic ashes (K-bentonites) are present in the upper Edinburg to lower Martinsburg interval – a fact that has been recognized for the past century. Previous efforts to form reliable stratigraphic correlations via bar-code-like patterns of bed thickness and spacing or X-ray fluorescence spectrography failed to reliably distinguish among the many similar beds and their variable occurrences (e.g., Haynes *et al*., 1995; Mitchell *et al.*, 1994; Sell and Samson, 2011). In recent decades, however, highly accurate analytical techniques have made it possible to obtain unique geochemical fingerprints and geochronological dates from the phenocrysts contained in these altered clay beds. The K-bentonites from this section have been examined numerous times but Adhya (2009) studied them most recently based on collections made by D. Goldman, C. E. Mitchell, and M.P. Joy in the late 1990's. We summarize those results here (Figure 1-8), supplemented by further data from nearby sections (especially the Route 11, Tumbling Run, and Fishers Hill exposures) from Sell (unpublished) and Sell *et al.* (2015). The most unambiguously identifiable bed in the present succession is the widespread Deicke K-bentonite. Apatite phenocrysts from this unit exhibit a narrow spectrum of compositions and date to 452.86 ± 0.29/0.34/0.59 Ma 2σ, where these uncertainties incorporate the analytical, tracer, and decay constant errors, respectively (Sell *et al*., 2013).

Immediately below the Deicke K-bentonite there occurs an unnamed but distinctive bed that is present in this same position in Pennsylvania (at the Reedsville site described below, and at the State College/Route-322 site (Figure 1-8A) and at the Oranda type section (Figure 1-8B). At the Fishers Hill site (Figure 1-8C) the Deicke K-bentonite appears to be amalgamated with this lower unnamed bed and to occur at the top of the Oranda Formation. At our Highway 11 site (Figure 1-8D), a yet lower bed, one that occurs some 5 m below the Deicke level at Fishers Hill, occurs at the Oranda-Martinsburg contact. Thus, these K-bentonites exhibit a variable relation to lithostratigraphic succession in the region. We discuss the potential implications of that variable relation below.

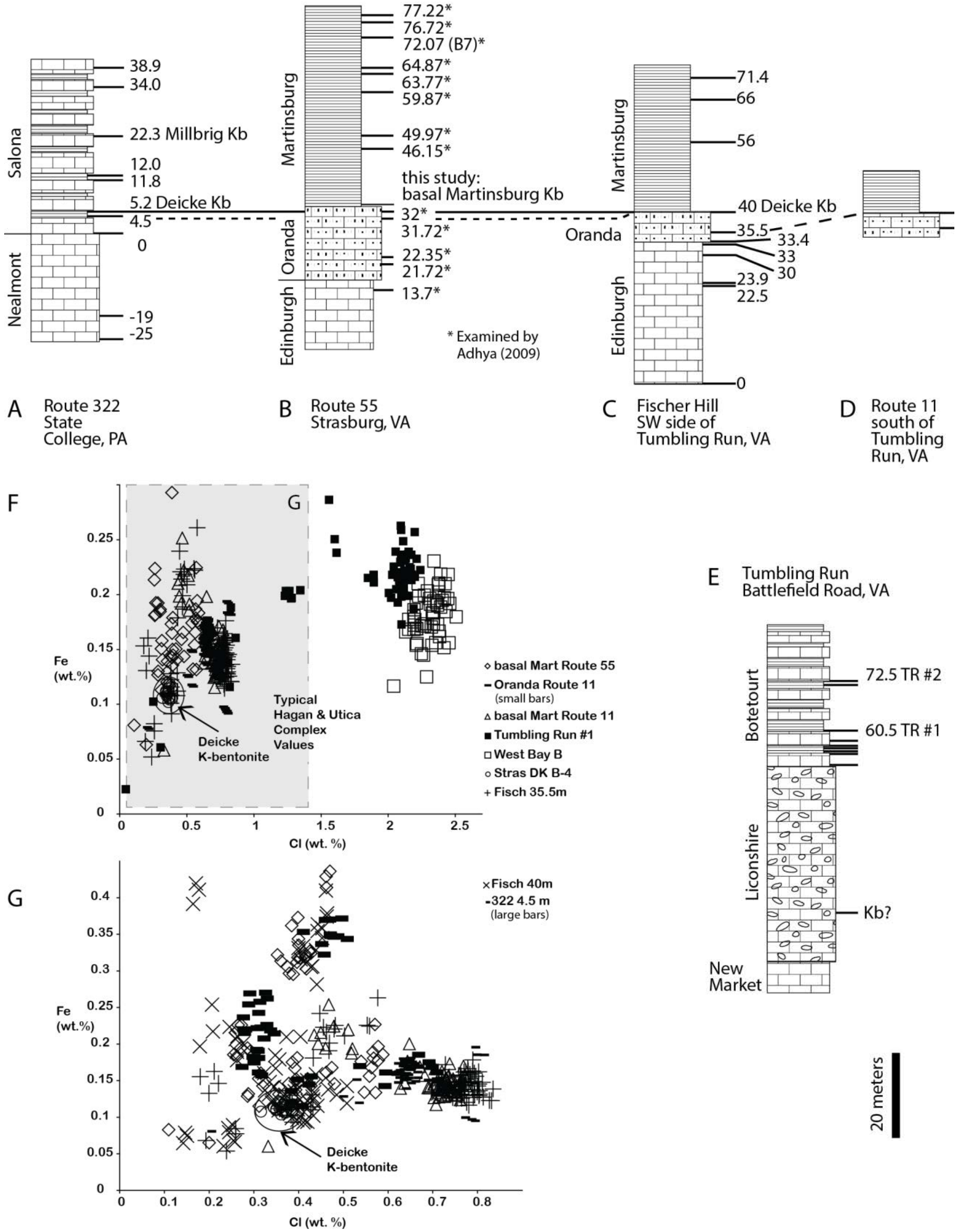
This interval spans the part of the M4 succession (Holland and Patzkowsky, 1997, 1998) that ought to include the equally widespread Millbrig K-bentonite. Bed 22 of Rader and Read (1989) at the Oranda type section has been reported to be the Millbrig K-bentonite (e.g., Kolata *et al.,* 1996; Leslie and Bergström, 1997), however, the apatite crystal chemistry does not support that contention. Rather, the apatite phenocrysts exhibit a widely scattered suite of compositions that overlaps broadly with some components of the complex Millbrig K-bentonite signature (Carey *et al*., 2009; Mitchell *et al.*, 2004) but which is not specifically identifiable (Figure 1-8F, G, "basal Martinsburg, Route-55"). It is likely that this is a redeposited unit that contains a mixture of more than one ash bed. In fact, none of K-bentonite beds in the Strasburg area sections that we have studied can be definitively identified as the Millbrig K-bentonite based on the data available to us. Unfortunately, most of the beds in these sections produce apatite phenocryst and glass compositions (inclusions in quartz) that have rather diffuse and non-distinctive signatures.

Discussion of the stratigraphic relations. We infer, from the data presented above, that the disconformable contact at the base of the Oranda Formation as defined by Cooper and Cooper (1946) may correspond to the M3-M4 sequence boundary. The Oranda Formation, therefore, is laterally equivalent to the Nealmont Formation and a portion of the Salona Formation in central Pennsylvania as well as the Tyrone Formation in Kentucky (Figure 1-9). The somewhat variable relationship between the Oranda-Martinsburg facies transition and the tephrochronology displayed among the Strasburg region sections may be interpreted in several ways. One possibility is that the carbonate interbeds in this interval are laterally discontinuous and that the formation boundary is rather arbitrary, as Epstein *et al.* (1995) emphasized. If this were indeed the case, it would support their conclusion that the two units form part of a continuous depositional succession, which they recognized as their Stickley Run Member of the Martinsburg Formation. Alternatively, the fact that the Millbrig K-bentonite appears to be missing locally and that the lowermost K-bentonite of the Martinsburg Formation differs among sections suggests that the boundary interval marks either a subtle disconformity or an interval of strong condensation. In that case, this interval may include a sedimentologically significant surface, such as the M4 maximum flooding surface, that merits the retention of the Oranda and Martinsburg formations as separate units. The latter interpretation is supported by the appearance of *Climacograptus bicornis* Zone graptolites in that same interval. Structural omission resulting from displacement between the more competent Cambrian - Ordovician carbonate succession and the relatively plastic Martinsburg clastic succession is a third, and not mutually exclusive, possibility. A major detachment zone is widely developed in central Pennsylvania near the contact between the Coburn Formation at the top of the Cambrian - Ordovician carbonate succession and the overlying Antes-Martinsburg shales (Nickelsen, 1996). Further sedimentological and structural research will be required to test these alternatives. Thus, we prefer to retain the Oranda and Martinsburg Formations as distinct units and, thereby, to continue to focus attention on this set of interesting geological questions.

Facing Page

Figure 1-8: Tephrochronology of the late Sandbian strata of the Strasburg, VA region.

- **A**) Road cut exposure along Route-322 – Nittany Highway at State College, Pennsylvania (latitude 40.796874° N; longitude 77.821914° W).
- **B**) Oranda type section, Virginia Route 55, Strasburg, Virginia (latitude 38.996760°; longitude. -78.361862°).
- **C)** Abandoned road cut along Fishers Hill, above south bank of Tumbling Run, across from Battlefield Road (latitude 38.970372° N; longitude 78.389173° W).
- **D**) Short road cut on west side of southbound lane, Highway 11, south of Tumbling Run, Virginia (latitude 38.976178° N; longitude 78.392656° W).
- **E**) Battlefield Road cut section along north shore of Tumbling Run, Virginia (latitude 38.981193° N; longitude 78.391972° N), the Botetourt Member is the relatively shaly, lowermost member of the Edinburg Formation.
- **F)** Plot of iron and chlorine content of apatite from a set of beds collected at the above sections as well as a similar (but much older) bed from the mid Darriwilian Table Point Formation, West Bay Centre Quarry, Western Newfoundland, for comparison with the unusual Tumbling Run#1 K-bentonite bed obtained in the lower Edinburg (Botetourt Member) at site E - Battlefield Road.
- **G**) An enlargement of the shaded region of typical Hagan Complex compositions. Apatites from the Deicke K-bentonite form a relatively tight cluster enclosed by the labeled circle, whereas all of the other sampled beds in this set contain several discrete or diffuse clusters of compositions and exhibit substantial overlap in compositions.



Salona
Nealmont
38.9
34.0
22.3 Millbrig Kb
12.0
11.8
5.2 Deicke Kb
4.5
0
-19
-25
Martinsburg
Oranda
Edinburgh
77.22*
76.72*
72.07 (B7)*
64.87*
63.77*
59.87*
49.97*
46.15*
this study:
basal Martinsburg Kb
32*
31.72*
22.35*
21.72*
13.7*
* Examined by Adhya (2009)
71.4
66
56
40 Deicke Kb
35.5
Oranda
33.4
33
30
23.9
22.5
0
A Route 322 State College, PA
B Route 55 Strasburg, VA
C Fischer Hill SW side of Tumbling Run, VA
D Route 11 south of Tumbling Run, VA
F
G
Fe (wt.%)
Cl (wt. %)
Typical Hagan & Utica Complex Values
Deicke K-bentonite
basal Mart Route 55
Oranda Route 11 (small bars)
basal Mart Route 11
Tumbling Run #1
West Bay B
Stras DK B-4
Fisch 35.5m
E Tumbling Run Battlefield Road, VA
Botetourt
Liconshire
New Market
72.5 TR #2
60.5 TR #1
Kb?
20 meters
Fisch 40m
322 4.5 m (large bars)

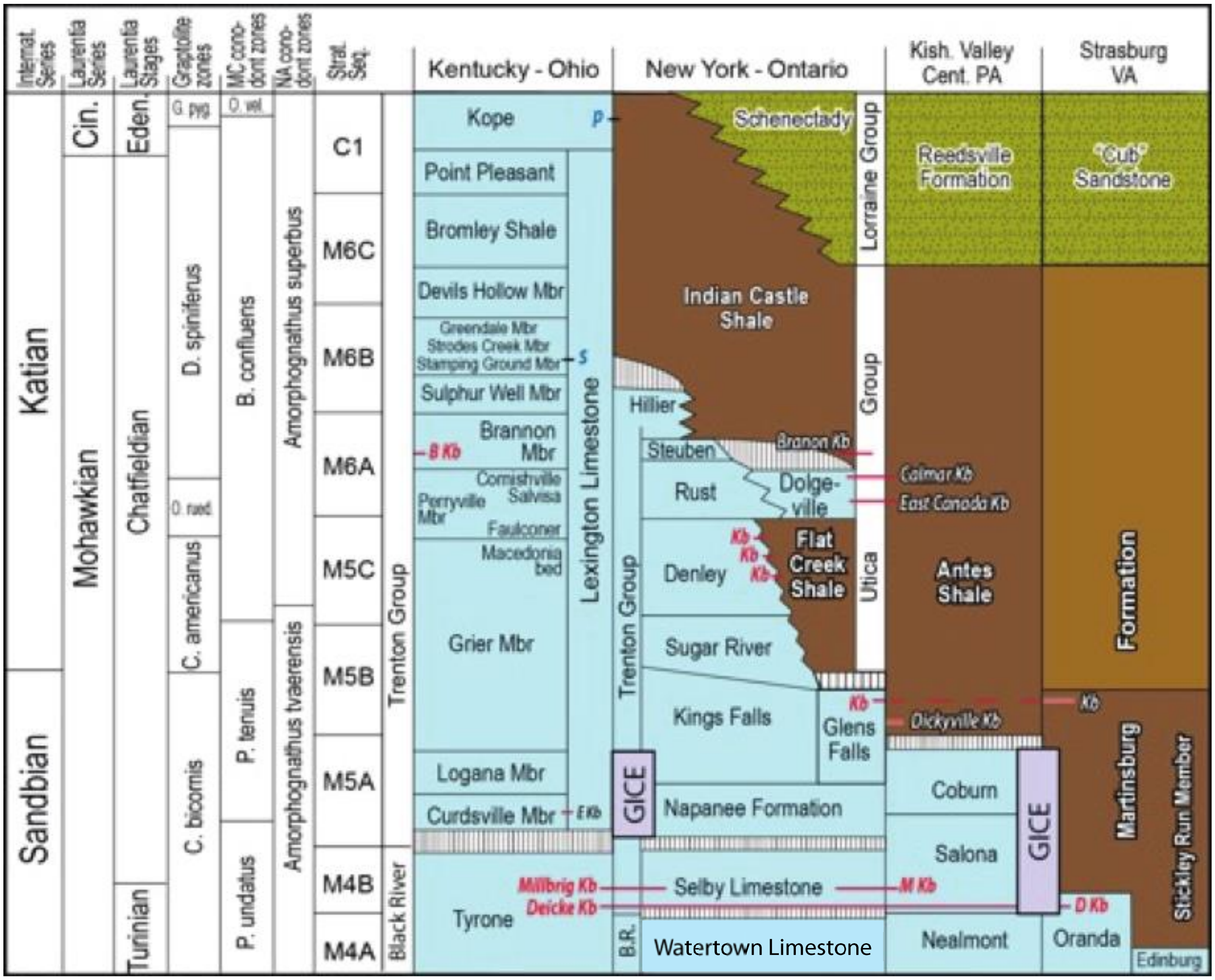


Figure 1-9: Chronostratigraphic correlation of the Late Ordovician strata of the Appalachian Valley and Ridge Province sites in northern Virginia and central Pennsylvania visited on this field excursion with the standard reference successions of the Mohawkian Series of Laurentia in Kentucky and New York. Abbreviation: GICE - the positive Guttenberg carbon isotopic excursion. Modified from Sell *et al.* (2015).

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Chapter 2: Furongian and Tremadocian platform carbonates of the Cumberland Valley and southernmost Nittany Arch

John F. Taylor, James D. Loch, John E. Repetski, and David K. Brezinski

Introduction

During the latest Cambrian and earliest Ordovician, the central Appalachian segment of the Great American Carbonate Bank (GACB) was a rapidly subsiding rimmed shelf (Demicco, 1985; Read, 1989; Brezinski e*t al*., 2012), whose seaward margin experienced deposition of cyclic, peritidal carbonates that now compose the Conococheague Formation in the Shenandoah and Cumberland valleys. The coeval Gatesburg Formation to the west in the Nittany Arch of Pennsylvania formed simultaneously near the inner margin of the GACB, and records the alternation of clastic- and carbonate-dominated facies of the inner detrital belt and carbonate bank, respectively. Both formations have received considerable attention as well-preserved archives of latest Cambrian sea level history. Prominent 5th order (meter-scale), upward shoaling cycles characterize these units and display distinct stacking patterns that allow recognition of longer-term, 4th and 3rd order transgressions and regressions. These strongly influenced not only the relative abundance of subtidal versus inter/supra-tidal lithologies in various parts of the Conococheague, but also proportions of siliciclastic versus carbonate rock types within five members discriminated in the Gatesburg (Figure 2-3). Several third-order transgressions that occurred during the latest Cambrian (Furongian) are presented in the Conococheague Formation as intervals characterized by thick (meter-scale) thrombolitic microbial reefs and other associated subtidal lithologies. Conversely, several intervals within the Conococheague with abundant dolomitic planar microbial laminite and some sandstone formed during significant (2nd and 3rd order) latest Cambrian regressions. The four transgressive packages with abundant thrombolitic reefs are referred to informally as Thrombolite I through Thrombolite IV, in ascending order. As discussed at Stop 1-2, the four physically indistinguishable thrombolite intervals within the Conococheague can be discriminated and correlated on the basis of unique trilobite faunas (Figure 1-7). A lithologic signal for some of these events is recognizable in the lithostratigraphy of deeper water deposits of the Frederick Formation to the east and Gatesburg Formation to the west (Figure 2-3).

Eustasy remained the primary control on sedimentation and stratigraphic architecture on the Appalachian shelf during the Early Ordovician and the formations within the passive margin carbonate stack mapped as the Beekmantown Group are delineated largely on the alternation of limestone-rich intervals, which formed during transgressions or sea level high-stands, with dolomite-dominated packages that represent regressive and low-stand conditions (Read, 1989; Brezinski *et al*., 2012). Not all dolomite intervals, however, are the products of regressions. Late stage dolomitization by brines generated during later Paleozoic orogenies replaced all or part of some carbonate intervals with coarsely crystalline dolomite locally. The Larke Dolomite in the Nittany Arch and the Rickenbach Dolomite in the Lebanon Valley of eastern Pennsylvania are good examples of such late-stage dolomites. Four 3rd or 4th order transgressions occurred during deposition of the Beekmantown Group (Figure 2-2), the first of which submerged the GACB in what was named the Stonehenge Transgression for the limestone dominated formation whose base records that earliest Ordovician rapid inundation of the platform (Taylor *et al*., 1992).

The second 3rd order flooding is also recorded in the Stonehenge, but higher in the formation, where the reappearance of similar thinly to medium-bedded, non-cyclic subtidal facies marks the base of the upper member of this unit. The third and fourth transgressions interrupted deposition of dolomite-rich peritidal cycles within the Rockdale Run Formation, forming a limestone interval that has been mapped as the oolitic member (Sando, 1957) and then an unnamed limestone interval somewhat higher within the unit (Brezinski *et al.*, 2012). We will see the subtidal packages created by three of these four Tremadocian transgressions here in the exposures at Stops 2-1 and 2-3. The stops selected do not include the stratigraphic interval that spans the oolitic member of the Rockdale Run.

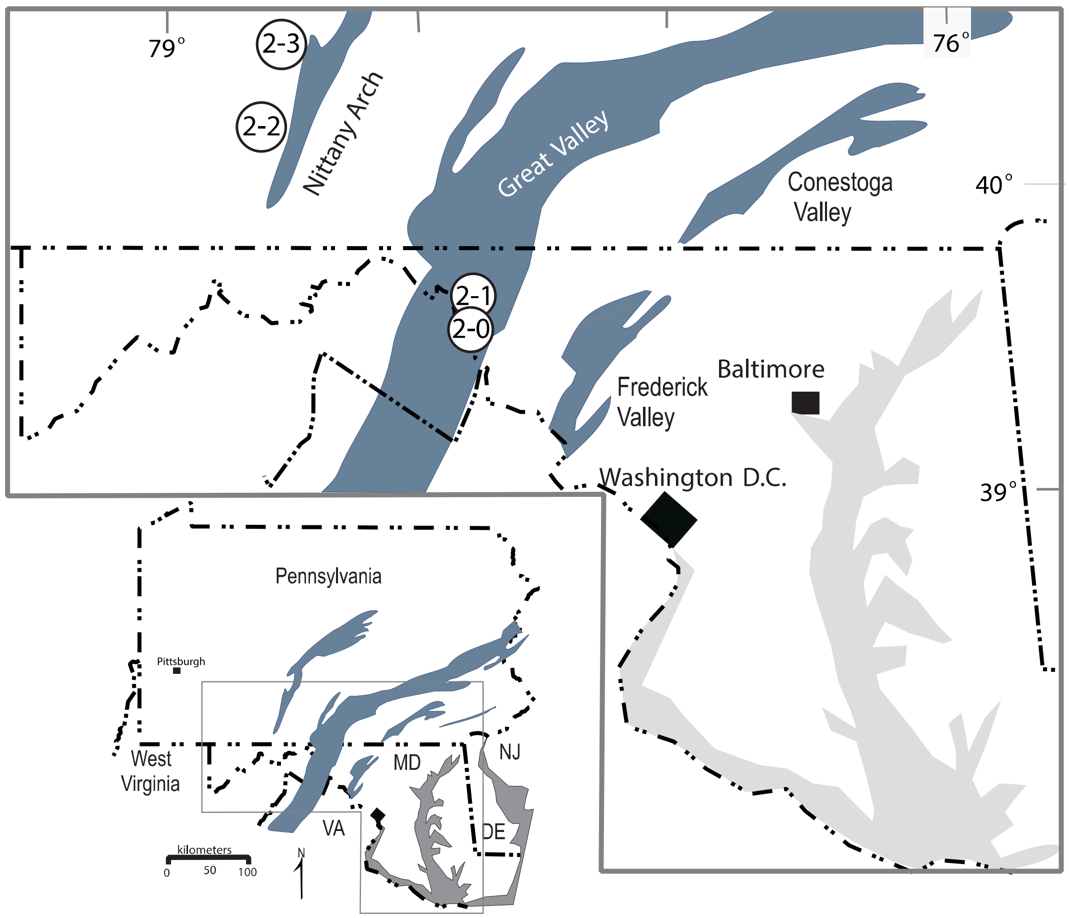

Figure 2-1: Location map for stops on Day 2 in the Great Valley (which includes the Shenandoah and Cumberland valleys) (Stops 2-0 and 2-1) and southern Nittany Arch (Stops 2-2 and 2-3).

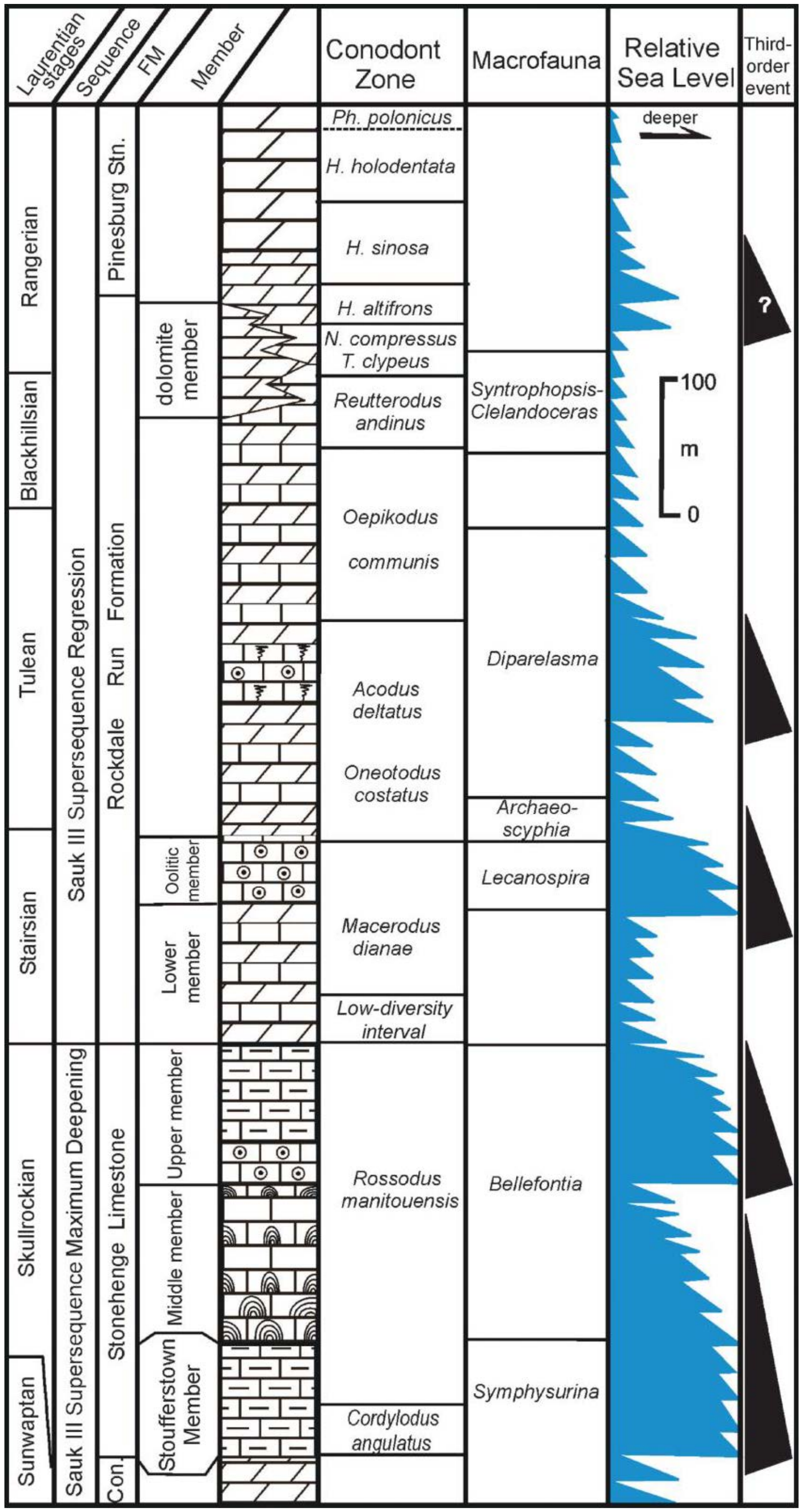

Figure 2-2: Lithostratigraphy and 3rd order sea level events recorded in the uppermost Furongian to Middle Ordovician in the Cumberland Valley of Maryland. From Brezinski *et al*., (2012). Abbreviation: Con. – Conococheague.

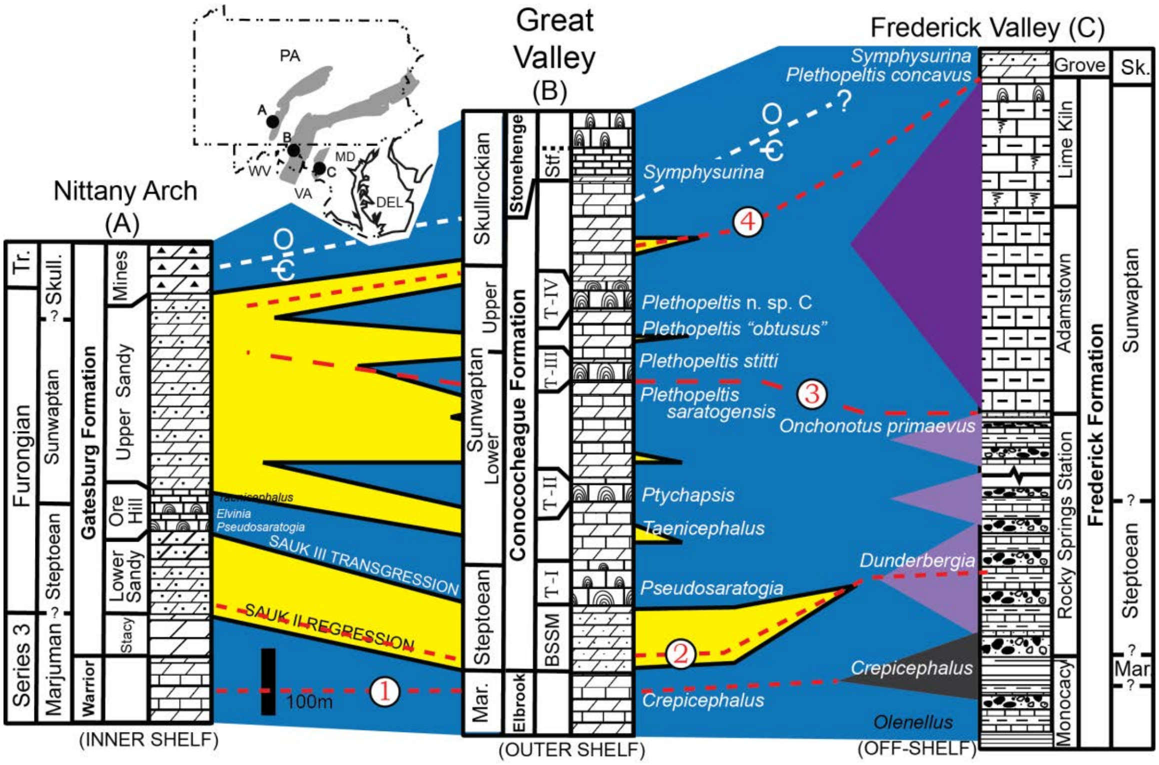

Figure 2-3: Stratigraphic cross section of Furongian strata in the central Appalachian region showing a number of 2nd and 3rd order transgressions and regressions that are recorded in the lithostratigraphy of inner shelf (A), outer shelf (B) and off-shelf (C) successions in the central Appalachians. Horizons marked by circled numbers correspond to 1 – upper Marjuman (*Crepicephalus* Zone) transgression, 2- lower Steptoean (*Dunderbergia* Zone) regression at Sauk II-Sauk III supersequence boundary, 3 – lower Sunwaptan (*Saratogia* Zone) Adamstown Submergence Event, and 4 – basal Ibexian regression. From Taylor (2010).

Stop 2-0: Dam 5 section, Chesapeake and Ohio (C&O) Canal National Historic Park, Cumberland, Maryland.
Co-ordinates: Latitude 39° 36' 23" N; Longitude 77° 55' 21" W.

NOTE: No sampling allowed at stops in the park. The biostratigraphic data presented here from the C&O canal exposures was collected under temporary permit from the National Park Service. Photography is permitted, but hammering and sampling are prohibited in the park.

Exit the parking area for Dam 5 by crossing the footbridge over the canal and descend the hill slope toward the canal back in the direction of the parking area. Near continuous exposure of the Conococheague Formation at this locality exhibits the shoaling-upward, meter-scale cycles evident in the formation between the major thrombolite units.

Stop 2-1: MP-108E and MP-107 measured sections, Chesapeake and Ohio (C&O) Canal National Historic Park, Cumberland Valley, Maryland.
Co-ordinates: Latitude 39° 36' 45" N; Longitude 77° 55' 30" W.

NOTE: No sampling allowed at stops in the park. The biostratigraphic data presented here from the C&O canal exposures was collected under temporary permit from the National Park Service. Photography is permitted, but hammering and sampling are prohibited in the park.

As we reach the C&O canal at Lock 46 after descending the steep road from our parking spot, a short walk to the west (right) along the towpath will take us down-section to exposures of microbial reefs and other associated subtidal lithologies whose trilobite fauna identify them as Thrombolite IV, the uppermost of four transgressive packages in the Conococheague Formation. Many of the characteristic lithologies from the Conococheague, especially its signature limestone-dolomite ribbon carbonate ("ribbon rock"), can be seen in the large blocks that stone masons used to construct the lock itself. A trilobite fauna recovered from the boundstone and flanking grainstone of Thrombolite IV at this location contains a new species of *Plethopeltis* (*P.* n. sp. 2 in Figure 1-7), and *P.* cf. *P. obtusus* occurs in the thinly bedded carbonates only a few meters lower in the section. Neither the undescribed species of *Plethopeltis* nor the associated endemic genus *Conococheaguea* provide any useful information on where these rocks lie within the *Saukia* Zone, but *Euptychaspis typicalis* is also present, and places Thrombolite IV high within that zone, somewhere above the base of its *Saukiella junia* Subzone (Miller *et al*., 2012).

Returning to the towpath, and back tracking to the restored lockkeeper's house at Lock 46, we climb stratigraphically through a covered interval that obscures the uppermost Furongian strata of the Conococheague. The lowest exposed beds of the Conococheague to the east of the covered interval, directly behind the lockhouse, are thinly bedded, cyclic carbonates of the uppermost member of the formation called the Shady Grove Member[1] (Root, 1968). Not much farther to the east, exposures on the slope to the north of the towpath span the boundary between the Conococheague and overlying Stonehenge Limestone. The gradational nature of the Conococheague-Stonehenge contact makes placement of this boundary challenging and somewhat arbitrary. We place it at the top of the uppermost cycle-capping, planar microbial laminite. The Stoufferstown Member at this locality is a monotonous sequence of non-cyclic, thinly bedded lime mudstone to wackestone that accumulated during and shortly after rapid flooding of the Laurentian carbonate platform by the Stonehenge Transgression (Taylor *et al.*, 1992).

The non-cyclic and, in places, somewhat shaly limestone of the Stoufferstown represents the maximum deepening attained in what Nielsen (2004) designated the Early to Mid-Tremadocian Highstand Interval. The thick interval of massive microbial reefs and associated thinly bedded ribbon carbonate that make up the overlying middle member of the Stonehenge (which actually can be considered Thrombolite V) reflect the unprecedented accommodation provided by that major transgression. This flooding is recorded elsewhere in Laurentian carbonate successions by replacement of cyclic peritidal deposition by accumulation of more

[1] – The name of the town that provided the name of this member has been found as "Shady Grove" as well as a single combined form, "Shadygrove", on various maps over the last 170 years. While Root (1968) utilized the name of this member as "Shadygrove" Member, we utilized "Shady Grove" Member as a more standard construction.

uniformly subtidal, heavily bioturbated and/or reefal facies at the bases of the Oneota Dolomite in the northern Mississippi Valley (Runkel *et al.,* 2007), Garden City Formation in southern Idaho (Ross, 1951), and Sailmhor Formation in northern Scotland (Raine and Smith, 2012). It even triggered a short spell of deposition of graptolitic shaly dolomite in the inner shelf, glaucarenite-rich facies of the Bliss Formation in southern New Mexico (Taylor and Repetski, 1995).

The transition upward out of the Stoufferstown and into the middle member records shallowing. In many locations in the Cumberland Valley the first evidence of that transition is a thin interval of thrombolitic boundstone interbedded with the ribbon limestone approximately 10m above the base of the Stoufferstown Member. The middle member here at Stop 2-1 is nearly 120m thick. The thrombolitic intervals within the middle member tend to become thinner up-section and the intervening ribbony limestone intervals become thicker. Some thin dolomitic intervals occur near the top of this member, reflecting the shallowing toward the top of the asymmetrical, shoaling, third order cycle whose base lies at the bottom of the Stoufferstown and top corresponds with the contact between the middle and upper members of the Stonehenge. The contact between the middle and upper members is relatively sharp everywhere, but at this locality a distinct rotation of the strike of the bedding where the basal strata of the upper member are exposed right next to a paved segment of the towpath suggests that here these members may be in fault contact.

Farther to the east lies the contact with the overlying Rockdale Run Formation, recognizable by the return of meter scale cycles, some with microbial reefs in the subtidal basal lithologies, but virtually all capped by conspicuous dolomitic planar microbial laminites. Like the mid-cycle boundary between the Stoufferstown and middle members of the Stonehenge, this formation contact generally is somewhat gradational recording the shoaling out of the 3rd order transgression represented by the base of the upper member of the Stonehenge.

Stop 2-2: Ore Hill Limestone Member of the Gatesburg Formation (Furongian), southern Nittany Arch, Pennsylvania.

Although not Ordovician by anyone's definition, the strata of the Gatesburg Formation warrant some attention on our field trip for several reasons. First of all, as some of the most fossiliferous rocks in the lower Paleozoic of the central Appalachian region, the bioclastic grainstone beds of the Ore Hill Member of this formation will provide a brief respite from the challenge of recovering macrofossils from the recalcitrant Ordovician carbonates, which yield their fauna only to the most diligent collector. More importantly, the highly resolved biostratigraphy of the Ore Hill, which straddles the boundary between the Steptoean and Sunwaptan Stages, and the boundary between the Pterocephaliid and Ptychaspid Biomeres (Palmer, 1965a, 1965b; Stitt, 1971a; Taylor, 2006), offers an opportunity to examine first hand the physical and faunal record of one of the three major extinctions that affected the Laurentian platform trilobite fauna during the Furongian. The highly refined biostratigraphic data from several sections in the Ore Hill document in exceptional detail the pattern of faunal turnover that characterized the late Cambrian, biomere-boundary extinctions – a pattern not duplicated in the extinctions associated with stage boundaries within the Lower Ordovician (Taylor *et al.,* 2009, 2012).

The Gatesburg Formation has been divided into five members (Figure 2-3): the Stacy Member, lower sandy member, Ore Hill Member, upper sandy member, and Mines Member (Butts, 1945; Wilson, 1952). The sandy members consist of cyclically interbedded quartz arenite and dolomite, including some stromatolitic reefs. The Ore Hill Limestone supports a low ridge, mostly forested, that stands above the adjacent outcrop belts of the sandy members. The Ore Hill has been intensively sampled in two areas near the southern end of the Nittany Arch (Location 2-2 on Figure 2-1): Morrison Cove just south of Roaring Spring and Friends Cove slightly south of Bedford. Today's stops include the Imler Quarry measured section in Friends Cove (Stop 2-2a) and two exposures in the Morrison Cove area originally described by Wilson (1951, 1952) at Potter Creek and Crossroads (Stop 2-2b).

Three lithologies dominate the Ore Hill: thinly bedded lime mudstone to wackestone (ribbon carbonate), thinly to medium-bedded intraclastic and bioclastic packstone to grainstone, and microbial boundstone. Tan dolomitic laminae in the thinly bedded ribbon carbonate facies weather recessively, giving outcrops a prominent ribbed appearance when they form continuous laminae or a mottled texture where disrupted by bioturbation. Fossils are scarce in this facies. Thinly to mediumly bedded packstone to grainstone beds, most of them intraclastic and some oolitic, contain abundant disarticulated trilobites.

A variety of microbialites occurs in the lower part of the Ore Hill (Taylor *et al*., 1999). Planar microbial laminite is rare because the Ore Hill formed under more consistently subtidal conditions than the age-equivalent strata of the Conococheague Formation and lacks the laminite-capped peritidal cycles that are so common in that unit. Laminites do, however, occur at a few levels within the Ore Hill Member. One particularly prominent and continuous laminite interval near the middle of the member within Morrison Cove has been used to correlate between the Potter Creek and Crossroads measured sections. Massive, hemispherical microbial bioherms occur in the lower half of the member in several sections. Wilson (1951, 1952) described the lowermost 6 meters of section at the base of the Ore Hill, including at Eschelman Quarry, as "massive, crystalline limestone". Subsequent weathering has enhanced surface textures that allow this interval to be recognized as an extensive thrombolitic reef complex (Taylor *et al*., 1999). The constituent bioherms are interstratified with medium-bedded, oolitic, intraclastic, and bioclastic grainstone and display some bathymetric relief on their upper surfaces. Somewhat higher in the member, a number of discrete meter-scale bioherms of thrombolitic or structureless microbial boundstone are interstratified with the ribbon carbonates.

Trilobite faunas recovered through the entire thickness of the Ore Hill Member (Figure 2-4) allow biostratigraphic discrimination of six different intervals, four within the *Elvinia* Zone and two within the overlying *Taenicephalus* Zone. The uppermost unit in the *Elvinia* Zone is the thin *Irvingella major* Subzone, for which the only documented occurrence in eastern North America is the Crossroads measured section in the Ore Hill Member. The base of this subzone is the extinction horizon that serves as the boundary between the Steptoean and Sunwaptan Laurentian Stages. The trilobite faunas, therefore, allow discrimination of a lower Ore Hill of Steptoean age and upper Ore Hill of Sunwaptan age.

The youngest Steptoean fauna in the Ore Hill is that of the *Cliffia lataegenae* Subzone of the *Elvinia* Zone, which has a nearly circum-Laurentian distribution, occurring in Pennsylvania (Taylor *et al*., 1999), Missouri (Kurtz, 1975), Oklahoma (Stitt, 1971a), Texas (Wilson, 1949), Nevada and Utah (Palmer, 1965a), Montana (Grant, 1965), and Alberta (Westrop, 1986). Although many species range through the subzone, in Pennsylvania we can differentiate lower and upper portions of the *C. lataegenae* Subzone (Loch and Taylor, 1995). The lower portion of the subzone is characterized by the short-ranging taxa *Bynumina terenda, Xenocheilos spineum*, and *Kindbladia wichitaensis*. *Camaraspis convexa, Drabia acroccipita, Drabia menusa,* and *Sulcocephalus granulosus* characterize the upper *C. lataegenae* Subzone in the Ore Hill. Stitt (1977) noted a similar association of *Bynumina* with *Kindbladia* in Oklahoma, as did Westrop *et al.* (2007) and Westrop and Adrain (2009) elsewhere. However, Loch and Taylor (2004) reported that most of these taxa are absent or at least rare in collections recovered from thrombolitic reefs in the *C. lataegenae* Subzone. The reef biofacies instead is dominated by genera rare or unknown from off-reef deposits, specifically *Buttsia, Imlerella, Stittaspis,* and *Pseudosaratogia.* Most all of the aforementioned genera in both the reef and off-reef biofacies disappear at the top of the *C. lataegenae* Subzone, i.e., the Steptoean-Sunwaptan stage boundary.

Throughout Laurentian North America, the basal Sunwaptan *Irvingella major* Subzone is characterized by the appearance of *Commanchia amplooculata* and *Sulcocephalus candidus* in conjunction with an increase in the abundance of *I. major* itself (Wilson and Frederickson, 1950). In addition to being the only location in eastern North America where this subzone has been documented, the Crossroads section is exceptional in that nowhere else has the fauna been recovered from microbial reefs. Taylor *et al.* (1999) compared the relative abundance of genera in the *I. major* Subzone bioherms in the Ore Hill to those reported from non-reefal facies in western North America. They discovered that *Sulcocephalus*, which is a relatively uncommon genus in non-reefal facies, dominates the microbial reef fauna and named this association the *Sulcocephalus* biofacies. The significance of this contrast is that it demonstrates that the extinction at that base of the *I. major* Subzone did not completely homogenize the shallow marine fauna, but left some Beta (between-habitat) diversity intact. Complete elimination of distinct biofacies on the Laurentian platform occurred at the next extinction at the base of the overlying *Taenicephalus* Zone.

The *Taenicephalus* Zone is divided into two subzones characterized by their low species diversity and dominance by their eponymous taxa: a basal *Parabolinoides* Subzone and overlying *Taenicephalus shumardi* Subzone. Grant (1965), in his study of faunas of the Snowy Range Formation in Montana, was the first to set apart the *Parabolinoides* Subzone on the basis of its trilobite content, superseding the *Eoorthis* brachiopod Subzone used in earlier studies for the basal, post-extinction strata that directly overly the *Irvingella major* Subzone. The species that dominates what we refer to as the *Parabolinoides* Subzone in the Ore Hill is a parabolinoidid species that Wilson (1951) referred to as *Parabolinella occidentalis* and we here (Figure 2-4) identify as *"Orygmaspis" occidentalis* to acknowledge both the uncertainty of generic assignment and the subsequent reduction in rank of *Parabolinoides* to a subgenus of *Orygmaspis* (Westrop, 1986). The base of the *Taenicephalus shumardi* Subzone is marked by the disappearance of "*O" occidentalis* and appearance of *T. shumardi.* One noteworthy change in the physical attributes of the Ore Hill Member at the base of the *Taenicephalus* Zone is the complete disappearance of microbial reefs. Not only are they entirely absent from this zone in the Ore Hill and Conococheague in the Appalachians, but also from the *Taenicephalus* Zone throughout western North America.

Palmer (1965b) introduced the biomere as a new type of suprazonal, extinction-bounded, biostratigraphic unit that records the evolutionary diversification of a taxon, typically at the family level, followed by its extinction and replacement. The beginning of a biomere involved immigration of a deep-water trilobite, later described as "olenimorphic", from deep-water environments onto the depopulated shelf following a mass extinction. These immigrants were then to have evolved and diversified on the continental shelf and in epicontinental seaways into a species-rich fauna, only to be decimated by the next extinction several million years later. The "type" biomere described by Palmer (1965a) is the Pterocephaliid Biomere, which began with repopulation of the Laurentian shelf by the olenimorphs of the *Aphelaspis* Zone, after the extinction of the diverse fauna of the *Crepicephalus* Zone at the top of the Marjuman Stage. The top of the Pterocephaliid Biomere records the extinction of the similarly diverse fauna of the *Elvinia* Zone and its replacement by the largely monogeneric faunas of the *Taenicephalus* Zone, which represent the return of platform trilobite diversity to minimal levels at the base of what later was named the Ptychaspid Biomere (Longacre, 1970; Stitt, 1971a).

Stitt (1971b) refined the internal anatomy of the biomere and reported a repeating, 4-stage developmental pattern within these units. Stage 1 involved the immigration of the "olenimorphic" trilobites onto the shelf and their adaptive radiation to fill vacated niches. Stage 2 within each biomere is characterized by a more diverse fauna, some species of which display significantly longer stratigraphic ranges than those of Stage 1 species. Stage 3 records attainment of a highly diverse stable shelf fauna consisting of highly specialized species with long stratigraphic ranges but were extirpated by the next extinction event. Stage 4 is a thin interval at the top of the biomere that records a brief (geologically) span of time following the major extinction at the end of Stage 3, during which a surviving opportunistic platform genus or species from Stage 3 proliferated and was joined by a few immigrant taxa from deep water prior to succumbing to the stressors that completed depopulation of the shelf. Taylor (2006) provided a historical narrative of the evolution of the concept and continuing controversy regarding the utility of biomeres, placement of their boundaries, and possible extinction mechanisms that will not be repeated here. Many aspects of Stitt's simple model have been challenged and even refuted by later work. However, what is unequivocal is the recurrence of the thin Stage 4 [re-named the "critical interval" by Taylor (2006)] at the top of the three well-characterized biomeres in the upper Cambrian, lying between the Stage 3-Stage 4 extinction horizon (below) and the base of the overlying biomere marked by the appearance of a minimum-diversity, olenimorph-dominated fauna (above).

Within the Ore Hill, the *Cliffia lataegenae* Subzone fauna represents the diverse fauna of Stitt's (1971b) Stage 3 of the Pterocephaliid Biomere. The disappearance of this fauna at the top of the *C. lataegenae* Subzone represents the extinction event that defines the base of the Critical Interval and the base of the Sunwaptan Stage. The fauna of the *Irvingella* major Subzone, which is the Critical Interval (Stage 4) of the Pterocephaliid Biomere, includes 3 species: *I. major* itself, which is a surviving species from the underlying subzone, *Sulcocephalus candidus*, which represents a surviving genus from the underlying subzone, and *Commanchia amplooculata*, an immigrant from deeper water environments. The extinction at the top of the *I. major* Subzone fauna marks the top of the Pterocephaliid Biomere. Stage 1 of the overlying Ptychaspid Biomere is represented by the olenimorph-dominated faunas of the *Parabolinoides* Subzone of the *Taenicephalus* Zone.

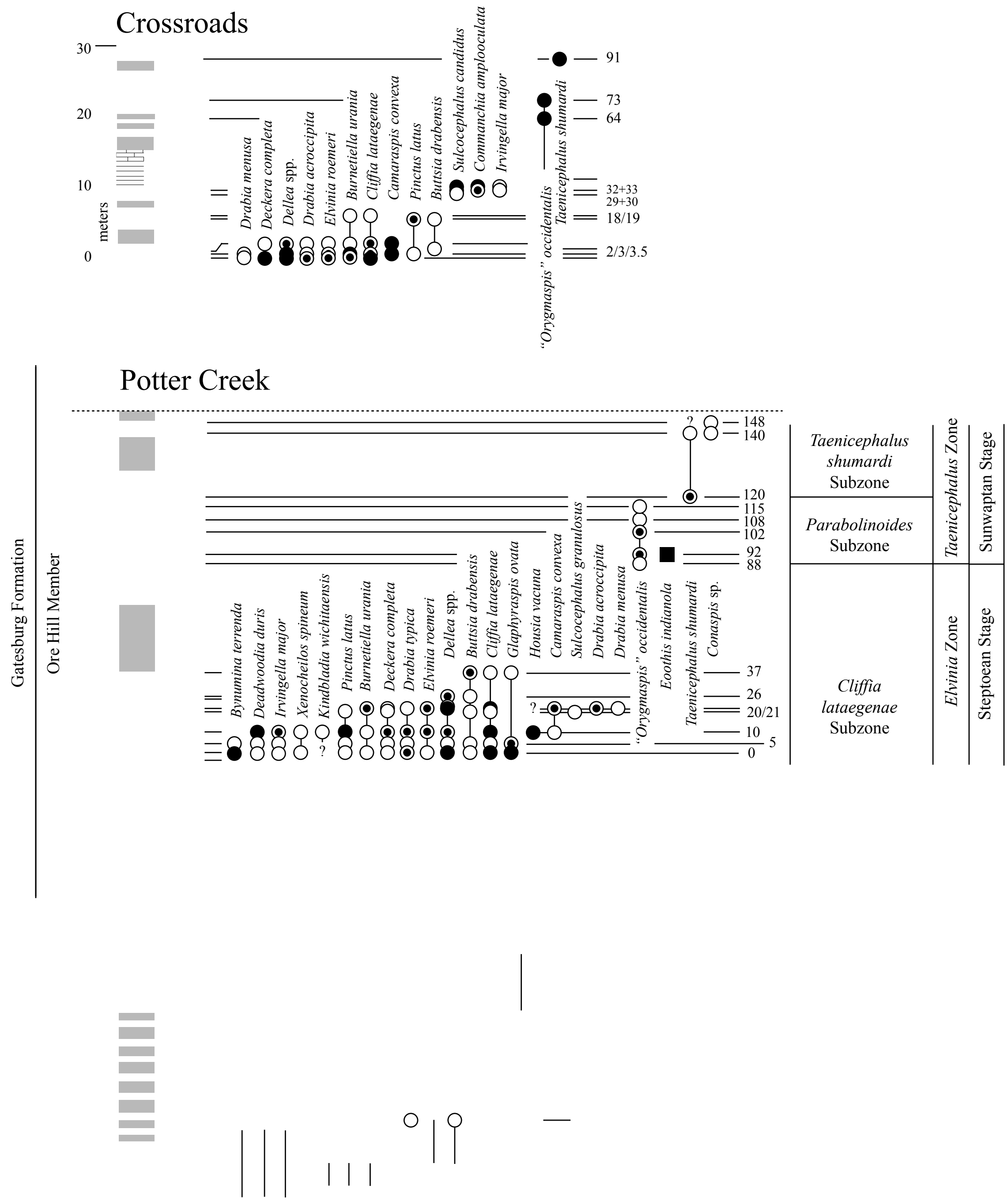

Figure 2-4: Species range charts for the Crossroads, Potter Creek, and Imler Quarry measured sections of the Upper Cambrian Ore Hill Member (Gatesburg Formation). Numbers in the right column are collection numbers in the original feet measured from the base of the exposure. Trilobite occurrences as circles, brachiopods as squares. Abbreviations: Crit. Intr – Critical Interval, *I.* – *Irvingella*, Sun – Sunwaptan, *T.* and *Taen.* – *Taenicephalus*.

Stop 2-2a: Imler Quarry measured section, Friend's Cove, Pennsylvania.

The Imler Quarry section is located in a typical, small, abandoned quarry that was excavated into the slopes of the Ore Hill ridge for extraction of limestone to make agricultural lime early in the 20th century. The remnants of the old kiln where the limestone was "fired" can be seen below the face of the quarry. The lowest strata exposed in this section are composed of thinly bedded lime wackestone and grainstone that contain the pre-extinction fauna of the *Cliffia lataegenae* Subzone. Above these basal strata, which extend as a low cliff northward along the slope from the quarry, is an interval that contains meter-scale thrombolitic bioherms from which the fauna described as a reef-related biofacies by Taylor *et al.* (1999) were recovered.

In these southerly exposures of the Ore Hill in Friends Cove, the Ore Hill Member contains an interval of coarsely crystalline dolomite that spans the stage and biomere boundary interval. The lowest preserved bioclastic limestone strata above this dolomite package yield the fauna of the *Taenicephalus shumardi* Subzone of *Taenicephalus* Zone. This stop provides an opportunity to collect some of that fauna from the low cliffs above the poorly exposed coarsely crystalline dolomite package.

Before leaving the Stop 2-2, we'll cross Route-326 to examine the rocks exposed a very short distance west of the highway in an active "borrow pit" where shale is being excavated. Rather than descending a relatively short distance stratigraphically relative to the eastward dipping strata we just examined in Imler Quarry, we'll have ascended several thousand feet through the section to examine the dark shale of the Upper Ordovician Reedsville Formation. By crossing the highway, we went from the hanging wall to the footwall of a major thrust fault that Route-326 follows through Friends Cove. As we drive north along Route-326 on our way to the next stop, note the abundance of sinkholes in the Cambrian carbonates in the fields along the road where fractures near the fault serve as conduits for groundwater flow.

Stop 2-2b: Potter Creek and Crossroads measured sections, Morrison Cove, Pennsylvania.

> **NOTE: We ask that you respect the property owners who have afforded us access to the Crossroads outcrops and not hammer or sample at this locality. We sampled here before the area was landscaped.**

The Potter Creek section, which was assembled from a series of outcrops along the length of the Ore Hill Ridge near Maria, Pennsylvania, provided some of the largest and most diverse collections recovered from the upper *Cliffia lataegenae* Subzone in our studies (Taylor *et al*., 1999; Loch and Taylor, 1995). Our purpose in stopping at Potter Creek, however, is to examine the laterally continuous planar microbial laminite and overlying thinly bedded, burrowed ribbon carbonates of the *Parabolinoides* Subzone in an old pocket quarry along the highway. That laminite not only allowed assembly of the Potter Creek composite section, but it also ties the Potter Creek composite to exposures in the Crossroads section a short distance to the west. This is important because the stage and biomere boundary interval is entirely covered at Potter Creek.

As previously mentioned, the Crossroads section is the only location in eastern North America where the very thin *Irvingella major* Subzone of the *Elvinia* Zone has been documented. It is also the only location anywhere that this fauna has been recovered from microbial reefs, and consequently the only *I. major* Subzone fauna dominated by the genus *Sulcocephalus* (Taylor *et al*., 1999). This stop is the third location where we request that no one hammer on the outcrop, because the rock exposures that include the reefs of the *I. major*

Subzone are part of the landscaping of the property owners. The bioherms consist of columns of structureless microbial boundstone that stand out on the weathered surface due to dissolution of the narrow bands of less resistant inter-column sediment.

Stop 2-3 – Lower Ordovician (uppermost Tremadocian to basal Floian) cyclic carbonates of the Axemann Formation, Roaring Spring, Pennsylvania.
Coordinates: Latitude 40° 20' 18" N; Longitude 78° 23' 33" W.

Mapping of the formations in the Beekmantown Group in the Nittany Arch is challenging because of pervasive, late-stage dolomitization of much of the group and the occurrence of identical dolomite-dominated facies in multiple units. The limestone-rich Axemann Formation serves a vital function in separating the similar dolomites of the underlying Nittany Dolomite and overlying Bellefonte Dolomite. The Axemann also is important as the product of the fourth 3rd order transgression that inundated the Appalachian shelf during the Early Ordovician. It is correlated with the unnamed upper limestone interval of the Rockdale Run Formation in the Cumberland Valley to the southeast and the Epler Formation in the Lebanon Valley to the east (Brezinski *et al*., 2012). Despite the relatively greater water depth produced by this transgression, deposition of most of the Axemann still occurred in environments shallow enough to produce well-developed 5th order (meter-scale) peritidal cycles capped by prominent dolomitic, planar microbial laminites.

At this outcrop along Route-36 in Roaring Springs, Pennsylvania, we will examine characteristic lithologies that are bundled in the meter-scale cycles of the unit. Subtidal lithologies low in the cycles include bluish-gray-weathering limestone with varied textures. Medium to thickly bedded limestone with dolomitic mottling at the base of some cycles represents either moderately burrowed lime mudstone or perhaps thrombolitic boundstone comprising thin microbial reefs with indistinct boundaries with intermound sediment. Other subtidal lithologies are bedded lime mudstone, flat-pebble conglomerate, and coarse bioclastic grainstone. Some thick cycle caps display syndepositional disruption of the fine laminae by scour, desiccation, and/or growth of enterolithic evaporites, vestiges of which remain as centimeter-scale carbonate-lined vugs. Thinly to very thinly bedded ribbon carbonate that represents very shallow subtidal to intertidal deposition occurs commonly in the middle of the cycles.

Fourth-order shoaling is recorded through roughly the lower half of the outcrop in the upward increase in thickness of laminate cycle caps to a point where one very thick laminite contains thin laminae of quartz sand, reflecting shallowing sufficient to cause influx of siliciclastic sediment from more nearshore areas. Above that prominent laminite, 4th order deepening is recorded with a return of limestone dominance, but the uppermost strata in the outcrop again record shallowing with an upward increase in number and thickness of dolomitic laminites. More massive and coarsely crystalline dolomite at the top of the section might, in fact, represent the basal strata of the overlying Bellefonte Dolomite.

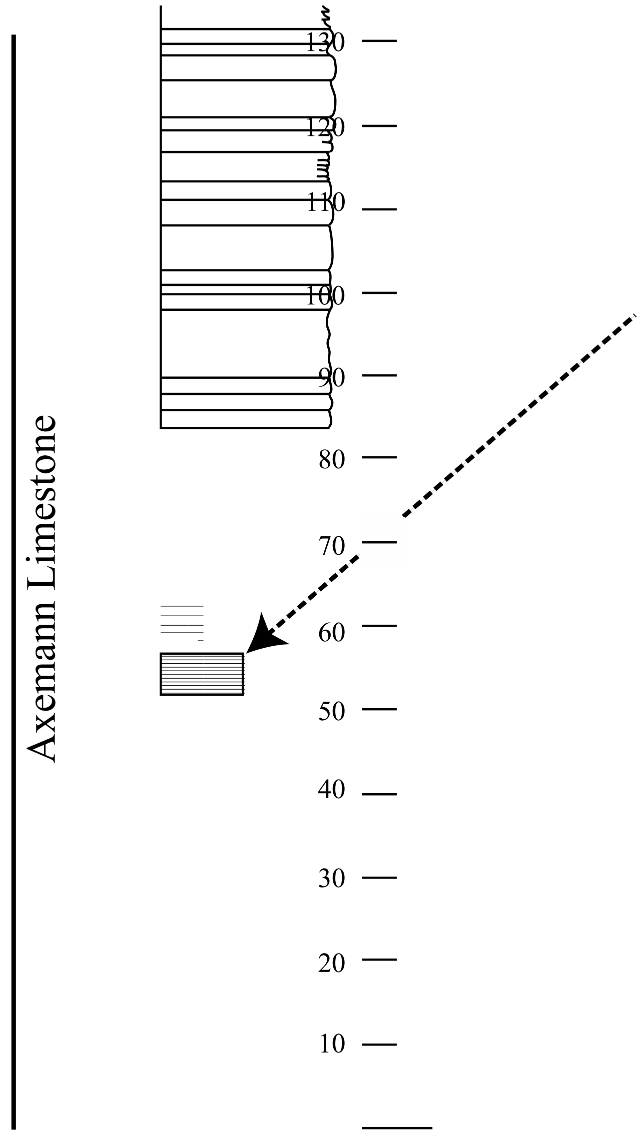

Figure 2-5: A. Lithologic column of the Axemann Formation at Stop 2-3; B. Field photograph of nearly complete meter-scale shoaling cycle from flooding surface at base of thrombolitic boundstone (black dashed line) to top of capping planar microbial laminite; C. Close-up of thick, planar microbial laminite with disrupted laminae and vugs (possible enterolithic evaporite casts) in sharp contact with subtidal limestone at base of overlying cycle (white dashed line).

Trilobite sclerites are relatively common within the coarse grainstone beds of the Axemann, but are typically fragmented and difficult to extract. Nonetheless, the known fauna (Lees, 1967) is sufficient to establish correlation (Figure 2-6) to the Kindblade Formation of Oklahoma (Loch, 2007). Although most species recovered from the Axemann are long-ranging within the Cassinian strata of Oklahoma, *Strigigenalis caudata* appears restricted to the upper Cassinian (Boyce, 1989). Conodonts recovered from the Axemann broadly confirm this conclusion.

The historical series nomenclature for the Ordovician rock of Laurentia was based upon unconformity-bound, typically poorly fossiliferous outcrops in eastern North America (Twenhofel, 1954). Subsequently, Flower (1964) proposed a four-fold suite of Lower Ordovician stages: (in ascending order) the Gasconadian, Demingian, Jeffersonian, and Cassinian. These stages were based upon strata from Missouri, New Mexico, and New York and reflected, at least in part, an evolutionary succession of cephalopod taxa. Ross *et al.* (1997) erected the Lower Ordovician Ibexian Series based upon the classic silicified trilobite faunas studied by Ross (1951) and Hintze (1953) from the continuous successions of western Utah and southeastern Idaho. The Ibexian was divided into the Blackhillsian, Stairsian, Tulean, and Skullrockian Stages (Ross *et al*., 1997).

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Figure 2-6: Biostratigraphic distribution of Cassinian Stage trilobite faunas.

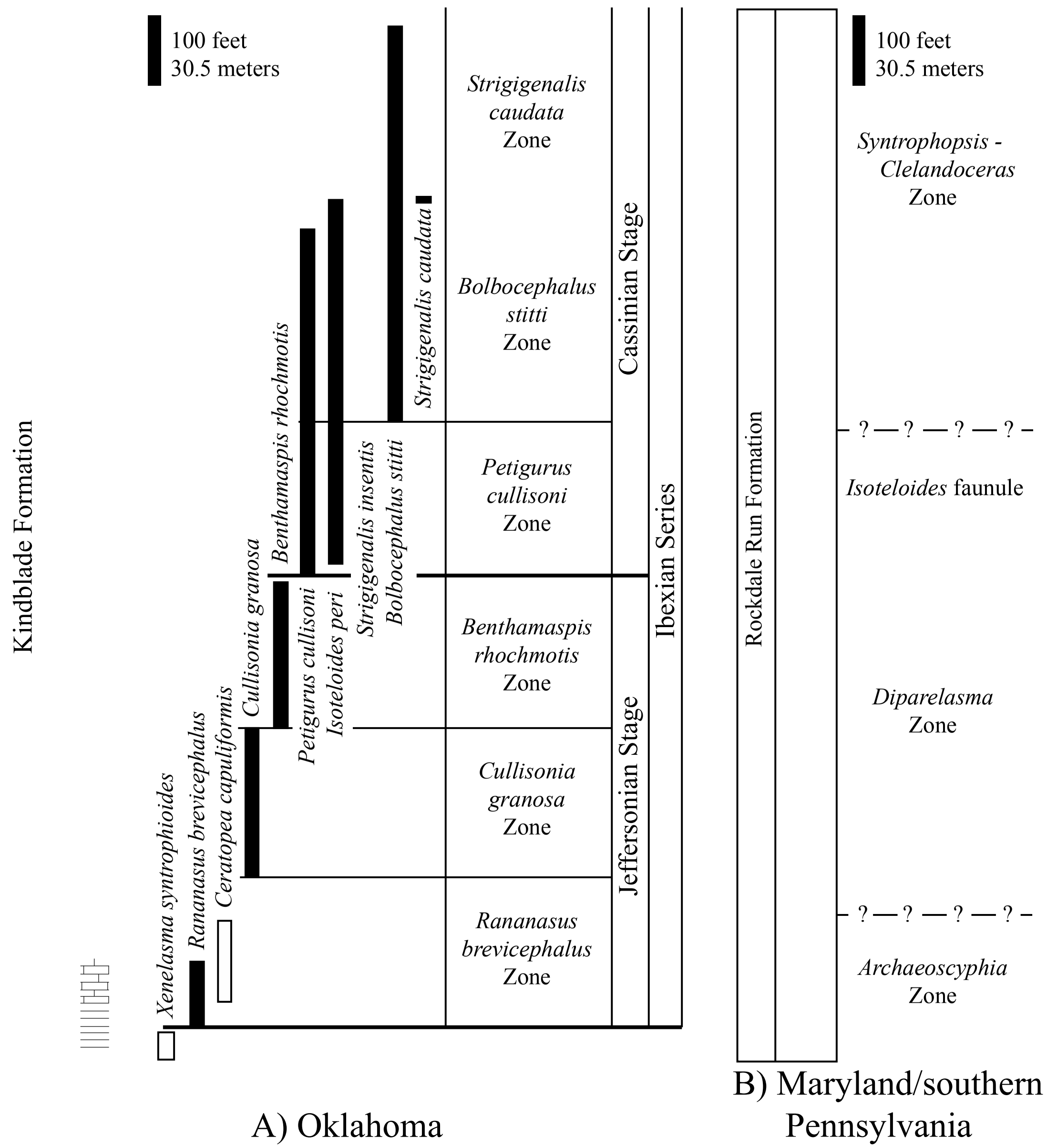
A. Oklahoma (after Loch, 2007), numbers indicate measured section unit numbers of the Kindblade Formation, black bars indicate species ranges of trilobites based upon composite standard thicknesses, open bars indicate taxon ranges of non-trilobite taxa (Derby *et al*. (1991);

B. Southern Pennsylvania (after Sando, 1958, p. 847-849), stratigraphic location of an *in situ* example of Sando's *Isoteloides* faunule within the Rockdale Run Formation;

C. Central Pennsylvania (after Lees, 1967), black bars indicate range data approximated from stratigraphic columns;

D. Cassinian trilobites:

1. *Isoteloides peri* [Fortey, 1979; UMC [University of Missouri – Columbia] 16805, x1.8] includes *Isoteloides* sp. of Lees (1967, pl. 12, figs. 1-3),
2. *Petigurus cullisoni* [Loch, 2007; UMC 16995, palpebral view of cranidium, x1.0] includes *Hystricurus* sp. 1 of Lees (1967, pl. 12, figs. 13, 14),
3. *Bolbocephalus stitti* [Loch, 2007; UMC 16923, palpebral view of cranidium, x1.2] compares closely with the cranidium illustrated as *Hystricurus* sp. 2 of Lees (1967, pl. 12, fig. 12 only and not fig. 13; only the illustrated cranidium was included on the range chart),
4. *Strigigenalis caudata* [Billings, 1865; UMC 17028, dorsal view of pygidium, x2.9] includes *Bathyurellus* sp. 2 of Lees (1967, pl. 12, figs. 4, 5),
5. *Strigigenalis insentis* [Loch, 2007; UMC 17079, dorsal view of pygidium, x2.0] compares closely with the pygidium illustrated as *Bathyurellus* sp. 1 by Lees (1967, pl. 12, figs. 8, 10).


Kindblade Formation
100 feet
30.5 meters
Xenelasma syntrophioides
Rananasus brevicephalus
Ceratopea capuliformis
Cullisonia granosa
Benthamaspis rhochmotis
Petigurus cullisoni
Isoteloides peri
Strigigenalis insentis
Bolbocephalus stitti
Strigigenalis caudata
Strigigenalis caudata Zone
Bolbocephalus stitti Zone
Petigurus cullisoni Zone
Benthamaspis rhochmotis Zone
Cullisonia granosa Zone
Rananasus brevicephalus Zone
Cassinian Stage
Jeffersonian Stage
Ibexian Series
A) Oklahoma
Rockdale Run Formation
100 feet
30.5 meters
Syntrophopsis - Clelandoceras Zone
? — ? — ? — ?
Isoteloides faunule
Diparelasma Zone
? — ? — ? — ?
Archaeoscyphia Zone
B) Maryland/southern Pennsylvania

Loch (1995, 2007) examined the trilobites of the Kindblade Formation of Oklahoma and employed them for correlation across southern Laurentia (Texas, Missouri, Pennsylvania, and Newfoundland, Canada). He was able to correlate from the Kindblade to the Jefferson City Dolomite of Missouri, the basis of Flower's Jeffersonian Stage, on the basis of shared trilobite species. He demonstrated a strong family-level differentiation between the trilobite faunas of Utah and those known from southern Laurentia. In the absence of shared species Loch (1995, 2007) argued that although the base of the Tulean Stage in western Utah was closely correlated with the base of the Kindblade and Jefferson City Formations, the preservation of a regionally applicable stadial terminology was appropriate. He endorsed the utility of the Jeffersonian and Cassinian Stages, proposed boundary stratotypes for these stages in Oklahoma, and erected a zonal terminology. Taylor *et al.* (2012) endorsed the utilization of the Jeffersonian and Cassinian Stages for southern Laurentian strata and we have applied it here.

The Axemann can be correlated into the Rockdale Run Formation of the Beekmantown Group of Maryland on the basis of its macrofauna (Sando, 1958). Within the Rockdale Run he outlined 4 faunas: (in ascending order) the *Lecanospira* fauna, the *Archaeoscyphia* fauna, the *Diparelasma* fauna, and the *Syntrophopsis – Clelandoceras* fauna. Biostratigraphically, the *Archaeoscyphia* fauna is the most intriguing. The *Archaeoscyphia* fauna featured the lithistid demosponge *Archaeoscyphia* in association with the gastropod operculum *Ceratopea capuliformis*, a relationship documented from the Jefferson City Dolostone of Missouri (Cullison, 1944, in the Rich Fountain Formation of his Jefferson City Group). *C. capuliformis* is also known from the Kingsport Formation of Tennessee, the Honeycut Formation of central Texas, and the Kindblade Formation of Oklahoma (Yochelson and Bridge, 1957). Sando (1958) also identified the brachiopod *Xenelasma syntrophoides* from the *Archaeoscyphia* fauna. Miller *et al.* (2012, fig. 8) used *X. syntrophoides* to correlate the base of the Kindblade Formation with the base of the Honeycut Formation in Texas. Further, Sando (1958) listed the genus *McQueenoceras* among the diverse cephalopods of the *Archaeoscyphia* fauna that is also known from the lower Jefferson City, along with the Honeycut and Kindblade Formations (Ulrich and Foerste, 1935; Unklesbay, 1961). Faunal evidence indicates, therefore, that the *Archaeoscyphia* fauna from the lower third of the Rockdale Run can be assigned to the lower Jeffersonian Stage.

Higher in the Rockdale Run, Sando (1957) described an "*Isoteloides* faunule". Identification of his *Isoteloides* specimens as *I. peri* also allows for the correlation of the middle Rockdale Run with the classic Fort Cassin outcrops of New York and Vermont (Brett and Westrop, 1996) and the Cassinian portion of the Kindblade in Oklahoma (Figure 2-6).

The conodont succession from the Axemann reinforces its correlation with the Rockdale Run Formation and the upper Kindblade Formation (Goodwin, 1972; Collamer, 1985; Collamer and Repetski, 1987). In her biostratigraphic and paleoenvironmental study of the conodonts of the Axemann type section, Collamer (1985) recovered 28 multi-element species and a further 18 form species. Faunal diversity repeatedly decreases significantly within the lithologic cycles through the Axemann, with the highest diversity in the subtidal limestones to very low diversity in the dolomite laminites. The first appearance of *Oepikodus communis* at approximately one-third through the thickness of the Axemann at Bellefonte gives a minimum base there for the Cassinian Stage as well as an approximation for the base of the Floian Stage globally.

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Chapter 3: Ordovician facies of the central and northern Nittany Arch, central Pennsylvania

John F. Taylor, John E. Repetski, James D. Loch

Introduction

The Ordovician strata in the northern Nittany Arch (Figure 3-1) provide an informative comparison to the coeval units of the Shenandoah and Cumberland Valleys seen on Days 1 and 2. The Lower Ordovician inner shelf carbonates of the Stonehenge and bounding units (Figure 3-2) near Bellefonte, Pennsylvania, reflect less accommodation space and shallower environments than the Great Valley equivalents to which they have been correlated via both biostratigraphy and event stratigraphy. The morning stop at Union Furnace (Stop 3-1) spans the active margin units, mostly Middle to Upper Ordovician seen at Tumbling Run, but of considerably greater thickness and with a more conformable contact between the Sauk and Tippecanoe Megasequences owing to its location closer to center of the Pennsylvania Depocenter.

Stop 3-1: Union Furnace measured section, Route-453 east of Birmingham, Pennsylvania. Coordinates: 40° 37’ 26” N; 78° 10’ 23” W.

This long and continuous exposure of the entire Middle and Upper Ordovician carbonate succession in central Pennsylvania has served for decades as something of a standard for these economically important formations in the Nittany Arch. It is situated in close proximity to the Union Furnace quarry where high calcium limestone is quarried primarily from the Linden Hall Formation at the top of the Black River Group. Farther to the northwest, on the steeply dipping and overturned northwestern limb of the same anticline, the coarsely crystalline dolomite of the Bellefonte Formation is mined for road aggregate. Having formed close to the center of the Pennsylvania Depocenter (Read, 1989), this succession is considerably thicker than the age-equivalent interval in the sections to the north near the New York promontory and to the south on the flank of the Virginia Arch. Conodont biostratigraphic data from the upper part of the Bellefonte Dolomite and overlying Loysburg Formation (Figure 3-3) suggest a conformable or nearly conformable contact between the Sauk and Tippecanoe megasequences in this area that results from greater subsidence, as reflected in the overall thickening of the Middle to Upper Ordovician units here, as compared to the Great Valley. No single surface has been identified as the interregional unconformity that separates these 2nd order cycles in most other areas of the continent. The proximity of this road cut to Union Furnace quarry has enabled geologists who have utilized it as a stop on previous field trips to identify not only all the relatively thin formations within the Black River and Trenton groups, but even the specific “mine units” that economic geologists in the area discriminate on the basis of geochemical analysis. The boundaries of these mine units are marked with green paint slashes and unit numbers along the length of the outcrop, as are the horizons (with a B preceding the number) of recessive lithologies suspected or known to be K-bentonites in the succession.

In 2004, geologists affiliated with the Pennsylvania Geological Survey and Penn State University prepared a superb guidebook (Laughrey *et al*., 2004) that provides detailed lithologic columns for much of this outcrop that are tied into the green paint numbers maintained on the outcrop. Most of the information provided in that guidebook is archived on the website of the

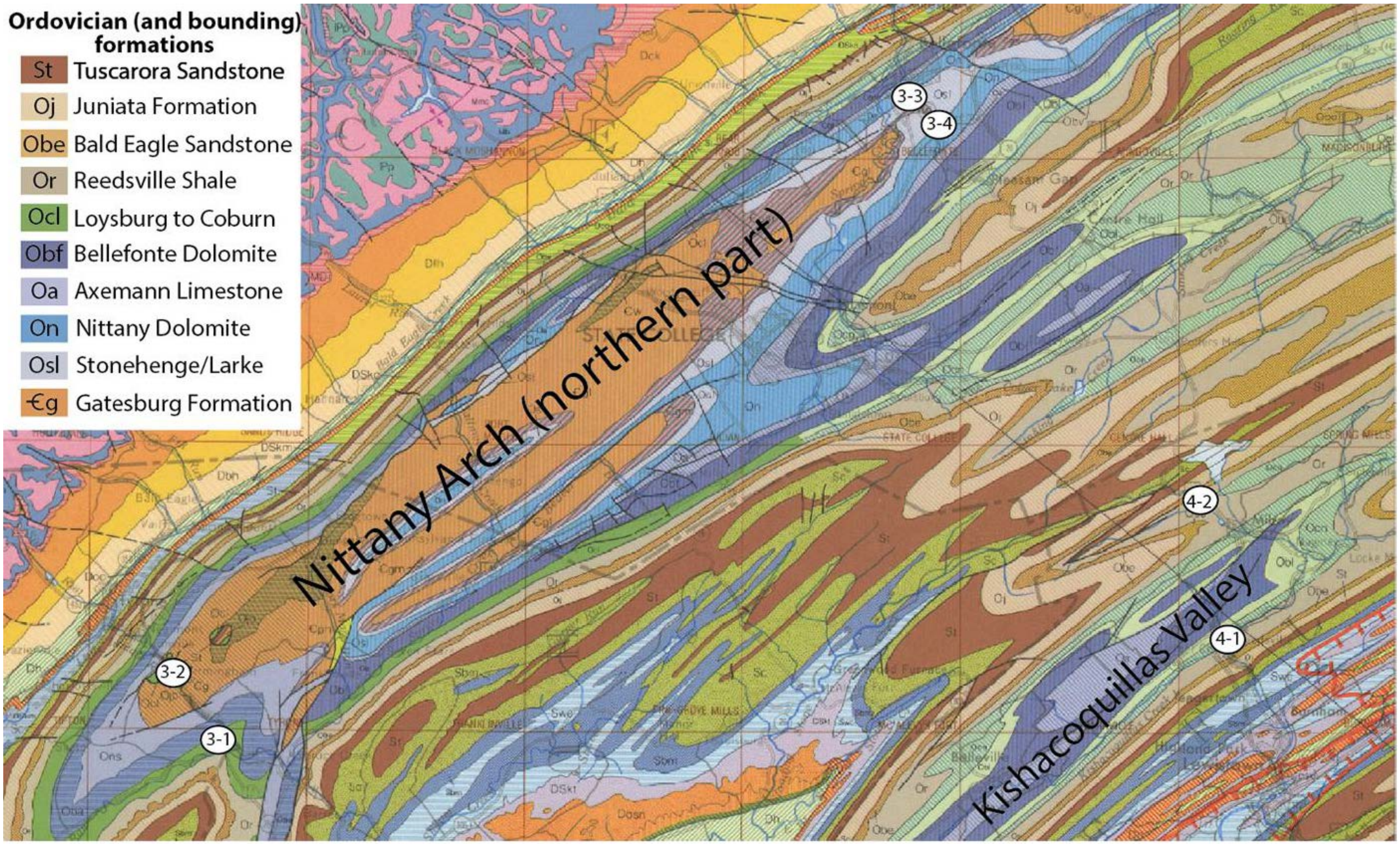

Figure 3-1 - Geologic map showing locations of stops on Days 3 and 4. (Base from 1980 Geologic Map of Pennsylvania)

Pennsylvania Geological Survey (URL listed in references) as a virtual field trip for those interested in learning more about these rocks. With the kind permission of the Pennsylvania Geological Survey, we have duplicated their lithologic columns (Figures 3-5 to 3-9) and legend (Figure 3-4) in this guidebook to allow trip participants to compare the features that they see in the outcrop to those reported by Laughrey *et al.* (2004) in support of their paleoenvironmental and sequence stratigraphic interpretations of the Black River and Trenton Group carbonates. Although the unit numbers on the outcrop and detailed annotation of the corresponding lithologic logs would suffice to effectively guide the reader through this classic section, a supplemental series of specific locations with noteworthy features is provided below. Also duplicated here is the diagram provided by Laughrey *et al.* (2004, fig. 14) showing the distribution of environments and derivative facies along the gently sloping surface of both modern (Figure 3-5A) and reconstructed ancient carbonate ramps (Figure 3-5 B, C). The colors used in this diagram also are used in the lithologic columns to link the facies in the formations exposed at Union Furnace to that environments in which they are interpreted to have formed.

Location 3-1a: Bellefonte Dolomite in outcrops to the west of parking area.

Having parked in the large pull-off on the north side of Route-453 just west of the outcrops of the Black River and Trenton units, we are in a position to walk west through exposures of the upper part of the Bellefonte Dolomite, the uppermost formation in the Beekmantown Group. Even a short walk toward the concrete bridge that lies west of the parking area provides some idea of the variety of dolomite found in this thick Lower to basal Middle Ordovician unit. It is within these outcrops that conodonts recovered from the section place the correlative conformity (or, as yet unrecognized unconformity) that separates the Sauk and Tippecanoe megasequences. Yield is very low from the Bellefonte; processing of 8-10 kg samples was required to extract the conodont data reported in Figure 3-3.

Location 3-1b: Transgressive facies of the upper Loysburg and basal Hatter formations on the south side of Route-453 across from the parking area.

Locate the green paint numbers and slash marks that indicate the boundaries between units 1, 2, and 3 at the base of the Hatter Formation and walk down section a short distance to the west (past a prominent mass of travertine exposed high on the cliff). You will find “03” painted on the outcrop near the top of an interval of cyclically interbedded limestone and dolomite in the Loysburg Formation. As the Tippecanoe transgression got underway, the very shallow, restricted depositional conditions that produced the laminated dolomite that abounds within the Bellefonte and lower part of the Loysburg gradually were replaced by more normal marine, subtidal conditions. This deepening culminates in the deposition of heavily bioturbated, massive limestone (unit 3) that Laughrey *et al.* (2004) interpreted as “lagoonal” facies.

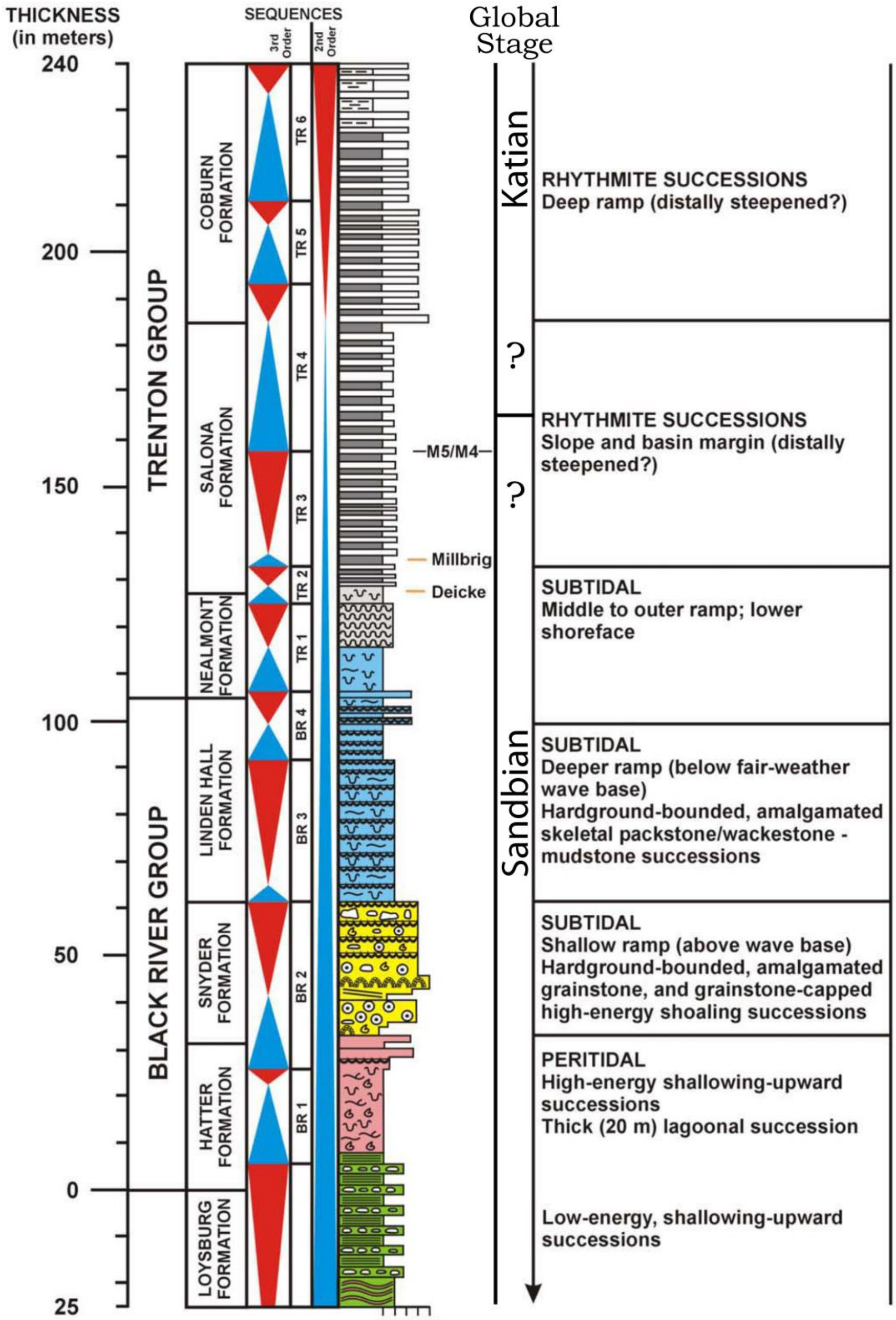

Figure 3-2: Upper Ordovician (Sandbian and Katian) lithostratigraphic units and depositional sequences in the Union Furnace measured section along Route-453 (Stop 3-1). Modified from Laughrey *et al.* (2004, fig. 17).

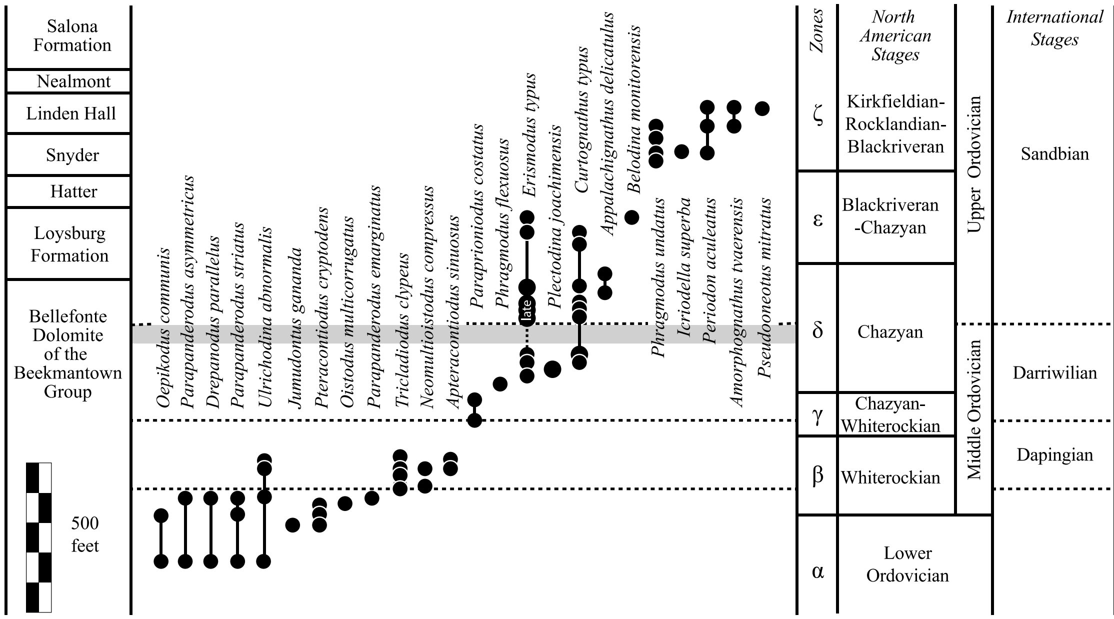

Figure 3-3: Conodont biostratigraphy in the uppermost Lower and Middle Ordovician strata of the Nittany Arch, Pennsylvania. The column headed as "Zones" and bearing Greek letters refers to conodont zones that are resolved into to the following:

α - *Oepikodus communis* to *Reutterodus andinus* zones,
β - *Neomultioistodus compressus-Tricladiodus clypeus* to *Histiodella sinuosa* zones,
γ - upper *Histiodella sinuosa* to very low *Phragmodus flexuosus* zones,
δ - *Phragmodus flexuosus* Zone,
ε - *Phragmodus flexuosus* to *Baltoniodus gerdae* zones,
ζ - *Phragmodus undatus* Zone.

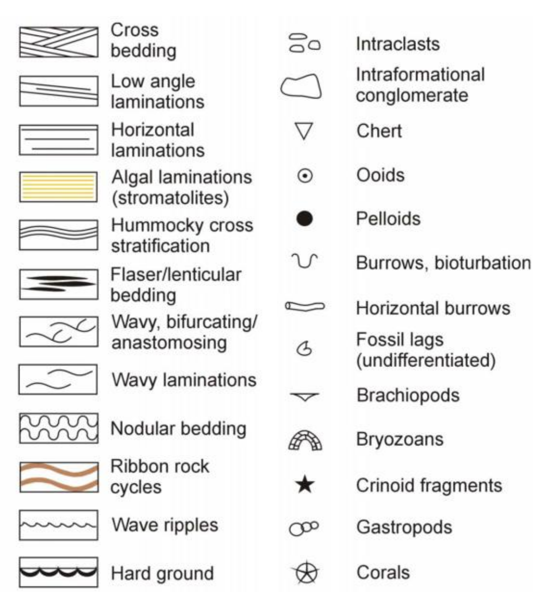

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Figure 3-4: Legend of symbols used for lithologic columns in Figures 3-6 to 3-9. From Laughrey *et al.* (2004, fig. 18).

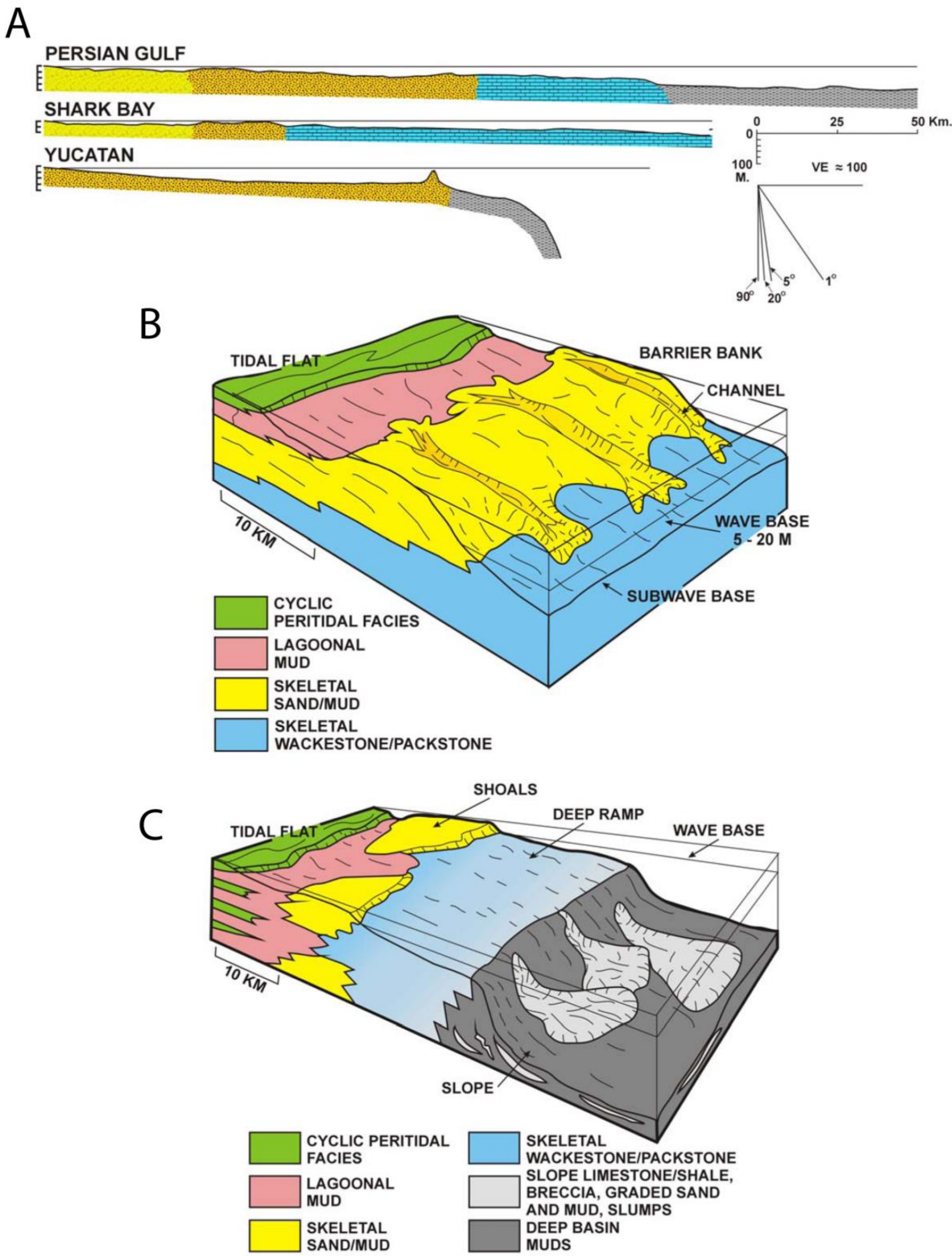


Figure 3-5: Models for carbonate ramps (From Laughrey *et al.,* 2004, fig. 14). A. Examples of modern carbonate ramps; B., C. End members of the spectrum of ancient ramp profiles described by Read (1985) from homoclinal back-barrier type ramp to distally steepened ramp.

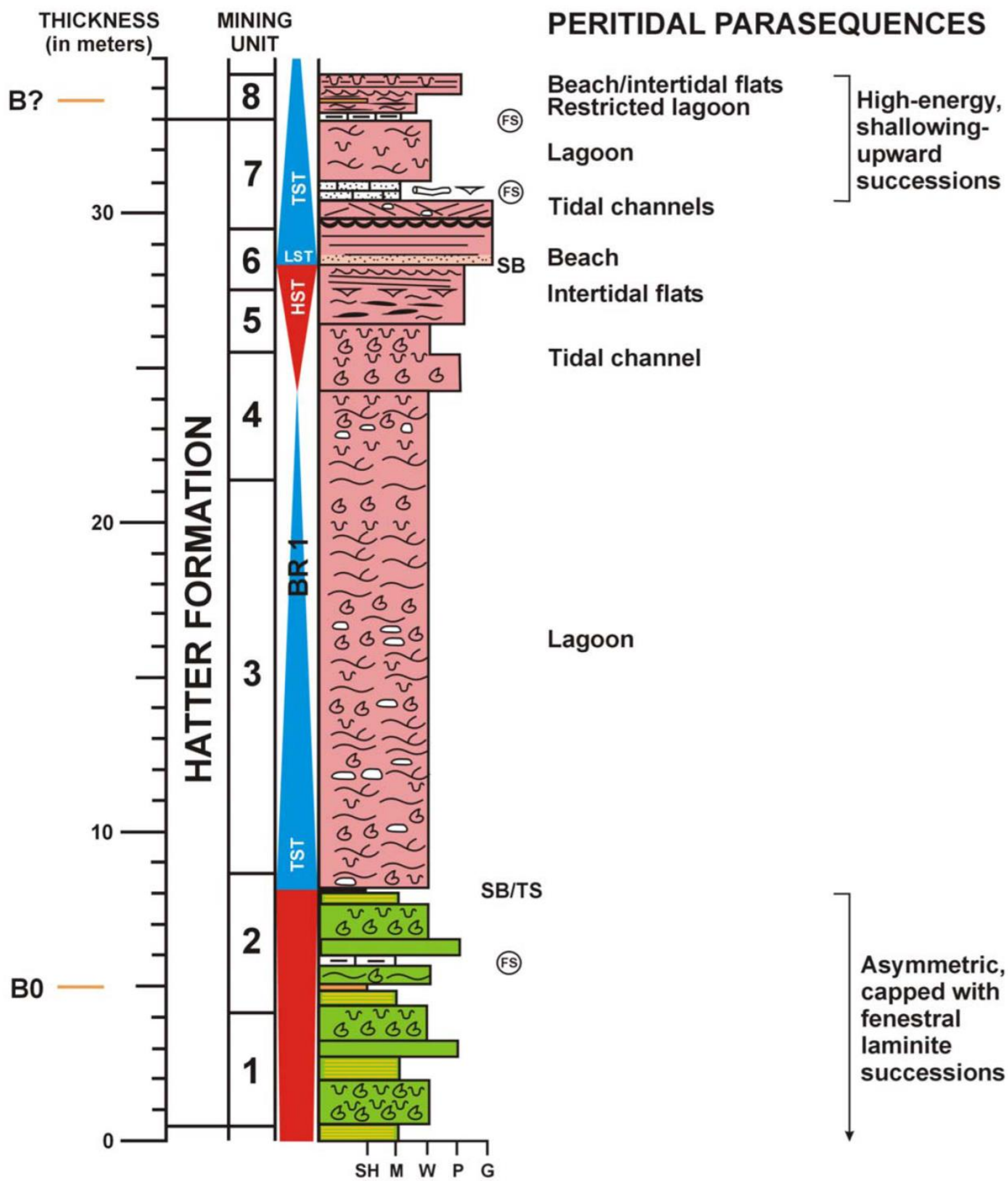


Figure: 3-6. Lithologic column showing facies, mining units, and sequence stratigraphic interpretation of Laughrey *et al.* (2004) for the Hatter Formation in the Union Furnace measured section. Abbreviations: B – Bentonite; HST- highstand systems tract; LST – lowstand systems tract; TST – Transgressive systems tract; SB – sequence boundary; SB/TS – combined sequence boundary/transgressive surface; FS – flooding surface.

Location 3-1c: Storm generated deposits in the upper Hatter Formation.

Please be careful as you cross the highway to the south side, avoiding vehicular contact. You will find the unit boundary numbers continuing upward from 3 toward the top of the Hatter Formation (Figure 3-6). The appearance of grainstone beds that are most likely tempestites and prominent hummocky cross-stratification (common in unit 5) attest to shoaling that followed the basal Hatter transgression.

Location 3-1d: Snyder Formation: short-lived transgression followed by shoaling and high-energy, highstand deposition.

A brief period of deeper subtidal deposition produced a thin but prominent dark limestone that marks a flooding surface at the base of unit 8. The remaining facies of the Snyder, however, reflect shallow conditions with extensive reworking and amalgamation of units under highstand conditions (Figure 3-7). Abundant, well-winnowed grainstone beds and numerous hardgrounds are conspicuous in the upper half of the formation, particularly in unit 15. Laughrey *et al.* (2004) interpreted the highly fossiliferous lithology that occurs at the base of several units in the Synder (e.g. unit 13) as bioherms or biostromes created by the baffling of carbonate sediment by bryozoans under subtidal conditions at the start of deposition of the small-scale, grainstone-capped, shoaling packages that compose the Snyder Formation.

Location 3-1d: Linden Hall Formation: pure carbonate deposited just prior to the arrival of fine Taconic siliciclastics (the calm before the storm).

The lithofacies of the Linden Hall (Figure 3-8) reflect deposition under somewhat deeper conditions than the underlying Snyder Formation. The greater abundance of burrowed, fine-grained carbonate and lower frequency of winnowed lithologies, attest to less frequent scour by storm waves. Having formed primarily during rising and highstand conditions, but prior to the arrival of significant amounts of fine siliciclastics generated to the east (modern coordinates) by Taconic orogenesis, the Linden Hall is an exceptionally pure carbonate that is the primary target for the quarrying of high-calcium limestone in the area.

Location 3-1e: Nealmont Formation: beginning of the end of the carbonate platform.

Dark shale interbeds appear and increase in abundance upward in the Nealmont Formation, the basal formation of the Trenton Group. This change reflects the increasing influence of an easterly fine siliciclastic sediment source and deepening of the environment as a result of increased subsidence and/or the damping effect of the fine clastic influx on carbonate production. This trend continues into the overlying Salona Formation.

K-bentonite beds are numerous in the Trenton Group carbonates due to the increased proximity of the volcanic arc providing the ash and/or more frequent preservation of ash fall deposits in deeper environments that experienced less scour and reworking of the sediment surface.

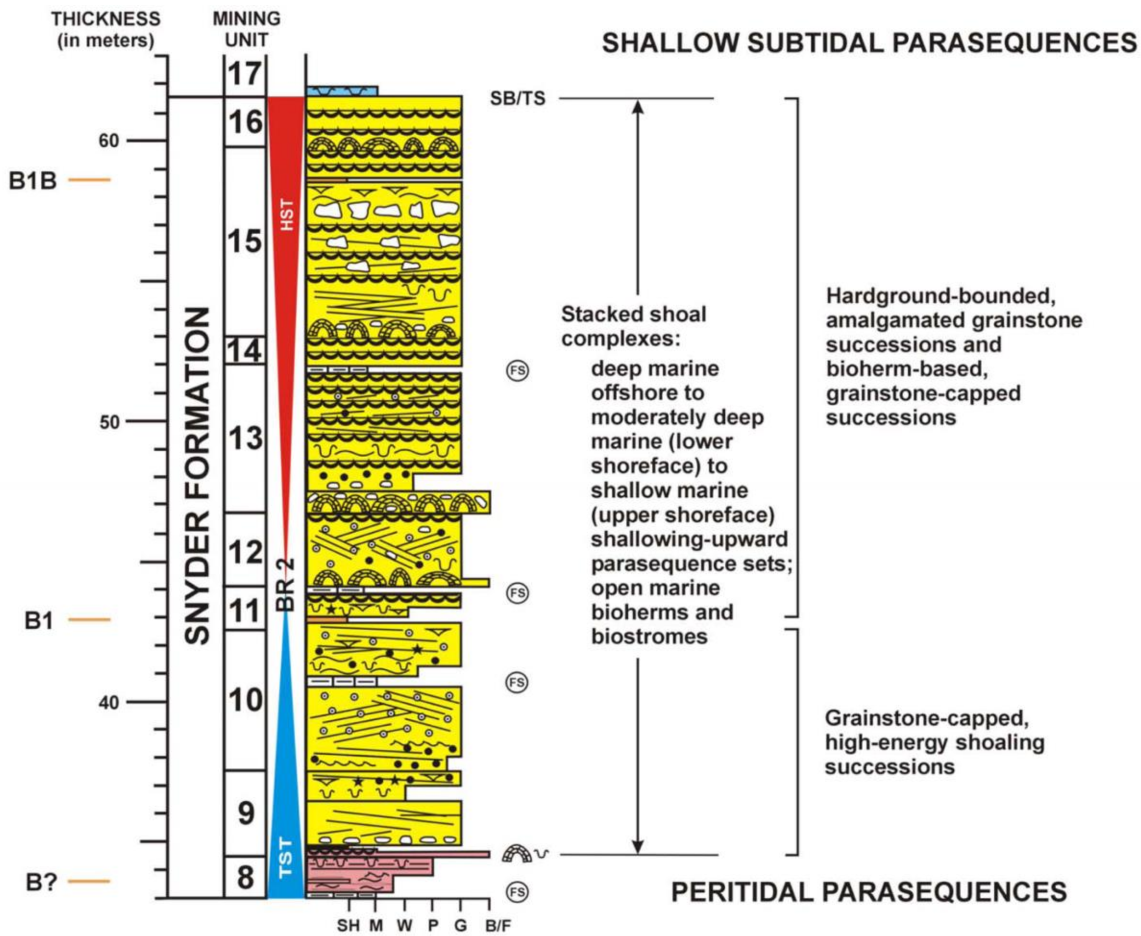


Figure 3-7: Lithologic column showing facies, mining units, and sequence stratigraphic interpretation of Laughrey *et al.* (2004) for the Snyder Formation in the Union Furnace measured section. Abbreviations: B – Bentonite; HST- highstand systems tract; LST – lowstand systems tract; TST – Transgressive systems tract; SB – sequence boundary; SB/TS – combined sequence boundary/transgressive surface; FS – flooding surface.

Location 3-1f: Salona Formation: foundering of the Great American Carbonate Bank.

The lime mudstone–dark shale rhythmites of the Salona Formation are the classic deep-water facies of the Trenton Group. Mitchell *et al.* (this guidebook, Stop 4-1; Lithostratigraphy) detail the two members recognized within the Salona and participants are referred to that thorough treatment.

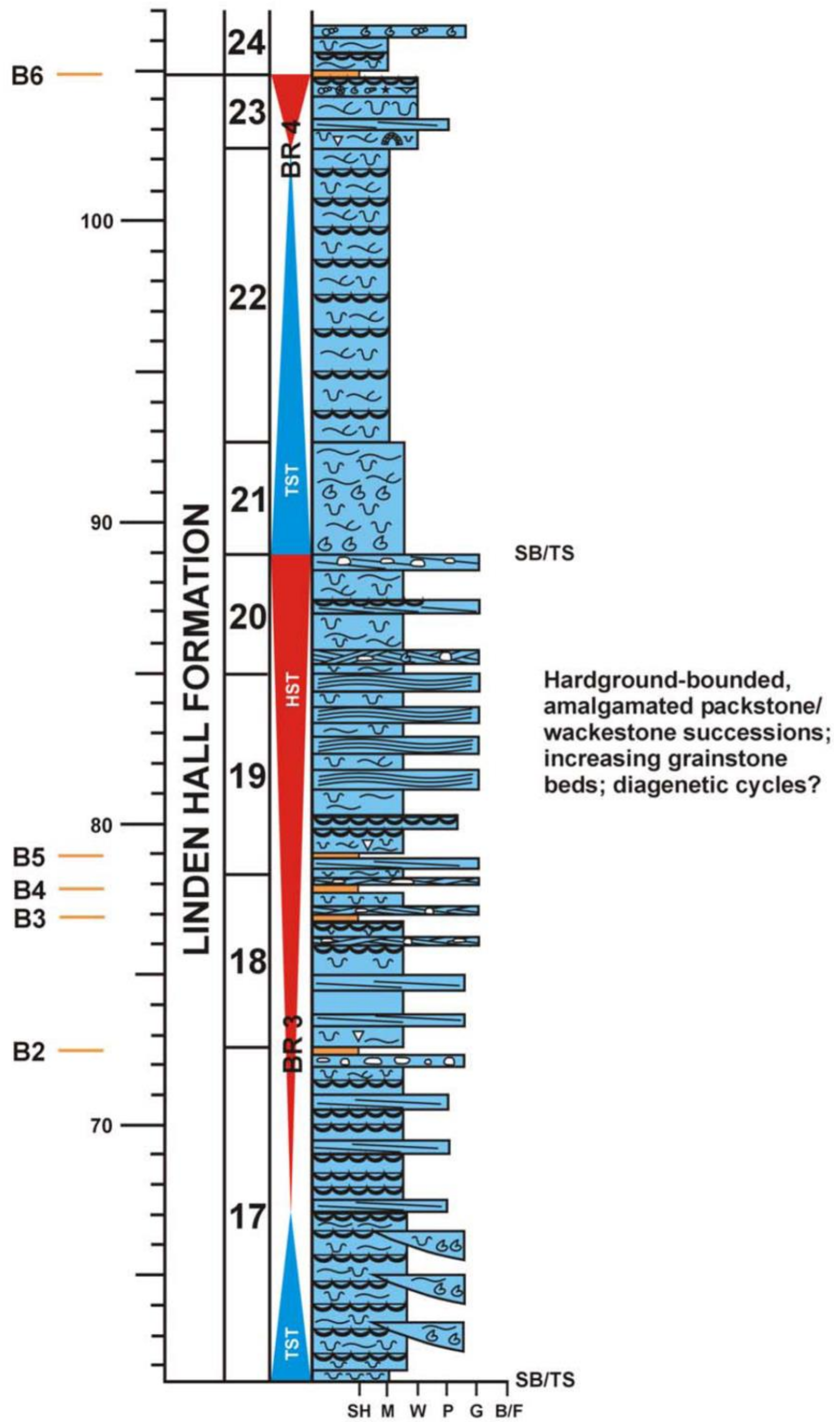


Figure 3-8: Lithologic column showing facies, mining units, and sequence stratigraphic interpretation of Laughrey *et al.* (2004) for the Linden Hall Formation in the Union Furnace measured section. Abbreviations: B – Bentonite; HST- highstand systems tract; LST – lowstand systems tract; TST – Transgressive systems tract; SB – sequence boundary; SB/TS – combined sequence boundary/transgressive surface; FS – flooding surface.

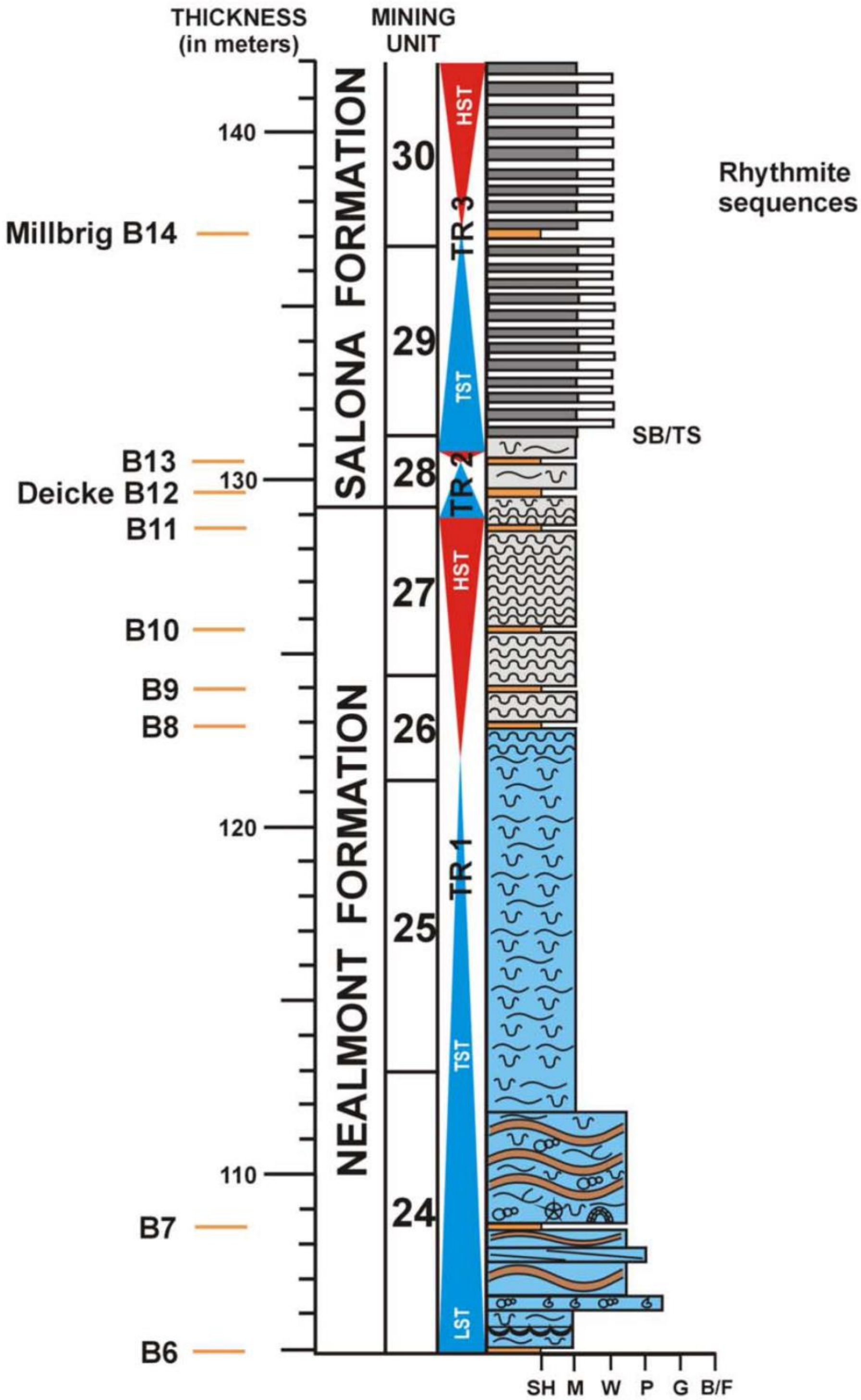


Figure 3-9: Lithologic column showing facies, mining units, and sequence stratigraphic interpretation of Laughrey *et al.* (2004) for the Nealmont and lower Salona formations in the Union Furnace measured section. Abbreviations: B – Bentonite; HST- highstand systems tract; LST – lowstand systems tract; TST – Transgressive systems tract; SB – sequence boundary; SB/TS – combined sequence boundary/transgressive surface; FS – flooding surface.

Location 3-1g: Coburn Formation: a brief (but futile) reversal of the deepening trend.

Somewhat surprisingly, this uppermost formation in the Trenton Group displays abundant bioclastic beds created by winnowing of the deep ramp sediment by storm scour. The reader is again referred to the description provided by Mitchell *et al.* (this guidebook, Stop 4-1; Lithostratigraphy) for a detailed treatment of the lithologic description and environmental interpretation of this unit. Among the features noted in that original description is the appearance of the trepostome bryozoan *Prasopora*, in a zone at the very base of the Coburn. Subsequent addenda credit Roger Cuffey and Donald Hoskins as having correctly identified the fossils as the tabulate coral *Lichenaria*. Specimens are well expressed here in the Union Furnace section where large coral colonies are visible on the weathered surface of the basal bed of the Coburn Formation. **PLEASE** do not hammer on or collect specimens from that bed; it has survived for decades despite visits of countless geologists to this outcrop and should be left for later visitors to examine.

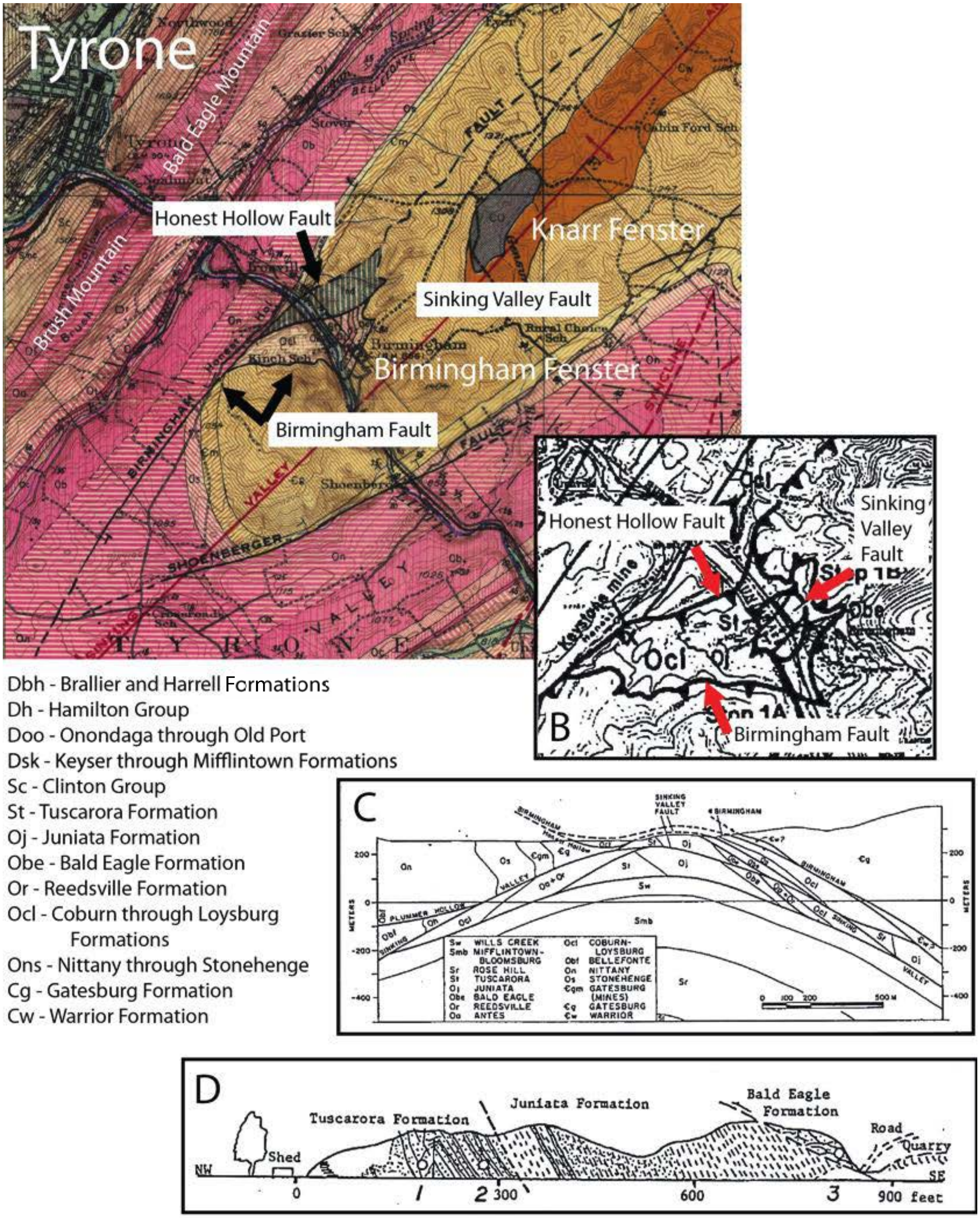
Stop 3-2: Birmingham Fenster, road cut along Route-453 northwest of Birmingham, Pennsylvania.
Coordinates: Latitude 40° 38' 59' 45" N; Longitude 78° 11' 56' 60" W.

In central Pennsylvania, the Silurian Tuscarora Quartzite supports the major ridges, including Brush Mountain and Bald Eagle Mountain to our immediate northwest. Viewed in profile the Ordovician Bald Eagle Sandstone forms a lower, secondary ridge separated from the Tuscarora by the Ordovician Juniata Formation. These 3 formations that form the prominent Bald Eagle Mountain are repeated in a low road cut along Route-453 and this exposure represent one of the significant geological enigmas in Pennsylvania, the Birmingham Fenster.

The rocks exposed within heart of the Birmingham Fenster include the Tuscarora to Bald Eagle to the northwest along the road to the Ordovician Reedsville Shale southeast of the parking area. Within the fenster these rocks are overturned and dip toward the southeast. Intriguingly, the stratigraphic thickness is reduced by as much as an estimated 90% (Swartz, 1966) for the Bald Eagle and Reedsville exposures without significant internal deformation evident. These rocks are surrounded by the Sinking Valley Fault (Figure 3-10). The fenster is completed with the exposure of Ordovician Coburn through Loysburg limestones outlined on the north by the Honest Hollow fault and on the south by the extension of the Birmingham Fault. To the south the Cambrian Gatesburg Formation is brought into fault contact with, and overlies the rocks of the fenster.

Facing page

Figure 3-10: Geology of the Birmingham, Pennsylvania, region including the Birmingham Fenster: A, Detail of the geologic map of the Tyrone 15' quadrangle from Butts *et al.* (1939); B, Geologic map and structural cross-section from Harper and Laughrey (1996); C, Structural cross-section from Faill (1987); D, Outcrop sketch from road cut along Route-453 from Gold and Pohn (1985).


Tyrone
Bald Eagle Mountain
Brush Mountain
Honest Hollow Fault
Knarr Fenster
Sinking Valley Fault
Birmingham Fenster
Birmingham Fault
Dbh - Brallier and Harrell Formations
Dh - Hamilton Group
Doo - Onondaga through Old Port
Dsk - Keyser through Mifflintown Formations
Sc - Clinton Group
St - Tuscarora Formation
Oj - Juniata Formation
Obe - Bald Eagle Formation
Or - Reedsville Formation
Ocl - Coburn through Loysburg Formations
Ons - Nittany through Stonehenge
Cg - Gatesburg Formation
Cw - Warrior Formation
B
Honest Hollow Fault
Sinking Valley Fault
Birmingham Fault
C
Sw WILLS CREEK
Smb MIFFLINTOWN-BLOOMSBURG
Sr ROSE HILL
St TUSCARORA
Oj JUNIATA
Obe BALD EAGLE
Or REEDSVILLE
Oa ANTES
Ocl COBURN-LOYSBURG
Obf BELLEFONTE
On NITTANY
Os STONEHENGE
Cgm GATESBURG (MINES)
Cg GATESBURG
Cw WARRIOR
METERS
D
Tuscarora Formation
Juniata Formation
Bald Eagle Formation
Shed
Road
Quarry
NW
SE
0
300
600
900 feet

The Birmingham Fenster, as well as the less well-exposed Knarr Fenster to the northeast, lie astride the axis of the Sinking Valley Anticline (Figure 3-10A). The Birmingham and Shoenburger Faults flank the anticlinal axis, converging as the anticline plunges toward the southwest. Traced into the subsurface in drill core, the Sinking Valley Fault is arched and appears to mimic the anticlinal fold. Given the small outcrop area and limited subsurface data, there have been multiple hypotheses advanced to explain the structural complications associated with the Birmingham Fenster (see Gold and Pohn, 1985, for a summary). The hypothesis illustrated by Faill (1987; Figure 3-10C) shows the Sinking Valley Fault as the major regional thrust accounting for up to 2 miles of offset to the northwest. In this hypothesis the Honest Hollow and Birmingham Faults are splays off of the Sinking Valley Fault. However, as Gold and Pohn (1985) noted, "It is unlikely that the final chapter on the Birmingham fenster will be written without additional deep drilling and detailed subsurface seismic profiling."

Stop 3-3: Stonehenge Formation in the northern Nittany Arch near Bellefonte, Pennsylvania.
Coordinates: Latitude 40° 53' 38" N; Longitude 77° 46' W.

A composite section of the entire Stonehenge Formation, from its basal contact with the Mines Member of the Gatesburg Formation to its boundary with the overlying Nittany Dolomite, was assembled from exposures on both limbs of an anticline crossed by Pennsylvania Route-144 on the southeastern outskirts of Bellefonte, Pennsylvania (Figure 3-11). The sections on the north limb are referred to as the Bellefonte North and Bellefonte South sections. Those on the southern limb near the village of Axemann are designated the Axemann North and Axemann South sections. Four informal members are recognized in the Stonehenge in this area (Donaldson, 1959; Taylor *et al*., 1992): the Spring Creek, Graysville, Baileyville, and Logan Branch members (in ascending order). As is discussed in greater detail below in the narrative for Stop 3-3a, the basal Spring Creek member is a thin interval of uppermost Gatesburg cyclic facies that escaped dolomitization by the fluids that formed the underlying Mines Member. The three higher members of the Stonehenge are more nearshore equivalents of the Stoufferstown, middle, and upper members of the Stonehenge in its type area in the Cumberland Valley.

Each of the five stops in the Bellefonte area provides continuous exposure across at least one of the member or formation boundaries within the Stonehenge (Figure 3-12). The entire Spring Creek member and both of its contacts are exposed in the Bellefonte South (Stop 3-3a) section. The contact between the overlying Graysville and Baileyville members is best exposed in the Axemann North section (Stop 3-4a). The Baileyville-Logan Branch member contact is visible in the Bellefonte North (Stop 3-3b) section, and is only slightly concealed in the Axemann South section (Stop 3-4b). A small section along railroad tracks at Stop 3-4c provides continuous exposure of the upper half (or more) of the Logan Branch member and basal strata of the overlying Nittany Dolomite. Tremadocian trilobites and conodonts recovered from all these sections allow fairly accurate placement of biozonal boundaries within the middle and upper part of the Laurentian Skullrockian Stage.

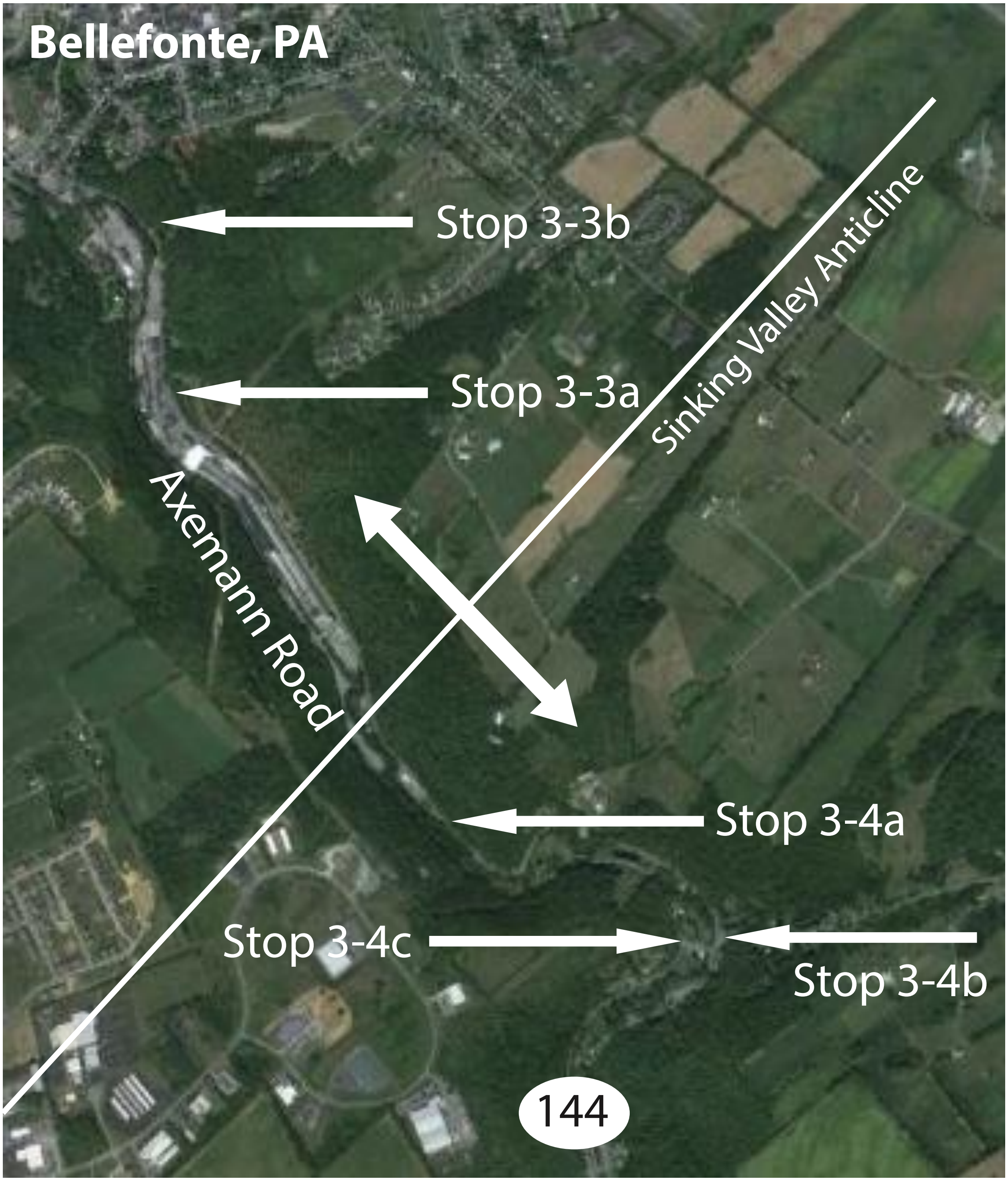


Figure 3-11: Modified Google Earth image showing stops in the Stonehenge Formation and bounding units along Route-144 south of Bellefonte, Pennsylvania.

Stop 3-3a: Bellefonte South measured section: Uppermost strata of the Gatesburg Formation (Mines Member) and basal members of the Stonehenge Formation.

NOTE: Regrettably, the location of this outcrop on the inner side of a sharp bend in Route-144 renders it extremely perilous; vehicles approaching from the south pass extremely close to rocks as they navigate the curve and drivers cannot see anyone alongside the road to the north. Given the danger posed by passing vehicles, we will not examine the outcrop on the east side of the road; we will gather as a group on the west side of the highway where trip leader(s) will point out the critical features of the outcrop from a safe position.

Patchy exposures of cherty dolomite on the slopes to the right (south) represent the uppermost part of the Mines Dolomite Member of the Gatesburg Formation. Careful inspection of these rocks reveals that the coarsely crystalline and vuggy dolomite alternates in cycles with finely crystalline and finely laminated dolomite in meter scale cycles. The chert in the Mines Member formed prior to the late stage dolomitization that produced the vuggy, non-laminated dolomite that occurs at the base of the cycles, and much of it preserves the primary fabric of the precursor carbonate. Those preserved fabrics reveal that the original lithology at the base of many cycles was oolitic grainstone. This silicified oolite, known locally as the "State College Oolite", displays such exquisite and visually appealing fabrics that it is used to by some local businesses to produce jewelry. The scientific significance of the preserved oolitic fabric in the cherts is to confirm that the precursor carbonate of the dolomite in the uppermost Mines Member was identical to the cyclically interbedded oolitic packstone/grainstone and dolomitic laminites that make up the Spring Creek member of the overlying Stonehenge. The contact between dolomite and limestone used to map the base of the Stonehenge in this area is a diagenetic boundary, not a depositionally significant horizon.

Even from across the highway, a stark contrast in lithofacies is apparent between the cyclic, laminite-rich facies of the Spring Creek member on the right (south) and less resistant, shaly, and non-cyclic strata of the overlying Graysville member to the left (north). The boundary between the two is sharp, coinciding with the base of a prominent flat pebble conglomerate (intraclastic rudstone) that represents a transgressive lag deposited atop the flooding surface formed during the Stonehenge Transgression. Biostratigraphic data from the base of the Graysville member in this and other sections in the Nittany Arch, compared with those from uppermost Conococheague and basal Stonehenge strata in the Cumberland Valley, confirm age equivalence of this flooding surface and the base of the Stoufferstown Member in the type area. Conodonts recovered from both areas time the Stonehenge Transgression as having occurred during deposition of the *Cordylodus angulatus* Zone. This is consistent with the age provided by recovery of *Clelandia texana* from the strata directly overlying the flooding surface in both areas (Figure 3-11, 3-12), a geographically widespread but short-ranging species restricted to the middle of the *Symphysurina* Zone throughout Laurentian North America (Taylor *et al*., 1992; Taylor, 1999). Like the facies of the Baileyville member, the abundant flat pebble conglomerate and coarse grainstone beds of the Graysville member reflect shallower, more energetic conditions in the inner shelf environment than prevailed during deposition of the thinly bedded lime mudstone that dominate the equivalent Stoufferstown Member in the Cumberland Valley.

Figure 3-12. Stonehenge Formation lithologies, interpretation of water depth, and relative position of the 5 measured sections of Stop 3-3 and Stop 3-4 in the Bellefonte, Pennsylvania, region. No stratigraphic thicknesses are implied.

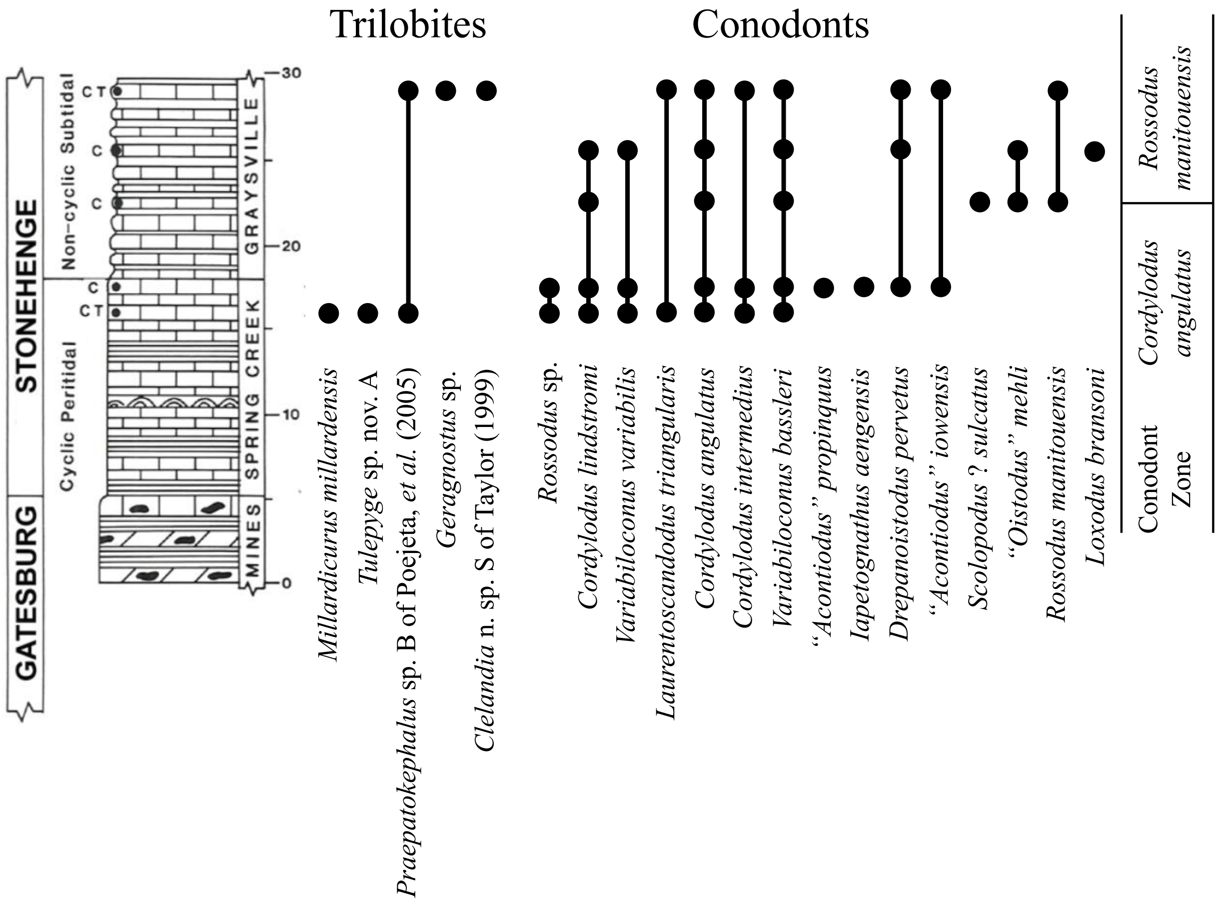


Figure 3-12: Generalized lithologic column and species range chart for the lower Stonehenge Formation in the Bellefonte South measured section (Stop 3-3a). Modified from Taylor *et al.* (1992).

An earliest Tremadocian trilobite fauna recovered from a burrowed oolitic packstone interval only 2m below the top of the Spring Creek member at this locality includes two species that extend correlations to successions well beyond the central Appalachians. One is a previously undescribed species of the dimeropygid *Tulepyge*, a genus first described from basal Tremadocian strata in Utah (Adrain and Westrop, 2006), and more recently reported from the basal Ordovician of Greenland (McCobb e*t al*., 2014). The dominant species in the upper Spring Creek collection, however, is a remopleurid species identified as *Praepatokephalus* sp. B by Pojeta e*t al*., (2005). This as yet undescribed, and apparently oldest known, species of *Praepatokephalus* very strongly resembles an important earliest Tremadocian species from the Nya Horizon in western Siberia described by Rosova (1968) as *Apatokephalus nyaicus.*

Stop 3-3b: Bellefonte North measured section: Upper part of the Baileyville member and lower to middle part of the Logan Branch member.

The uppermost part of the Baileyville member is exposed in an abandoned (and badly overgrown) quarry at this location. The member is truncated by a large fault a short distance south of the quarry. Characteristic lithofacies of the Baileyville include medium to thickly bedded microbial boundstone and associated coarse intraclastic and bioclastic grainstone. One thick, prominently burrowed grainstone bed in the center of the quarry contains numerous rostroconchs of the genus *Anisotechnophorus.* Throughout the Baileyville, these blocky, reef and grainstone packages are regularly interbedded with dolomitic planar microbial laminite, a supratidal lithology very rare in the equivalent middle member of the Stonehenge in the Cumberland Valley. This contrast in facies with the outer shelf strata in the Cumberland Valley, along with significant thinning of the formation northwestward into the Nittany Arch, reflects less accommodation space and shallower environmental conditions in inner shelf areas during Stonehenge deposition. The upper surface of one laminite bed is spectacularly exposed just to the north of the quarry, displaying conspicuous desiccation cracks and perhaps horizontal burrow networks. A unique, particularly thick and arenaceous laminite very high in the Baileyville is exposed in the north wall of the quarry. This sandy laminite, which is also exposed in the Axemann South section on the other limb of the anticline, records extreme shallowing at the top of the asymmetrical, 3rd order shoaling cycle that the Graysville and Baileyville together compose.

The small outcrops just north of the quarry on the east side of Route-144 consist of the highly fossiliferous, thinly bedded grainstone of the Logan Branch or upper member of the Stonehenge. Some of the coarser beds yield numerous sclerites of the asaphine trilobite *Bellefontia collieana*. This is, in fact, effectively type material for that species and also for the genus as *B. collieana* is the type species. These highly fossiliferous beds also contain other trilobite species of such typical Skullrockian genera as *Clelandia* and several hystricurid genera. The presence of *Hintzecurus*, which is restricted to the upper third of the *Bellefontia* Zone in the type area of the Ibexian Series in Utah, confirms that these strata lie very near the top of the Skullrockian Stage. In addition to trilobites, the grainstone beds of the Logan Branch yield abundant large, nearly planispiral gastropods (*Ophileta?* sp.). Loss of outcrop to the north as the intersection with Forge Road is approached precludes evaluation of the uppermost beds of the Stonehenge. The next exposure to the north consists of Nittany Dolomite on the north side of Forge Road.

Stop 3-4a: Axemann North measured section: Graysville (Stoufferstown) and Baileyville members of the Stonehenge Formation.

Although the base of the Stonehenge Formation is concealed at the base of this measured section, the uppermost coarse, bioclastic grainstone beds of the Spring Creek member are exposed. A small logging road that ascends the hillside on the east side of Route-144 at this locality provides access to those isolated, uppermost Spring Creek strata, and to the more remarkable facies of the overlying Graysville member. The Graysville includes a large patch reef of thrombolitic microbial boundstone with flanking and draping beds of coarse bioclastic grainstone. Additional, isolated thrombolitic reefs occur higher in the member, occurring in larger numbers toward the gradational boundary with the overlying Baileyville Member. These small patch reefs, and the abundant intraclastic rudstones that characterize the Graysville member, are reasonably well exposed in the small roadcuts along the east side of Route-144 to the south of the large patch reef higher on the slope along the logging road. The base of the Baileyville is placed at the lowest, thickly bedded coarse grainstone that lies only a short distance stratigraphically below the lowest blocky microbial biostrome with a dolomitic laminite cap.

Trilobites recovered from several horizons within the Graysville member in this section, and another section near Graysville, Pennsylvania a short distance to the south, reveal rapid turnover of *Clelandia* species through the member with *C. texana* occurring only from the basal meter the Graysville, giving way upward to a new species (referred to here and in Taylor [1999] as *C.* n. sp. S) in the middle of the member, and *C. parabola* in the uppermost few meters of the unit (Figure 3-13). Recovery of the asaphine trilobite *Xenostegium franklinense* with *C. parabola* in the Graysville section assigns that youngest species of *Clelandia* in the Graysville to the *Bellefontia* trilobite Zone. This is consistent with the association of *C. parabola* in the Tribes Hill Formation to the north in New York State with *Bellefontia gyracantha* (Westrop *et al*., 1993). The two older species of *Clelandia* from the middle (*C. texana*) and upper (*C.* n. sp. S) parts of the *Symphysurina* Zone are not present in New York because rocks of that age are not preserved there, but are missing at the unconformity at the base of the Tribes Hill (Landing *et al*., 2012).

Stop 3-4b: Axemann South measured section: Upper part of the Baileyville member and Logan Branch member of Stonehenge Formation.

The lower part of the Axemann South section displays the alternation of blocky, thick-bedded limestone and dolomitic planar microbial laminites that characterizes the Baileyville member. Some of the limestone is coarse bioclastic grainstone, but most consists of fine-grained carbonate with dolomitic mottling whose origin is difficult to impossible to determine on outcrop. Without clear delineation of the margins of constituent bioherms by termination of bedding in inter-mound sediment against the non-bedded microbial boundstone of the reefs, these fine-grained carbonates might be moderately burrowed lime mudstone to wackestone. One prominent bed with well-defined bioherms in the upper part of the Baileyville member is among the features worth examining at this stop. The grainstone beds in the Baileyville have not been as productive for identifiable trilobites as those in the Graysville and Logan Branch. One exception is a series of undulating, thin, very coarse-grained bioclastic grainstone just below the bed with prominent microbial mounds. A large collection recovered from those thin grainstone beds contains a fourth, again not-yet-described, species of *Clelandia* (*C.* n. sp. T) and a hystricurine species very similar to, if not conspecific with, what Stitt (1977) described as *Hystricurus globosus* from his *Bellefontia collieana* Subzone in Oklahoma. Not far above these grainstone beds, the unique arenaceous dolomitic laminite toward the top of the Baileyville is well exposed. As previously noted, these uppermost strata of the Baileyville record very shallow deposition prior to the second major Tremadocian transgression that again rapidly submerged the platform initiating deeper subtidal deposition at the base of the Logan Branch member. Like the Graysville and Baileyville members below them, the Logan Branch and cyclic peritidal deposits at the base of the overlying Nittany Dolomite constitute an asymmetrical, 3rd order, upward shoaling (regressive) cycle.

Although discontinuously exposed, the Logan Branch member in the Axemann South section has yielded some of the richest collections yet recovered from the Stonehenge Formation. The fauna differs little from that recovered from the Logan Branch exposures in the Bellefonte North section, except that some of the highest collections are exceptionally rich in hystricurid species. In addition to *Hintzecurus*, some of the beds very high in the Logan Branch here have yielded a rather smooth hystricurid that might represent the genus *Paraplethopeltis*. This genus has never been reported from the Skullrockian Stage; it appears at the base of the overlying Stairsian Stage throughout Laurentian North America, dominating the fauna of a thin *Paraplethopeltis* Zone at the base of that stage. Two new subzones based on different species of *Paraplethopeltis* were recently established in western North America (Adrain *et al*., 2014). If the relatively smooth genus in the beds at the top of the Axemann South section is indeed *Paraplethopeltis*, then either the highest strata of the Stonehenge span the Skullrockian-Stairsian Stage boundary, or they contain an older species of that genus than previously reported and extend the established range of *Paraplethopeltis* downward into the uppermost Skullrockian.

Stop 3–4c: Axemann Railroad measured section: Logan Branch member of the Stonehenge Formation and basal strata of the Nittany Dolomite.

Most of the Logan Branch member is present in the continuous exposure along the eastern side of a railroad cut just south and west of the top of the Axemann South section. Most importantly, the low cliffs here allow examination of the transition into the overlying Nittany Dolomite, a contact that is covered in most sections in the Nittany Arch. Although the depositional fabrics are difficult to discern in the basal strata of the Nittany, some beds not far above the uppermost definite Logan Branch limestone do appear to be dolomitized meter-scale cycles, providing physical evidence of shallowing. Although this is equivocal, conclusive evidence of shallower conditions is found farther up-section at the south end of the railroad cut where a thin interval of non-dolomitized stromatolitic boundstone is preserved. These stromatolitic reefs low in the Nittany also yielded a conodont fauna with abundant *Clavohamulus densus*, a species characteristic of the *Rossodus manitouensis* Zone that is commonly recovered from reefs in the upper Skullrockian, but also in the very lowest Stairsian.

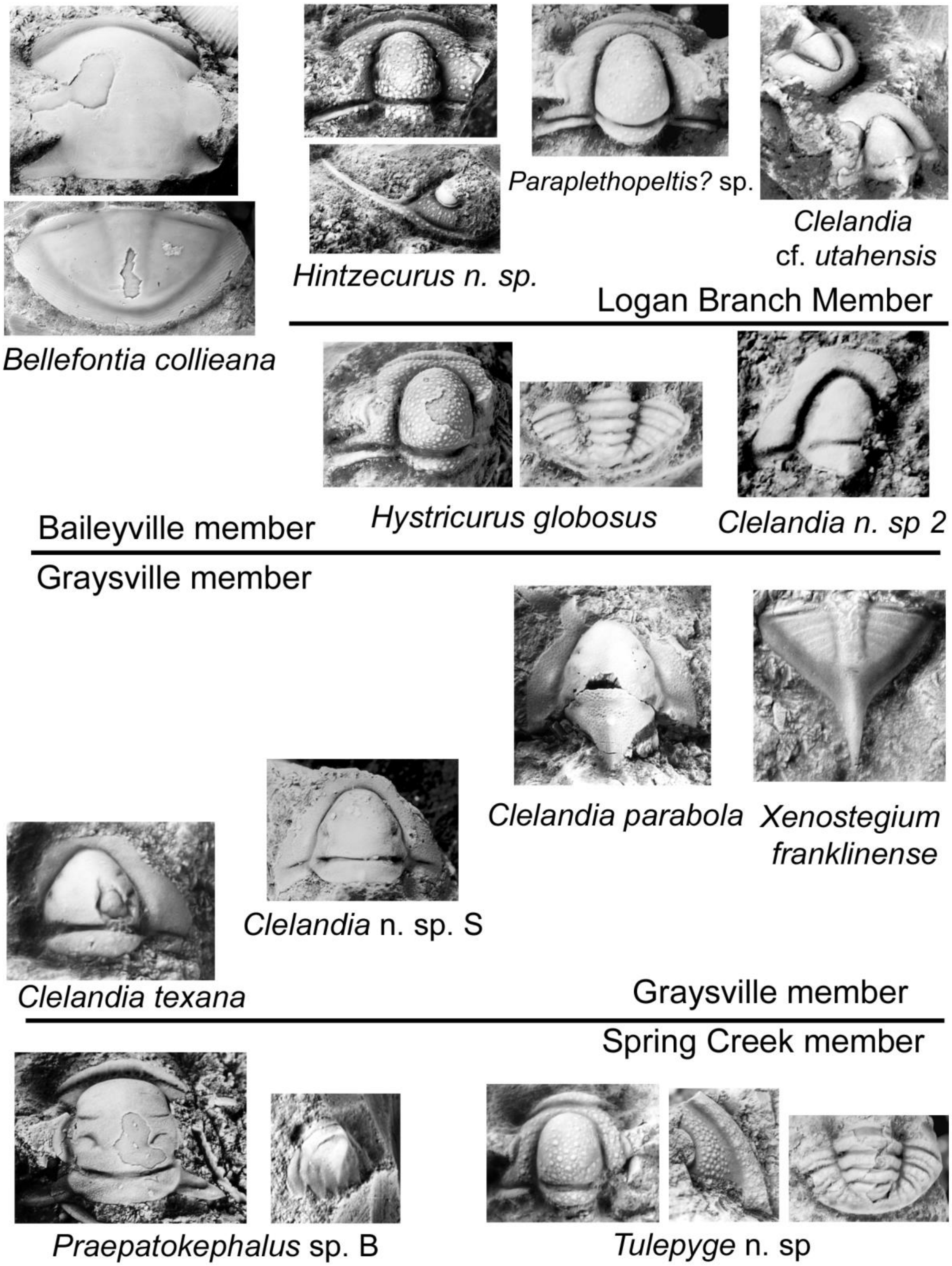


Figure 3-13: Trilobite species recovered from the informal members of the Stonehenge Formation in the measured sections southeast of Bellefonte, Pennsylvania.

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Chapter 4: Active margin carbonates and basal Martinsburg Formation (Antes Shale) in the northern Kishacoquillas Valley, Reedsville, Pennsylvania

Charles. E. Mitchell, Bryan K. Sell, and Daniel Goldman.

Stop 4-1: Reedsville, Pennsylvania. Roadside exposure along the exit ramp from State Route-322 northbound onto Pennsylvania Route-665.
Co-ordinates: Latitude 40° 40' 05" N; Longitude 77° 36' 18" W.

Section overview. The descending exit ramp passes through a long road cut exposure. The rocks form part of the southeastern limb of the Jacks Mountain Anticlinorium, strike northeast and dip at about 45° to the southeast. Behind us, to the northwest, lies the broad Kishacoquillas Valley, which was formed by the deep erosion of the Cambrian - Ordovician carbonate core of the structure, and in front of us rises the high, narrow Jacks Mountain, which is held up by the quartzites of Tuscarora Formation (lower Silurian). The base of the off-ramp succession lies in the Nealmont Formation at the intersection with Route-665 and its top is within the lower part of the Antes Shale (Figures 4-1, 4-3). The section includes several of the late Sandbian super ash-fall deposits, a diverse (but not easily collected) shelly fauna, as well as the interval of the GICE (Guttenberg carbon isotope excursion) and early Katian graptolites. The upper part of the Coburn Formation, both here and at a road cut along Route-322 near the Milroy, exhibits an interval of strong deformation. Nickelsen (1988, 1996, 2009) and others have mapped this deformed zone as a folded thrust, regionally known as the Antes-Coburn detachment, which extends along the entire length of the Jacks Mountain Anticlinorium and marks the location of a roof thrust between the duplex of Cambrian - Ordovician carbonates that form the cores of the Valley and Ridge anticlinal structures and the overlying, dominantly clastic cover succession (Figure 4-2).

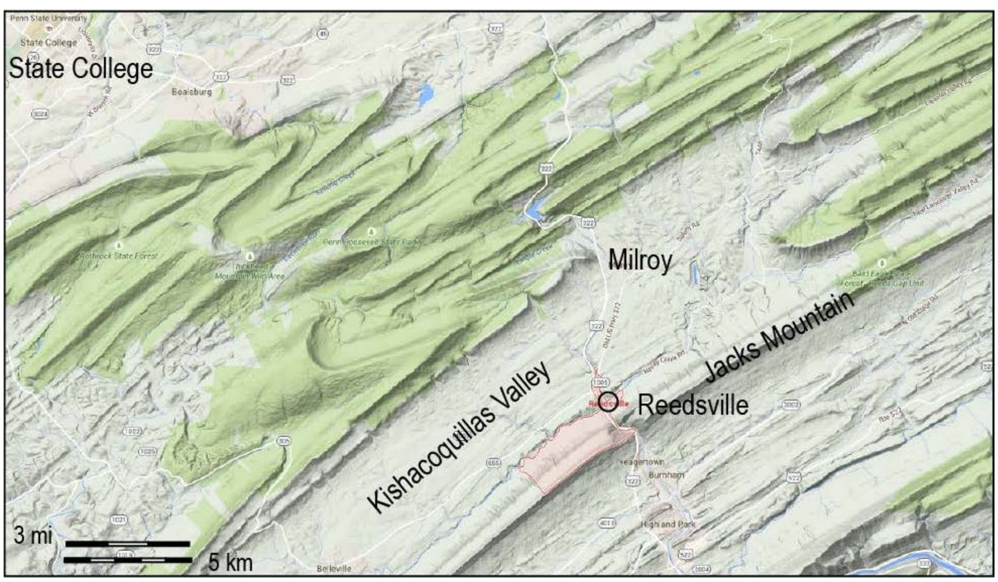

Figure 4-1: Shaded relief map of State College to Reedsville, Pennsylvania (modified from Google Maps) showing the location of the site relative to the regional physiography.

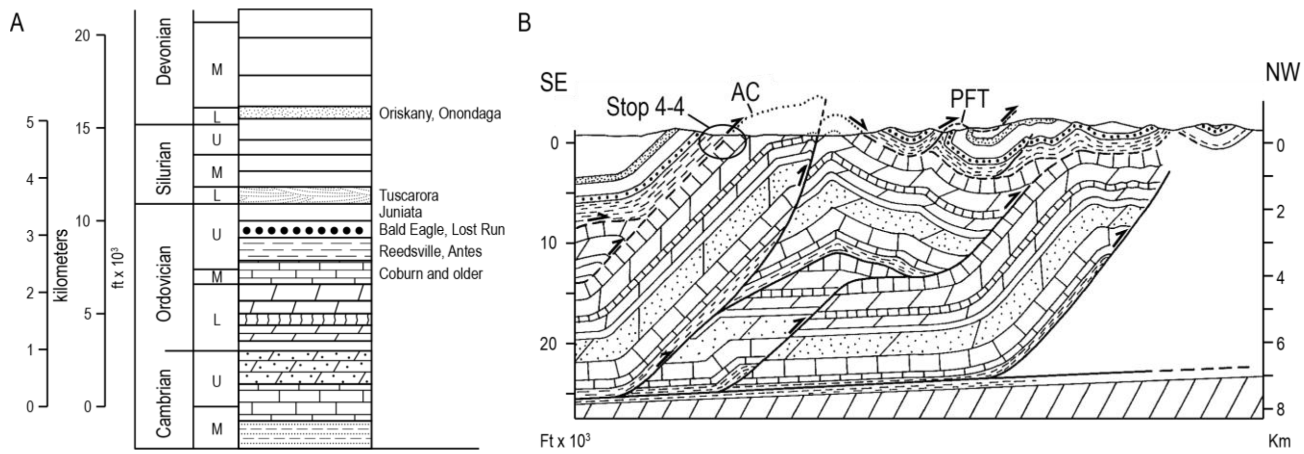

Figure 4-2: A. Generalized stratigraphy and thickness in the vicinity of the Jacks Mountain Anticlinorium at Reedsville, Pennsylvania; B. Structural cross-section of the Jacks Mountain Anticlinorium (redrawn from Nickelsen, 1988) showing location of Stop 4-4 at Reedsville relative to this regional picture. Abbreviations: AC - Antes-Coburn detachment; PFT - Potlicker Flat Thrust.

Lithostratigraphy. The upper part of the **Nealmont Formation** forms the base of the Reedsville off-ramp succession (Figure 4-4; Kay, 1944; Thompson, 1963; Laughrey *et al*., 2004). According to Laughrey *et al.* (2004, p. 66) this unit consists of "…thick bedded, bioturbated wackestones and mudstones, with subordinate packstone lags and discontinuous skeletal floatstone and pelloidal/skeletal grainstone lenses. Wavy and undulatory, argillaceous and dolomitic laminae and bands grade up to nodular bedding in the upper part of the formation." The upper member of the unit, the Rodman Member, is predominantly nodular bedded, "…coarser grained and more fossiliferous than the underlying wavy bedded Centre Hall Member." They concluded that these strata appear to have been deposited in a mid-ramp setting, beyond the inner ramp shoals as part of a single ~ 40 m-thick stratigraphic sequence (T-R) cycle. The contact with the overlying Salona Formation is conformable and falls within the early transgressive part of the succeeding T-R cycle (Laughrey *et al*., 2004, fig. 59).

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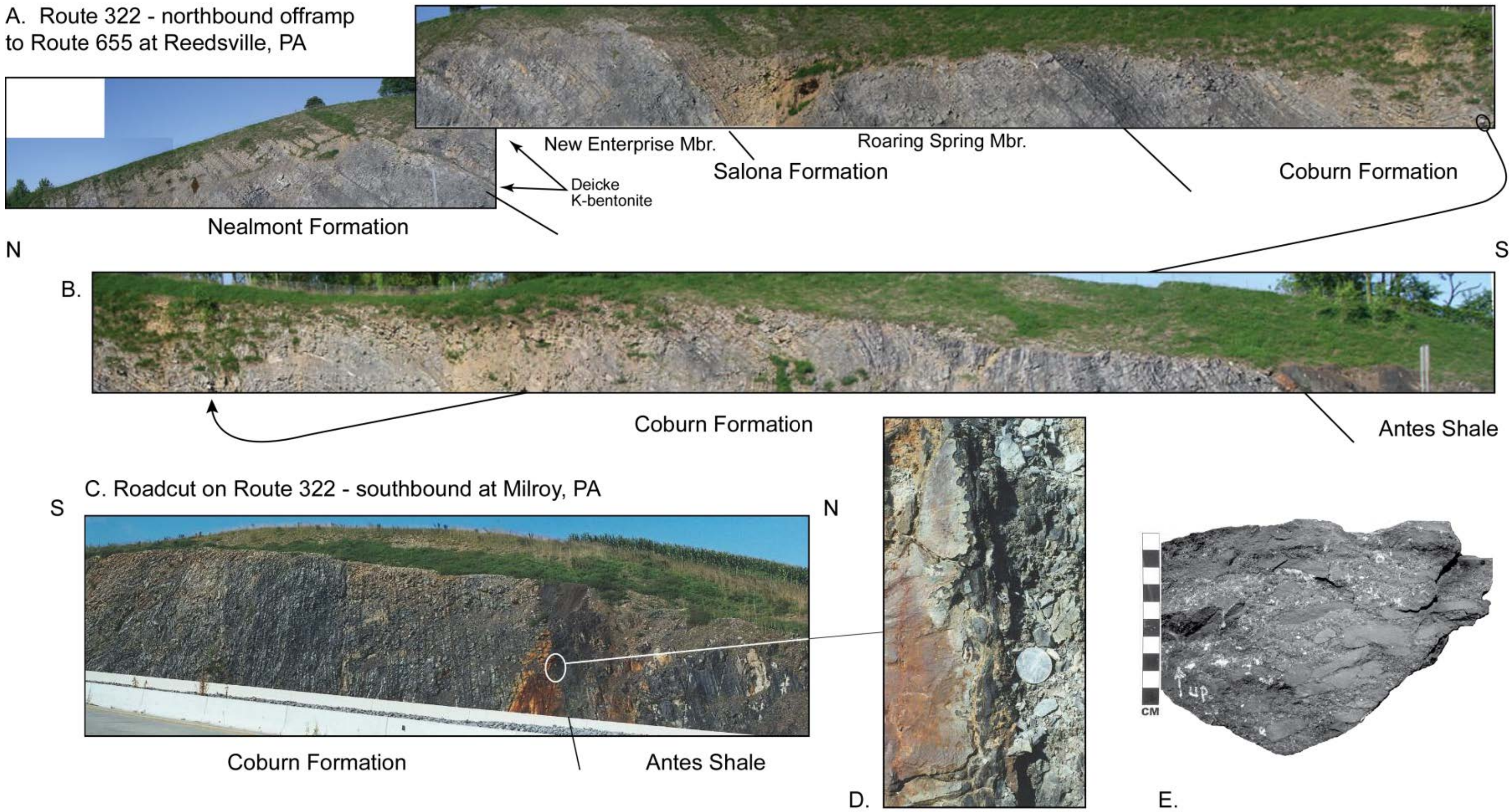
Figure 4-3. A., B. Panorama of the lower and upper parts of the road cut at Reedsville; C. upper part of Coburn Formation and lower Antes Shale at Milroy; D. Detail of the contact between Coburn and Antes formations at Milroy; E. Intraformational conglomerate (storm bed? debris flow?) with imbricated and rounded calcareous mudstone clasts supported by a dominantly pelmatozoan rudstone matrix, lower Coburn Formation.



A. Route 322 - northbound offramp
to Route 655 at Reedsville, PA
New Enterprise Mbr.
Roaring Spring Mbr.
Deicke
K-bentonite
Salona Formation
Coburn Formation
Nealmont Formation
N
S
B.
Coburn Formation
Antes Shale
C. Roadcut on Route 322 - southbound at Milroy, PA
S
N
Coburn Formation
Antes Shale
D.
E.
CM
up

The **Salona Formation,** named by Field (1919), consists of the New Enterprise Member and the overlying Roaring Spring Member. The Salona Formation is characterized by weakly bioturbated dark gray to black wackestone and mudstone. Quartz silt is increasingly abundant upsection. The carbonate beds are commonly graded with planar to wavy scoured bases and thin shelly lags overlain by poorly fossiliferous wackestone that commonly exhibit faint cross-lamination, hummocky cross-stratification, or ripples. Shelly material is dominantly brachiopods, trilobites, gastropods, and pelmatozoan debris. Beds in this interval and continuing into the overlying Coburn Formation are prominently distal storm rhythmites that form regular carbonate-shale couplets. These rhythmites are generally organized into larger scale (~10 m), parasequences with more thin-bedded wackestone-shale couplets (10-15 cm-thick) in the lower part, grading up to thicker-bedded cycles (roughly 15-25 cm-thick) in the upper part. The conodont assemblage recovered from these rocks is a relatively low diversity, deep water, *Phragmodus-Rhodesognathus-Periodon* assemblage (see below); diagenetic pyrite is common, and rare graptolites (*Amplexograptus perexcavatus* and *Normalograptus brevis*) occur in the shale interbeds. The Salona Formation appears to have been deposited in an outer ramp, basin margin setting (Laughrey *et al*., 2004) dominated by background mud deposition punctuated by carbonate event beds washed off the higher parts of the ramp. Intraformational conglomerate beds (storm beds? olistostromes?) with imbricated, rounded carbonate mudstone and wackestone clasts up to several centimeters thick and a decimeter long are present occasionally within both the Salona and Coburn formations at this site and at the Union Furnace site to the northwest.

The lower New Enterprise Member is dominated by thick-bedded calcareous mudstone and wackestone. These beds are generally 8 to 20 cm thick and fracture conchoidally. Dark grey to black, calcareous shale interbeds are present but generally thin. The basal few meters of the New Enterprise Member contains several 2 to 5 cm thick echinoderm grainstones as well. Upsection, black shale partings become more common and the New Enterprise Member becomes abundantly argillaceous 20 m above its base. Bed thicknesses in the argillaceous interval vary between 3-20 cm, with a few thicker wackestone beds in the upper few meters.

Thompson (1963) placed the base of the Roaring Spring Member at the occurrence of a 20 cm thick, strongly laminated, grainstone containing *Sowerbyella*, *Dalmanella*, and rare *Isotelus*. Bed thickness varies between 2.5 and 45 cm in the Roaring Spring Member; however, most beds average between 2.5 and 10 cm and thus are noticeably thinner than in the underlying New Enterprise Member (Thompson, 1963). The basal few meters of the Roaring Spring Member are argillaceous, containing wackestone and fine-grained, partly laminated, grainstone as well as a higher silt content than the units below. These strata grade upward into interbedded, laminated, and cross-laminated, wackestone and fine to coarse-grained packstone and grainstone. The proportion of grainstone beds decreases upsection. The basal 2-4 m contain as much as 50% partly laminated packstone and grainstone, decreasing to 30% throughout the next 10 m; with grainstones becoming rare above 15 m. Overall, the Salona parasequences appear to have back-stepped, suggesting the succession was dominantly transgressive.

The sharp but conformable base of the **Coburn Formation** is marked by a prominent step back to more thin-bedded and shale-rich rhythmite couplets that is accompanied by the appearance of abundant *Prasopora* (distinctive hemispherical or “gum drop”-shaped bryozoan colonies). The lower or Milesburg Member of the Coburn Formation is characterized by rudstone rhythmically interbedded with calcareous mudstone, wackestone, or chippy, calcareous shale layers up to 5 cm thick. The rudstone in the lower Milesburg is characterized by the brachiopod *Sowerbyella* while *Sowerbyella*-trilobite rudstone dominates the upper half (Thompson, 1963).

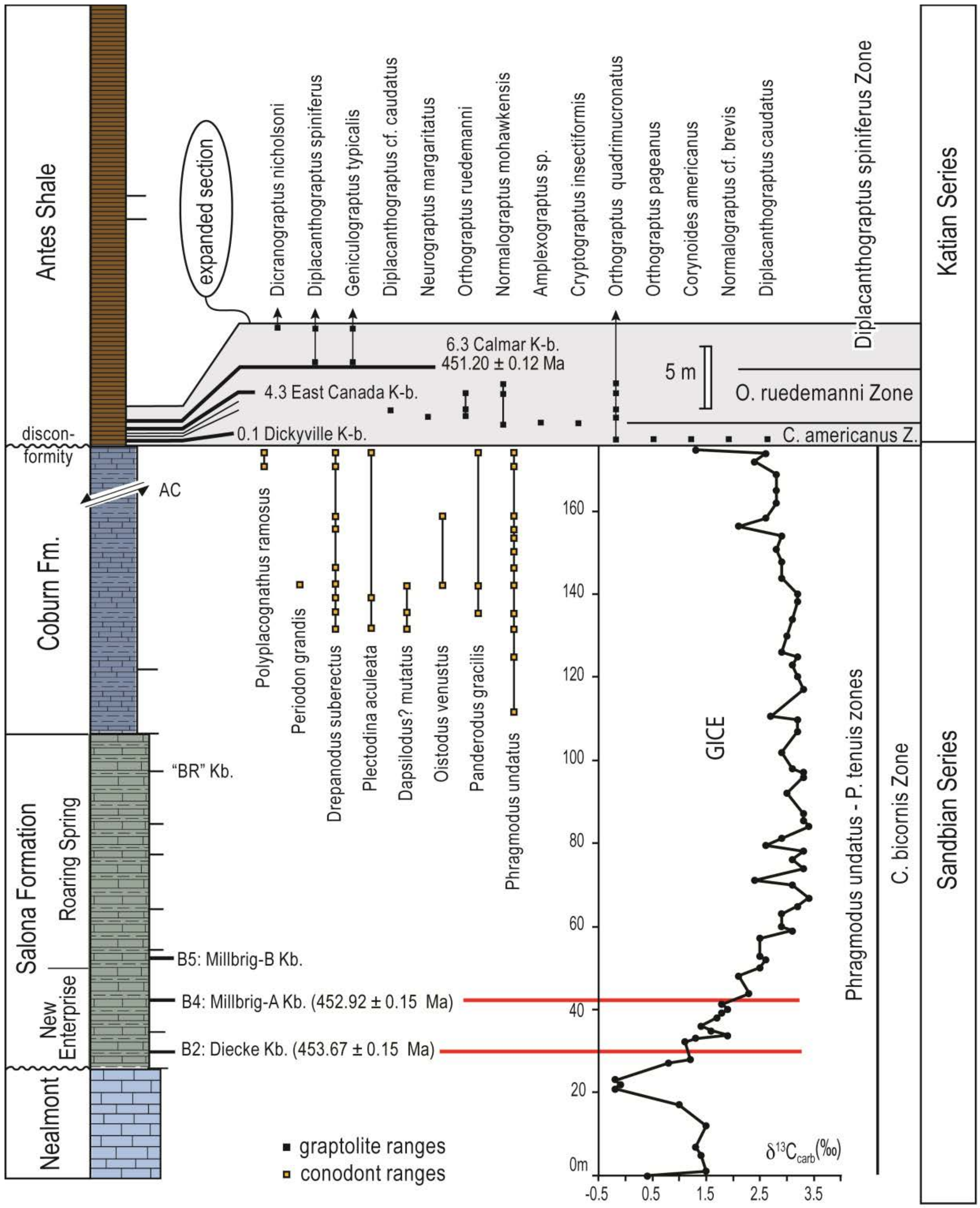


Figure 4-4: Schematic stratigraphic column, upper Nealmont to lower Antes formations at Reedsville, Pennsylvania (Site 4-4). Conodont range data from Bellomy (1999), graptolites by CEM (unpublished), and carbon isotopic data from Pancost *et al.* (2013); see text for further discussion of stratigraphic relations, K-bentonite fingerprinting and geochronology.

Dalmanella bioskeletal rudstone and *Dalmanella*-crinoid bioskeletal rudstone characterize the upper or Coleville Member (Thompson, 1963). Bed thicknesses within the Coleville Member range from 2.5 to 25 cm but are most commonly 5 to 10 cm. Beds are again bundled into parasequences with shale content decreasing and carbonate bed thickness increasing upwards until the uppermost Coleville Member strata are medium bedded to amalgamated rudstones. Overall, the Coburn Formation appears to shallow upwards (Thompson, 1963) from deep ramp to mid-ramp conditions with carbon content of the rocks increasing upsection through the formation (Laughrey *et al.,* 2004).

At Reedsville and the section at Milroy (approximately 4.8 km to the north) the contact with the overlying Antes Shale is sharp and clearly disconformable, although it is generally said in the literature to be gradational (e.g., Field, 1919; Kay, 1944; Thompson, 1963; Laughrey *et al*., 2004). The contact is marked by a dissolution-sculpted surface that is strongly coated by pyrite (Figure 4-3).

The Reedsville roadcut exposes 104 m of the basal part of **Antes Shale** (Kay, 1944) in continuous outcrop (mainly on the southwest side of the southbound lane), which is similar to the thickness of the Antes Shale across the basin (Ryder and Crangle, 2014). The Antes shale is generally a finely-laminated, calcareous, black shale; the lower few meters of the Antes Shale at this site are particularly carbonaceous and pyritic. Skeletal debris of the trilobite *Triarthrus* is common within a limited number of horizons; graptolites occur abundantly on many bedding surfaces, although their preservation is generally poor. Upsection, the Antes Shale becomes more calcareous and often fractures conchoidally. Lenticular pyrite layers, several centimeters thick, occur throughout the exposure at Reedsville. The entire succession exposed along the Reedsville roadcut is sheared and cleavage is faintly to moderately well-developed.

The Antes Shale grades into the overlying **Reedsville Formation**. The latter unit consists of less calcareous, silty gray shale and mudstone with interbedded sandstones, many of which contain transported shelly fossils and strong evidence of storm deposition (Lehmann and Pope, 1989). Although the contact with the Reedsville Formation is covered at this locality it is exposed on the northwest side of the Kishacoquillas Valley along Route-322 and in road cuts along Main Street on the southeast side of the village of Reedsville.

Carbon Isotope Chemostratigraphy. Patzkowsky *et al.* (1997) documented the presence of a strong and sustained positive excursion in $\delta^{13}C_{carb}$ values together with a similar (but not identical) change in $\delta^{13}C_{org}$ values through the Salona and Coburn strata at this site. Values rise from starting values in the range of 0.5-1.0‰ (Figure 4-4) to peak values of 3.0-3.5‰ in the middle of the Salona Formation and then decline only slightly. They are still ~2.5‰ at the top of the Coburn Formation (the sample set does not extend into the lower Antes Shale, in contrast to the pattern shown by Pancost *et al*., 2013; M. Patzkowsky pers. com., March, 2015). Both they and many subsequent authors have equated this excursion with the Guttenberg carbon isotope excursion (GICE). Pancost *et al.* (2013) expanded the $\delta\,^{13}C_{carb}$ sample set and made use of the previous $\delta\,^{13}C_{org}$ values from these and a number of other sections around the globe to argue that the changing $\Delta^{13}C$ values record a distinctive global alteration in carbon storage, in part as a result of changing algal floral composition, during the waning phase of the GICE interval. Recent K-bentonite correlations in this interval (Sell *et al*., 2015) suggest additional local cycling effects may be important contributors to the preserved record of the GICE (see also Young *et al*., 2008) and that the carbon isotopic system may have been in flux through a longer portion of the late Sandbian than originally supposed. Nevertheless, the presence of elevated values $\delta\,^{13}C_{carb}$

through the entire ~140 m thickness of the Salona and Coburn Formations at Reedsville suggests that these strata accumulated here during an interval of rapid accommodation space growth.

Conodont Biostratigraphy. Conodont faunas from the Middle Ordovician carbonates of central Pennsylvania have received relatively little study (Shore, 1971; Valek, 1982; Sweet, 1984; Leslie, 1995, 2000). Conodont faunas described by Leslie (1995) from the upper Nealmont and lower Salona Formations clearly establish that the base of the latter at Union Furnace (Stop 3-1) lies within the lower part of the *Phragmodus undatus* Chronozone of Sweet (1984, 1988). Given the presence of the Deicke and Millbrig K-bentonites both at Union Furnace and Reedsville sites (Fig. 4-4 and discussed below), we are confident that the base of the unit lies within this same interval here.

Conodonts from the Coleville Member at Reedsville (Bellomy, 1999) contain relatively few species (Figure 4-4) most of which range through the late Sandbian and early Katian interval. However, there are two species of particular interest: *Polyplacognathus ramosus* and *Plectodina aculeata*. The top of the range of the highly distinctive and well-known taxon *P. ramosus* lies within the lower levels of Sweet's (1984) *Belodina confluens* Chronozone and just overlaps the base of the range of *Amorphognathus superbus*, guide fossil of the eponymous zone of Bergström (1971). *P. aculeata* has an even more restricted range. Its upper occurrence is limited to the *Phragmodus undatus* Chronozone and the lower part of the succeeding *P. tenuis* interval.

Based on this evidence, the age of the top of the Coburn Formation *can be no younger than* the latest Sandbian, early *P. tenuis* Chronozone interval. This suggests that the Coburn-Antes contact may be as young as the interval of the Curdsville to Logana members of the Lexington Limestone of Kentucky (early M5 interval of Holland, 1993; Holland and Patzkowsky, 1996) and Napanee Formation in the Mohawk Valley (Figure 4-4). The presence of these same species in the uppermost Coburn Formation strata at Bellefonte (Valek, 1982) suggests that the top of the Coburn Formation could be of similar age across the region between these sites, at least within the constraints of these minimum ages.

Graptolite Biostratigraphy. Graptolites are rare within the Salona and Coburn Formations. We discovered small collections of poorly preserved material at two levels within the Salona Formation at Union Furnace (Stop 3-1) but found none in any other section in either unit. Numerous specimens of *Amplexograptus perexcavatus* occur in shale interbeds 21.3 m above the base of the Salona Formation, slightly below the Millbrig K-bentonite bed at 23.2 m. We also found a single specimen of *Normalograptus brevis* in shale float near the contact of the New Enterprise and Roaring Springs members at 37 m in that section. Both species are consistent with the *Phragmodus undatus* Chronozone age suggested by the conodont faunas in this part of the section and with the biostratigraphic position of the Deicke K-bentonite bed reported from the Salona Formation in this section (Kolata *et al*., 1996; Adhya, 2009).

Graptolites are abundant at many levels within the fresh exposures of the Antes Shale at Reedsville (Figure 4-4). Although most specimens exhibit tectonic distortion associated with cleavage development in these rocks, we have obtained identifiable material of a moderately diverse fauna. Graptolite collections were made at closely spaced intervals within the lower 15 m of the Antes Shale and at more widely spaced intervals in the remaining section. The graptolite fauna from the lowermost seven meters of the Antes Shale at this locality spans the interval of the uppermost *Corynoides americanus* Zone, the *Orthograptus ruedemanni* Zone, and the lower part of the *Diplacanthograptus spiniferus* Zone. The lowest collections, sampled from 10 cm above the contact with the Coburn Formation contain numerous specimens of *Orthograptus pageanus*, which elsewhere in the Taconic foreland basin is restricted to the early Katian *C. americanus* Zone, the *Climacograptus baragwanathia* Zone of east Gondwana, and the *Dicranograptus clingani* Zone in Avalonia and Baltica (Goldman *et al*., 1994; Goldman, 1995). Also present at this level is *Diplacanthograptus caudatus*, the first appearance of which marks the base of the Katian Stage (Goldman *et al*., 2007). A *C. americanus* Zone fauna is also present 20 cm above the base of the Antes Shale in the nearby Milroy road cut. These beds are succeeded at 1.5-2.0 m above the contact at both the Reedsville and Milroy sites by collections that contain *Normalograptus mohawkensis* and *O. ruedemanni.* This *O. ruedemanni* Zone fauna continues for some seven meters of rock and includes, near the top of the interval, two K-bentonites that correspond geochemically with beds in the upper part of the *O. ruedemanni* Zone in the Mohawk Valley (see below). At 7.4 m above the base of the Antes Shale, *Diplacanthograptus spiniferus* first appears together with *Geniculograptus typicalis*, followed by *Dicranograptus nicholsoni.*

The *Corynoides americanus* to *Orthograptus ruedemanni* Zone interval in the lower Antes Shale in the Kishacoquillas Valley is strongly condensed. The former zone in the central Mohawk Valley of New York State is some ~90 m thick in contrast to the less than 2 meters that it is here. Similarly, the *O. ruedemanni* Zone is nearly five times thicker in the Mohawk Valley than at Milroy and Reedsville. The overlying *Diplacanthograptus spiniferus* Zone, however, appears to occupy nearly the full ~ 100 m thickness of the Antes Shale and extends into the lower part of overlying Reedsville Shale at this site and at Antes Gap. One of us (CEM) has recovered sandstone blocks from talus near the middle part of the Reedsville Shale exposed in the Route-322 cut on the northwest of side of the Kishacoquillas Valley, southeast of the Laurel Creek Reservoir, that contain *Geniculograptus pygmaeus*, which is the index of the overlying graptolite zone. Thus, the rock accumulation rate of the Antes Shale appears to exponentially decrease downwards, toward the mineralized, solution-sculpted upper surface of the Coburn Formation upon which it rests.

Goldman *et al.* (1999) described a pattern of facies relations in the Mohawk Valley succession that suggested that both facies and graptolites were responding to a common physical forcing. They attributed the appearance of the *Diplacanthograptus spiniferus* Zone fauna to a series of regional immigration events. The fauna here is considerably less well known, but initial data appear to agree with their suggestion that the changes which permitted the localized evolution of the endemic elements of the *Orthograptus ruedemanni* Zone fauna and its replacement by the *D. spiniferus* Zone immigrants effected a wide area of the Appalachian Basin, an area extending at least from Quebec to Pennsylvania.

K-bentonite tephrochronology and geochronology. Trenton Group strata in central Pennsylvania bear a prominent set of K-bentonites that have been described and employed as timelines (with varying degrees of success) for a long time (e.g., Rosenkrans, 1934; Whitcomb and Rosenkrans, 1935; Thompson, 1963; Cullen-Lollis and Huff, 1986; Kolata *et al.*, 1996). Analysis of ash fingerprints from glass inclusions within quartz phenocrysts and apatite crystal compositions provides additional constraints on the correlation of these beds. Those from the Reedsville section were examined by Adhya and colleagues (Mitchell *et al*., 1998; Mitchell *et al*., 2000; Adhya, 2009), Sell (2010), and Sell *et al.* (2015), with additional work by one of us (BKS) reported here.

In his summary of the regional correlations of the Nealmont to Coburn Formation interval, Thompson (1963) reported 5 K-bentonites within the New Enterprise Member of the Salona Formation, 6 in the Roaring Spring Member (including his "BR" or reference K-bentonite near the top of the latter unit), and 7 K-bentonites in the Coburn Formation. These beds range in thickness from a centimeter or two to nearly 40 cm. At the Reedsville and Milroy exposures, we have examined 12 K-bentonites from the interval below the Antes-Coburn detachment in the upper Coburn Formation and an additional five beds from the lower 6.3 m of the Antes Shale (Fig. 4-4). Thompson's B2, at 4.2 m above the base of the Salona Formation, exhibits the distinctive geochemistry of the Deicke K-bentonite (Cullen-Lollis and Huff, 1986; Adhya, 2009) and that immediately below (at 4.1 m above the base of the Salona Formation) matches the compositions of a bed just below the Deicke K-bentonite in the upper Oranda Formation strata of the Strasburg region (Adhya, 2009; Sell, 2010; see discussion for Site 1-2 above). Although previously considered to be the Millbrig K-bentonite by Cullen-Lollis and Huff (1986), Thompson's B3 is not a good match for that unit based on phenocryst geochemistry. Instead, the Millbrig K-bentonite appears here as two discrete beds: B4 and B5, at 16.7 m and 26.8 m, the latter in the lower part of the Roaring Spring Member (Adhya, 2009). The populations of apatite phenocrysts and glass inclusions from these two beds differ very slightly in composition from one another (mainly in the relative frequencies of the several compositional groups present in this complex bed) in a way that is consistent with the previously documented compositional zonation of the unit from sites in the upper Mississippi Valley, Kentucky, and Virginia (Carey *et al*., 2009; Sell, 2010). None of the other K-bentonites in the Salona and Coburn Formations could be correlated by this means. Several beds lack one or the other of the studied crystal phases, lack clearly distinctive chemical signatures, or lack both.

The Antes Shale at this site contains 5 K-bentonites (Figure 4-4). The lowest of these, located 0.10 m above the contact, matches the apatite compositions of the Dickyville K-bentonite (Sell *et al.* 2015, figs. 3-5, 8). The Dickyville K-bentonite is named for occurrences near the town of Dickyville in southwestern Wisconsin (Willman and Kolata, 1978), where it occurs in the upper part of the Guttenberg Formation near the top of the GICE interval (Ludvigson *et al*., 1996). Accordingly, it appears to occupy a similar position relative to the GICE in central Pennsylvania. In the Reedsville section, shales bearing *Corynoides americanus* and other graptolites of the basal Katian *Diplacanthograptus caudatus* Zone fauna directly overlie the Dickyville K-bentonite, but the beds below are without biostratigraphic constraints and so it is unclear whether this bed is highest Sandbian or lowest Katian, but it must lie very close to that boundary.

Two additional beds in the lower Antes Shale produced distinctive signatures (Adhya, 2009). The bed at 4.3 m above the base of the unit, within the interval of the *Orthograptus ruedemanni* Zone matches the glass and apatite compositions of the East Canada K-bentonite from the central Mohawk Valley (Mitchell *et al*., 1994, their "Bed III"; Jacobi and Mitchell, 2002). The East Canada K-bentonite occurs there within the same graptolite zone and in the middle part of the Dolgeville Formation. In that region a distinctive bed that has been locally referred to as the Manheim K-bentonite occurs in the uppermost Dolgeville, just above the base of the *Diplacanthograptus spiniferus* Zone (Baird and Brett, 2002; Jacobi and Mitchell, 2002). That bed matches the composition of a bed at 6.3 m in the Reedsville section (Adhya, 2009), and both are indistinguishable from the Calmar K-bentonite (Willman and Kolata, 1978; Sell *et al*., 2015). The Calmar K-bentonite occurs in the Rivoli Member of the Dunleith Formation in Iowa and Minnesota, in the upper Mississippi Valley region (Kolata *et al.,* 1996).

Correlation of the Calmar K-bentonite with a bed at the base of the *Diplacanthograptus spiniferus* Zone in New York and Pennsylvania suggests that the middle to upper part of Dunleith Formation is somewhat younger in terms of the Taconic succession (equivalent to the Indian Castle Formation in upper part of the Utica Group of New York, and above nearly all of the classic Trenton Group in that region) than previously thought (e.g., Sweet, 1984; Sloan, 1987; Witzke and Bunker, 1996). This relation is supported, however, by the occurrence of *Amplexograptus praetypicalis* (which is a common species in the lower part of the *D. spiniferus* Zone; Riva, 1987) at two sites in the upper Mississippi Valley. CEM has recovered this species from the lower part of Rivoli Member at 1079.6 ft. (329.1 m) in the Peterson No. 1 well, near Vincent, Webster Co., Iowa (sample supplied by Brian Witzke, Iowa Geol. Survey, 1998). CEM also collected specimens of *A. praetypicalis* from loose slabs in the upper Dunleith Formation at 5-6 m below base of the Wise Lake Formation at the C.C. Link Quarry, Dodge County, eastern Wisconsin.

One of us (BKS) conducted U-Pb isotopic dating of eight individual zircon phenocrysts obtained from the Calmar K-bentonite sample at the Reedsville site (Figure 4-5). Analytical procedures followed those described in Sell *et al.* (2013). The results of those analyses are a tightly clustered series of crystallization ages that have a weighted mean value of 451.20 ± 0.12/0.25/0.55 Ma 2σ. The reported errors (age ± *x*/*y*/*z* Ma) integrate sequentially the analytical uncertainty, tracer and decay constant errors (see Sell *et al*., 2013, for a discussion of the error calculations and their uses).

Discussion. The data presented above provide new constraints on the age and correlation of the Salona and Coburn formation succession, but several uncertainties remain. Among those is the location of the M4-M5 sequence boundary of Holland and Patzkowsky (1996; 1997; 1998). This interval has been widely recognized in the early Late Ordovician epicratonic succession of eastern Laurentia (e.g., Brett *et al*., 2004; Laughrey *et al*., 2004; McLaughlin e*t al*., 2004; Mitchell *et al*., 2004), where the boundary has been associated with a regional change in environmental conditions and faunal reorganization (Patzkowsky and Holland, 1993, 1996, 1997; Layou, 2009; Wright and Stigall, 2013; among others). Patzkowsky *et al.* (1997) and Laughrey *et al.* (2004) placed that boundary within the upper part of the Salona Formation. The fact that the GICE anomaly extends essentially without return to the top of the Coburn Formation, however, together with the fact that overall the Salona parasequences seem to deepen upward while those of the Coburn Formation appear to shallow-upward, raises the possibility that this boundary may lie within the grainstone package just below the strong deepening event that marks the base of the Antes Shale (Mark Patzkowsky, pers. com. 2015; [see Figure 1-7]). Further work in the region is needed to resolve the sequence stratigraphic interpretation of this succession.

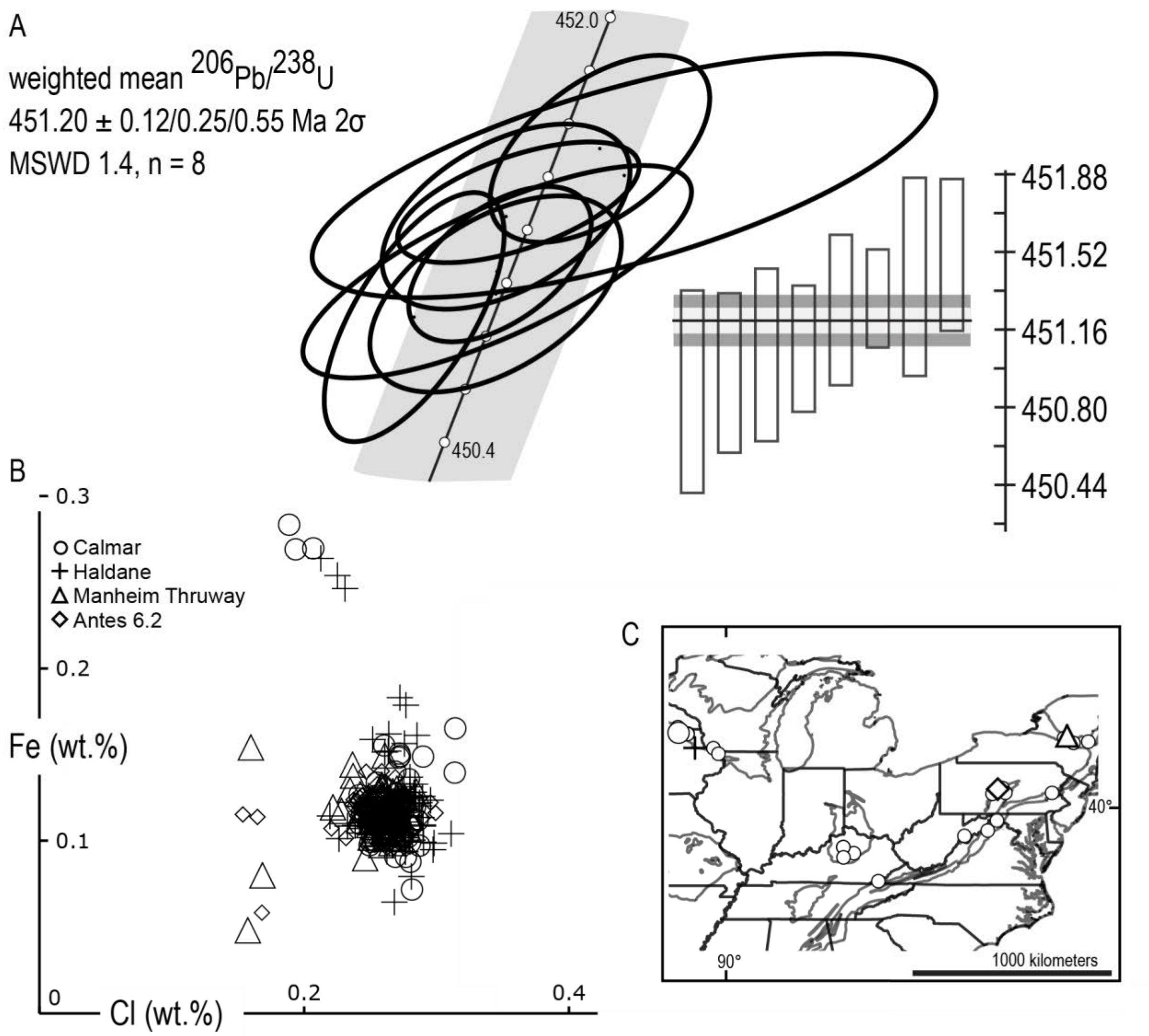


Figure 4-5: A. U-Pb Concordia plot for zircons from the Calmar K-bentonite at Reedsville, Pennsylvania; B. Plot of apatite phenocryst chemistry for Calmar K-bentonite based; C. Sites in New York, Pennsylvania, and the upper Mississippi Valley region that produced zircons used in B.

Stop 4-2: Taconic clastic wedge shallowing succession, Manns Narrows.
Co-ordinates: Latitude 40° 39’ 29” N; Longitude 77° 35’ 36” W.

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South and east of Reedsville, State Route-1005 passes through the water gap in Jack’s Mountain known as Manns Narrows. Road cuts along the north side of SR-1005 (Manns Narrows Road), which extend for roughly half a kilometer south of its junction with the south end of Station Hill Road, provide nearly continuous exposure of the uppermost strata of the Reedsville Formation, the overlying Bald Eagle Sandstone, and much of the overlying Juniata Formation. The gradational nature of the contacts between these formations, which collectively record replacement of a deeper shelf setting (upper Reedsville) with shallow marine (Bald Eagle) and finally meandering fluvial (Juniata) environments, makes their precise and objective placement in the outcrops somewhat challenging. But the contrast in sedimentary facies on the larger scale is conspicuous, and manifested in the topography by the prominent secondary ridge supported by the Bald Eagle Sandstone, separated from the primary Tuscarora (basal Silurian clastics) ridge by an elevated valley that marks the location of the less resistant, mudstone rich Juniata Formation.

In the outcrops along SR-1005, fossils are plentiful in the thin, normally graded sandstone beds in the uppermost Reedsville, which formed as turbidites and/or tempestites in a deeper shelf environment. Crinoids and thin ramose (branching) bryozoans dominate the fauna, with less numerous brachiopods and a few trilobites. All typically occur as molds near the bases of the graded sandstone beds. Fossils are far less common in the coarser and prominently cross-laminated shallow marine sandstone beds in the Bald Eagle, and almost non-existent in the coarse, hematitic, often conglomeratic sandstone packages in the Juniata. Large quartz pebbles and rock fragments in the Juniata record re-working of sedimentary source rocks to the east (modern coordinates) in the later stages of the Taconic orogeny. The recessive reddish mudstone intervals that cap the upward-fining fluvial packages of the Juniata represent overbank deposition. The greenish mottling in the upper parts of some of these mudstone intervals probably is pedogenic and represents patches of more reducing conditions within floodplain soils. These road cuts afford the visitor an opportunity to observe the final stages of infilling of the Taconic foredeep in the latest Ordovician. Considerable caution should be exercised, however, as the road is narrow, with relatively blind curves, narrow shoulders in places, and the traffic surprisingly heavy and alarmingly brisk.

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Chapter 5: The Taconic Sequences of the Great Valley of Pennsylvania

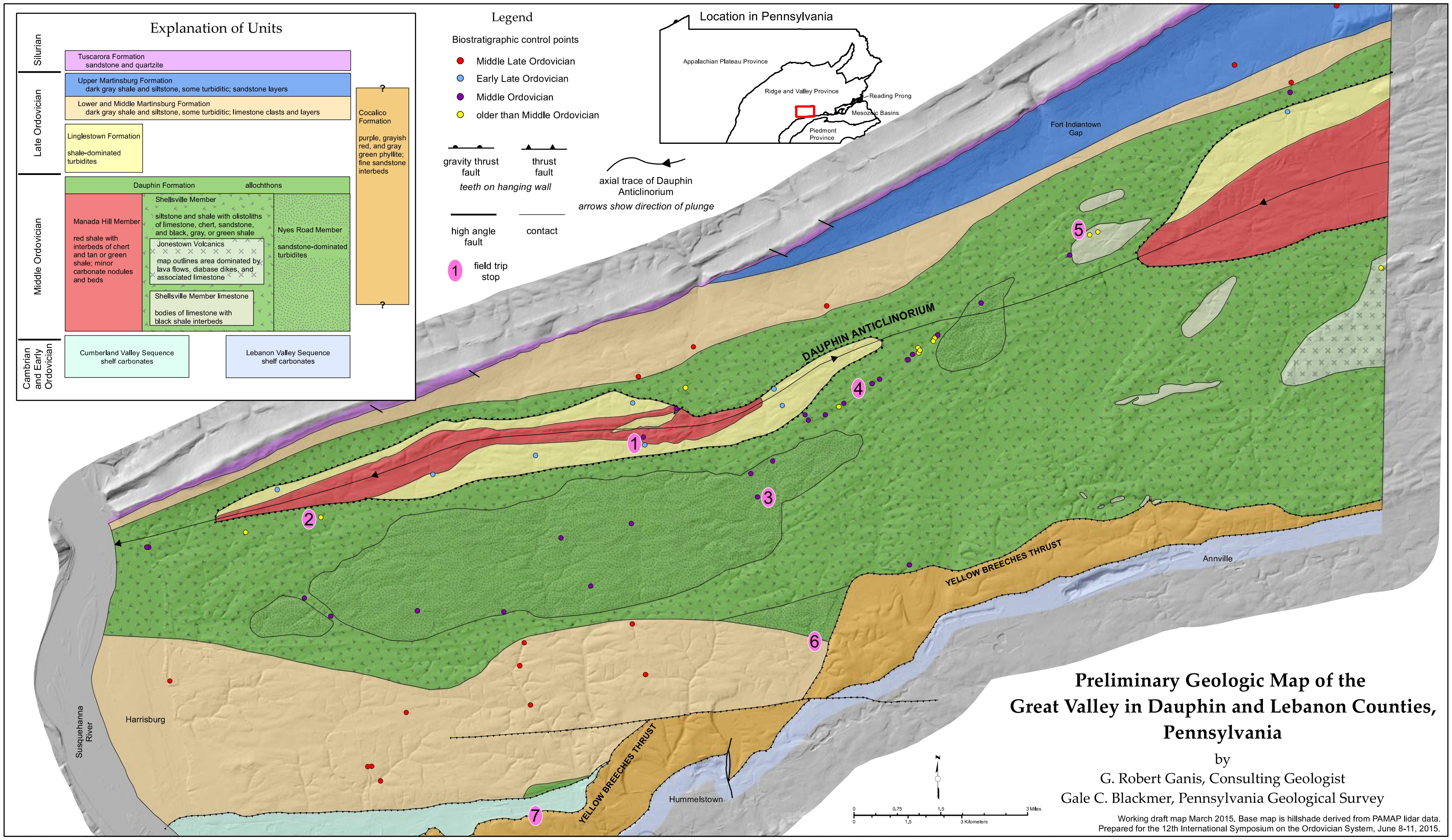
G. Robert Ganis, Gale Blackmer, and John Repetski

Introduction

Day 5 of the field trip is dedicated to rocks of the Taconic foreland preserved in the Ordovician clastic rocks of the Great Valley. In southeastern Pennsylvania, the proximal portion of the Taconic fill sequence is represented by the Late Ordovician (Katian-Sandbian) Martinsburg Formation, but also includes tectonically transported allochthons of much older, and somewhat different, rock. The initial discovery of a belt of older allochthonous rocks in the Martinsburg foreland in this area (dated by graptolite fossils) prompted Stose (1946) to propose a large overthrust above the Martinsburg Formation, which he named the "Hamburg klippe." Stose also suggested a comparison to the great Taconic thrust of Vermont and New York, not only in tectonic origin and age, but also in rock types. Subsequent workers (for summary see Ganis *et al*., 2001; Ganis and Wise, 2008) continued to discover rock older and different from the Martinsburg in the "Hamburg klippe" belt, but some also found rock they claimed was compatible with the Martinsburg Formation. In addition, some workers saw field relations suggesting the allochthonous rock was contained within the Martinsburg Formation rather than thrust over it. Using graptolite fossils, Ganis *et al.* (2001) confirmed the presence of both Martinsburg-age strata and older allochthonous rock in this belt and presented field evidence that the allochthons are covered by the Martinsburg Formation. They presented an internal stratigraphy for the allochthonous "Hamburg Sequence" based on new graptolite and conodont biostratigraphy and renamed these rocks the Dauphin Formation.

The tectonic setting for the emplacement of the Dauphin allochthons, including the presence of syntectonic piggyback basins, was described in Ganis and Wise (2008) and Wise and Ganis (2009). These authors identified the Dauphin Formation as the core rocks of the Dauphin anticlinorium, overlain by the Martinsburg Formation on the flanks of the structure. The Pennsylvania Geological Survey undertook systematic field mapping of the Dauphin anticlinorium in the western part of this terrane (Dauphin and Lebanon counties) with a preliminary map released by Ganis and Blackmer (2010e). During this mapping, additional graptolite and conodont localities were identified in both Martinsburg-age and older allochthonous rocks. In addition, they named the piggyback basin rocks the Linglestown Formation. We are pleased to announce an updated edition of the Ganis and Blackmer map for this field trip as Figure 5-1.

Starting in the Middle Ordovician, the Great American Carbonate Bank of the southern Laurentian margin collapsed and drowned during the closure of the Iapetus Ocean. It was replaced, in stages, by muddy foreland flysch. In the central Appalachians, it is believed that the Iapetus closure involved an outboard microcontinent, as well as further removed island arcs (see Faill, 1997, for a possible scenario). The formative strata (Furongian-Tremadocian) of the Dauphin Formation were derived from detritus eroded from the microcontinent. Conodonts from the Dauphin Formation have a temperate North Atlantic province faunal affinity and no midcontinent province indicators have been found, indicating that the microcontinent was separated from Laurentia by a significant seaway. As Iapetus closure proceeded, the Dauphin Formation rocks were pushed towards and into a peri-Laurentian trench as fragments (Ganis *et al*., 2001; Ganis, 2005; Ganis and Wise, 2008; see also Lash and Drake, 1984). The trench


Preliminary Geologic Map of the
Great Valley in Dauphin and Lebanon Counties, Pennsylvania
by
G. Robert Ganis, Consulting Geologist
Gale C. Blackmer, Pennsylvania Geological Survey
Working draft map March 2015. Base map is hillshade derived from PAMAP lidar data.
Prepared for the 12th International Symposium on the Ordovician System, June 8-11, 2015.
Explanation of Units
Silurian
Tuscarora Formation
sandstone and quartzite
Late Ordovician
Upper Martinsburg Formation
dark gray shale and siltstone, some turbiditic; sandstone layers
Lower and Middle Martinsburg Formation
dark gray shale and siltstone, some turbiditic; limestone clasts and layers
Linglestown Formation
shale-dominated turbidites
Middle Ordovician
Dauphin Formation
allochthons
Manada Hill Member
red shale with interbeds of chert and tan or green shale; minor carbonate nodules and beds
Shellsville Member
siltstone and shale with olistoliths of limestone, chert, sandstone, and black, gray, or green shale
Jonestown Volcanics
map outlines area dominated by lava flows, diabase dikes, and associated limestone
Shellsville Member limestone
bodies of limestone with black shale interbeds
Nyes Road Member
sandstone-dominated turbidites
Cocalico Formation
purple, grayish red, and gray green phyllite; fine sandstone interbeds
Cambrian and Early Ordovician
Cumberland Valley Sequence
shelf carbonates
Lebanon Valley Sequence
shelf carbonates
Legend
Biostratigraphic control points
Middle Late Ordovician
Early Late Ordovician
Middle Ordovician
older than Middle Ordovician
gravity thrust fault
thrust fault
teeth on hanging wall
axial trace of Dauphin Anticlinorium
arrows show direction of plunge
high angle fault
contact
field trip stop
Location in Pennsylvania
Appalachian Plateau Province
Ridge and Valley Province
Reading Prong
Mesozoic Basins
Piedmont Province
Fort Indiantown Gap
DAUPHIN ANTICLINORIUM
YELLOW BREECHES THRUST
Annville
Hummelstown
Harrisburg
Susquehanna River
1
2
3
4
5
6
7
0 0.75 1.5 3 Miles
0 1.5 3 Kilometers

matrix, with olistolithic fragments on many scales (many with graptolite and conodont fauna), is a diverse mixture of lower ramp to abyssal facies, which formed during the late Darriwilian (Da 3 to early Da 4a0. This interval is recorded by a rich graptolite fauna in the Dauphin Formation (Ganis *et al*., 2001; Ganis, 2004; Ganis, 2005). The trench contents were then expelled by continued Taconic convergence that also weakened the trench wall allowing localized intrusion of basaltic magma and diabase dikes (preserved as the Jonestown volcanics within the trench strata; Lash, 1984).

The allochthons were transported over the subsided carbonate platform rocks and into the nascent Martinsburg Foreland. The timing of this tectonic transport is remarkably recorded by a piggyback basin containing graptolitiferous turbidites of early Sandbian age (*Nemagraptus gracilis* Zone) deposited atop one of the moving Darriwilian allochthons, which is itself overthrusted by a subsequent Darriwilian allochthon. Once emplaced into the newly formed sag of the foreland, the Dauphin Formation allochthons were buried by the Martinsburg Formation starting in the Sandbian (*Climacograptus bicorni*s Zone) and continuing into the Katian. This sequence of events is shown on Figure 5-2. The Dauphin Formation allochthons and Martinsburg Formation cover preserved in the foreland rocks of the Great Valley are only part of what must have been an immense sedimentary and tectonic complex covering most of the carbonate bank strata of the Piedmont.

The terminal Taconic events led to colossal nappe building, resulting in elevated metamorphic grade near the hinterland. The Great Valley foreland rocks, however, are preserved in a very low metamorphic state (Ganis and Wise, 2008; Wise and Ganis, 2009). The Cambrian-Ordovician carbonates and foreland clastics were again highly deformed and folded during the Alleghanian orogeny. Folding of the Dauphin anticlinorium (Ganis *et al.*, 2012) and transport of an overturned Taconic nappe on the Yellow Breeches Fault (including the lower-greenschist-facies Cocalico Formation) are attributed to the Alleghanian orogeny (MacLachlan, 1967; Ganis and Wise, 2008).

Facing page

Figure 5-1: Preliminary geologic map of the Great Valley in Dauphin and Lebanon counties, Pennsylvania.

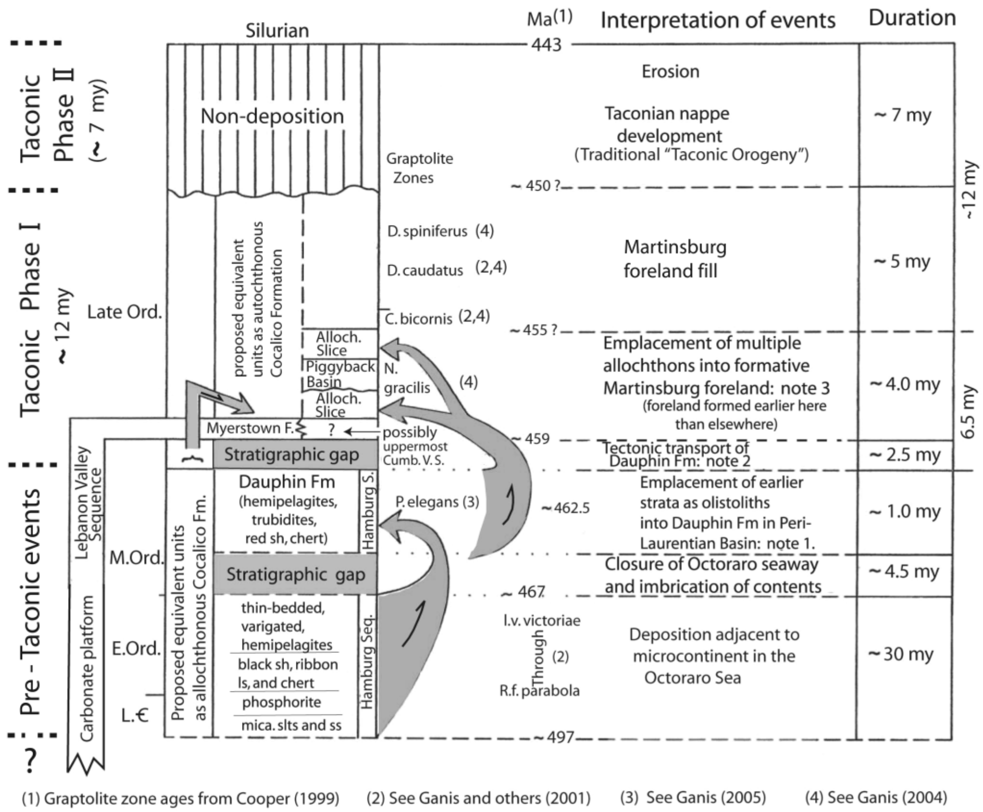


Figure 5-2: Fossil-dated relations among phases of the Taconic orogeny (*senso lato*) in the Martinsburg/Dauphin foreland. Numerical ages are based on world-wide radiometric dating of the fossils (Cooper, 1999). The arrows indicate packages that have been moved as allochthons to be embedded into younger units with fossil-dated matrices. Stratigraphic time gaps of a few million years commonly separate the two events. References to fossil dates are at the bottom of figure.

Under the column for Interpretation of events:

Note 1 - the Jonestown volcanics were emplaced into the olistostromes;
Note 2 - from its Peri-Laurentian depositional site onto the Laurentian margin;
Note 3 - in this area the foreland basin formed about one graptolite zone or perhaps 1 to 1.5 m.y. earlier than areas to the east. From Ganis and Wise (2008).

Stop 5-1: Abyssal Pelagites: Manada Hill Member (type locality), Dauphin Formation and the Linglestown Formation.
Coordinates: Latitude 40° 21' 20" N; Longitude 76° 43' 36" W.

Although the Dauphin allochthons were transported over the carbonate platform sequence, the structurally lower carbonates are not exposed in the part of the Great Valley containing allochthonous rocks. The lowest structural unit exposed in the core of the Dauphin anticlinorium (Figure 5-1) is the Manada Hill Member, believed to be one of the earlier allochthons to arrive. Stop 5-1 at Manada Hill (at the northeast corner of a truck stop parking lot) is the type locality for the member, which is defined by thick (greater than 10 meters) accumulations of pelagic pelites, commonly with interbedded chert. The shales are commonly shades of red, but tan or green strata are also present. The interbedded cherts also occur in a variety of colors, from red to black. At the Manada Hill exposure, the cherts and shales occur in cm-scale couplets. Thin, fine-grained greywackes, meta-ash beds, and carbonate nodule accumulations can be found locally in this member (such as an exposure at Lenhartsville in Berks County; Ganis, 1997). The Manada Hill Member has been dated as Middle Ordovician with conodonts from this outcrop and from Lenhartsville. The fauna from Lenhartsville are described in Ganis (2004). At Manada Hill, conodonts and sponge spicules can be found as external molds in red shale (Figure 5-3).

The rocks of the Manada Hill Member are interpreted as deep ocean abyssal plain, where sedimentation was slow and may have consisted of only wind-blown dust during starved episodes. The cherts likely resulted from the accumulation of radiolarian tests. Occasionally, very distal turbiditic sediment reached the plain, and after such events the sedimentation would return to a pelitic or cherty content. The age of this member is similar to the trench matrix (discussed below), but clearly these strata would have been distal to the active trench axis.

A limited exposure of the Linglestown Formation piggyback basin above the Manada Hill Member occurs in a low cut at the southeast corner entrance to the parking lot. Although now largely overgrown, this turbidite exposure of greywacke and shale yielded a *Nemagraptus gracilis* Zone fauna including *N. gracilis* (Ganis, 2004; unit M-1).

This stop was also Stop #11 for the 75th Field Conference of Pennsylvania Geologists (Ganis and Blackmer, 2010a).

Stop 5-2: Boulder olistostrome: Shellsville Member, Dauphin Formation.
Coordinates: Latitude 40° 20' 03"N; Longitude 76° 49' 49' 57" W.

In the introduction, we describe the tectonic movement of Late Cambrian – Early Ordovician strata from a position across a seaway to a peri-Laurentian trench where these strata fragmented into olistoliths. At this stop near Linglestown, Dauphin County, we will see the deep water carbonates, greywacke, shale, and chert boulders scattered in a hemipelagic matrix of siltstones and shales. Earliest Tremadocian fossils were recovered from selected carbonate boulders; the fauna includes the euconodonts *Cordylodus lindstromi, Laurentoscandodus* sp., and gen. and sp. indet., as well as the protoconodonts *Phakelodus elongatus* or *P. tenuis.* Unfortunately, the matrix here has not proved especially productive for graptolites except for a few scraps of *Pterograptus*, but that is permissive for the Darriwilian 3/4a age from many other exposures (such as Stop 5-4) of this matrix material.

This stop was also Stop #10 for the 75th Field Conference of Pennsylvania Geologists (Ganis and Blackmer, 2010b).

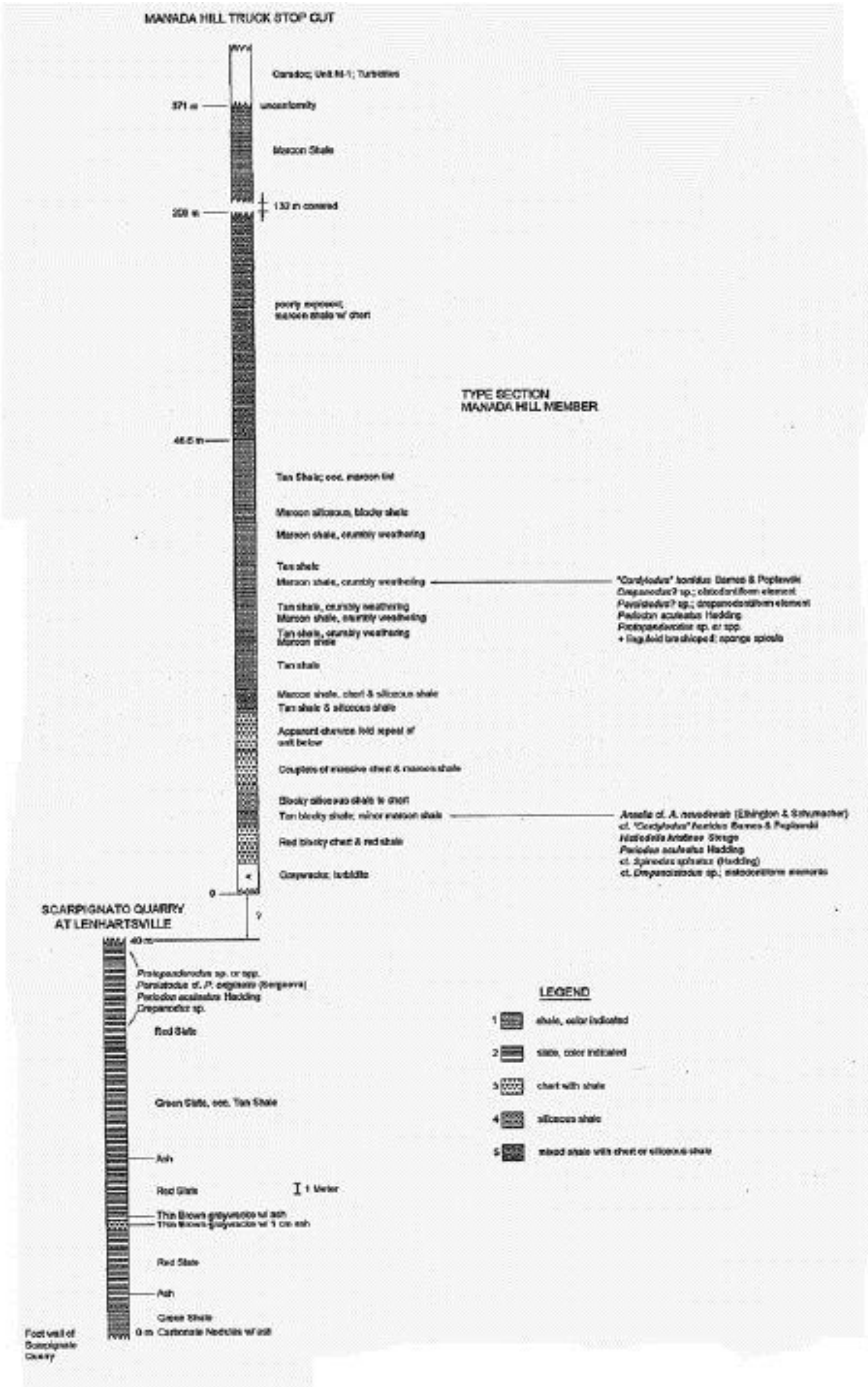


Figure 5-3: Composite sections from Manada Hill (Stop 5-1) and Lenhartsville for the Manada Hill Member. From Ganis (2004).

Stop 5-3: Submarine channel turbidites: Nyes Road Member, Dauphin Formation. Coordinates: Latitude 40° 22' 12" N; Longitude 76° 39' 11" W.

At this stop, well-developed Bouma cycles of turbiditic flysch are exposed in a road cut along Manada Creek, Dauphin County. Although graptolite fossils occur only sparingly here, numerous localities in this member fall in the restricted age of the Da 3 to Da 4a zones. These strata are interpreted as submarine channels, cut into the trench wall apron (Shellsville Member facies). Some exposures are interbedded with minor (usually less than 10 m) red shale and chert, interpreted as starved pelagic deposition on top of turbidite beds between flow events, and subject to cover from further turbidite activity. This long exposure has several complete Bouma cycles and many examples of sole marks and sedimentary features associated with turbidite sedimentation. A list of graptolite fauna from this member is found in Ganis (2005).

Stop 5-4: Hemipelagites: Shellsville Member (type locality), Dauphin Formation. Coordinates: Latitude 40° 20' 35" N; Longitude 76° 41' 24" W.

This stop illustrates another scale of possible olistolith occurrence that differs from that seen at Stop 5-2. A long roadcut exposes an along-strike section of hemipelagic trench fill, consisting of closely interbedded, flaggy siltstones and shales, similar to the matrix lithology at Stop 5-2. This exposure also has thin, black (anoxic) shales with abundant Da 4a graptolites, and possibly a small Da 3 representation, indicating a depositional interval at this section very near the zonal boundary. Most of the graptolite fossils here fit very well into the Middle Ordovician *Pterograptus elegans* Zone, and very fine examples of this species can be found here. For a complete list of Da 3/4a graptolite fauna found at this outcrop and at other Dauphin Formation localities, see Ganis (2005).

In contrast to Stop 5-2, the possible olistoliths here are large and less detectible as entrained in the hemipelagic matrix. To the east, the County Line olistolith has a very similar appearance to the Shellsville Member strata. To the west, the Hill Drive olistolith is mostly blackish, micaceous siltstone. Both are within sight of this stop, and are truck- to house-size "chunks," essentially one outcrop, of Lower Ordovician rock, dated with graptolites. A figure illustrating this olistostrome configuration and including a description of fauna found in each of these olistoliths can be seen in Ganis *et al.* (2001, fig. 3, where we are at locality G-6, the Hill Drive olistolith is G-5, and the County Line olistolith is G-18).

There are many sedimentological features at this outcrop. Especially prominent are soft sediment slump fold features. Much of this rock is bioturbated and contains trace fossils. In places there appear to be "mixtures" of red and green chert which could be olistolithic.

Stop 5-5: Carbonate turbidites, very large olistoliths.
Coordinates: Latitude 40° 24’ 31” N; Longitude 76° 34’ 57” W.

This stop illustrates the largest scale of olistolith occurrence found thus far in the western part of the terrane, large enough for a mappable internal stratigraphy. The Middle Ordovician Da 3/4a trench matrix of the Shellsville and Nyes Road Members continues throughout the countryside, but the contained olistoliths are very large “fragments” of older strata, up to 1.5 km in length and 0.5 km wide. Figure 5-4 (Ganis *et al.*, 2001) shows the location and distribution of large olistoliths near Harper Tavern, Pennsylvania, entrained within the Shellsville Member country rock. Figure 5-5 (Ganis, 2004) illustrates three sections through parts of this olistolithic complex. In both figures, reference is made to the Onyx Cave and Sacony Members of Lash and Drake (1984), who recognized similar units in the eastern part of the Hamburg Sequence (aka “Hamburg klippe”; see introduction). The large mappable scale of rock masses attributed to similar units in other areas led Lash and Drake to refer them to tectonic slices. However, we recognize these rock masses near Harper Tavern (and elsewhere) as within the context of very large olistoliths within a trench matrix . The section we will visit on this trip is along Vesle Run, which has excellent exposures of carbonate turbidites. This class of turbidites is far less common than its clastic counterparts, but the sedimentology is familiar. Many striking sedimentary features can be seen in this section, including a variety of sole marks and graded bedding. The age of this section is (at least partly) Late Cambrian (Furongian) of the *Eoconodontus* Zone; the following faunule was recovered: *Proconodontus serratus, P. muelleri*?, and the protoconodont *Phakelodus*. With apologies to the “O” in ISOS, this Cambrian “chunk“ now finds itself expropriated to an Ordovician trench matrix as a mega-clast! To the west, the Gravel Hill olistolith was also at this scale and contained an internal section of the entire Tremadocian Stage (Ganis *et al*., 2001; fig. 5, p. 114).

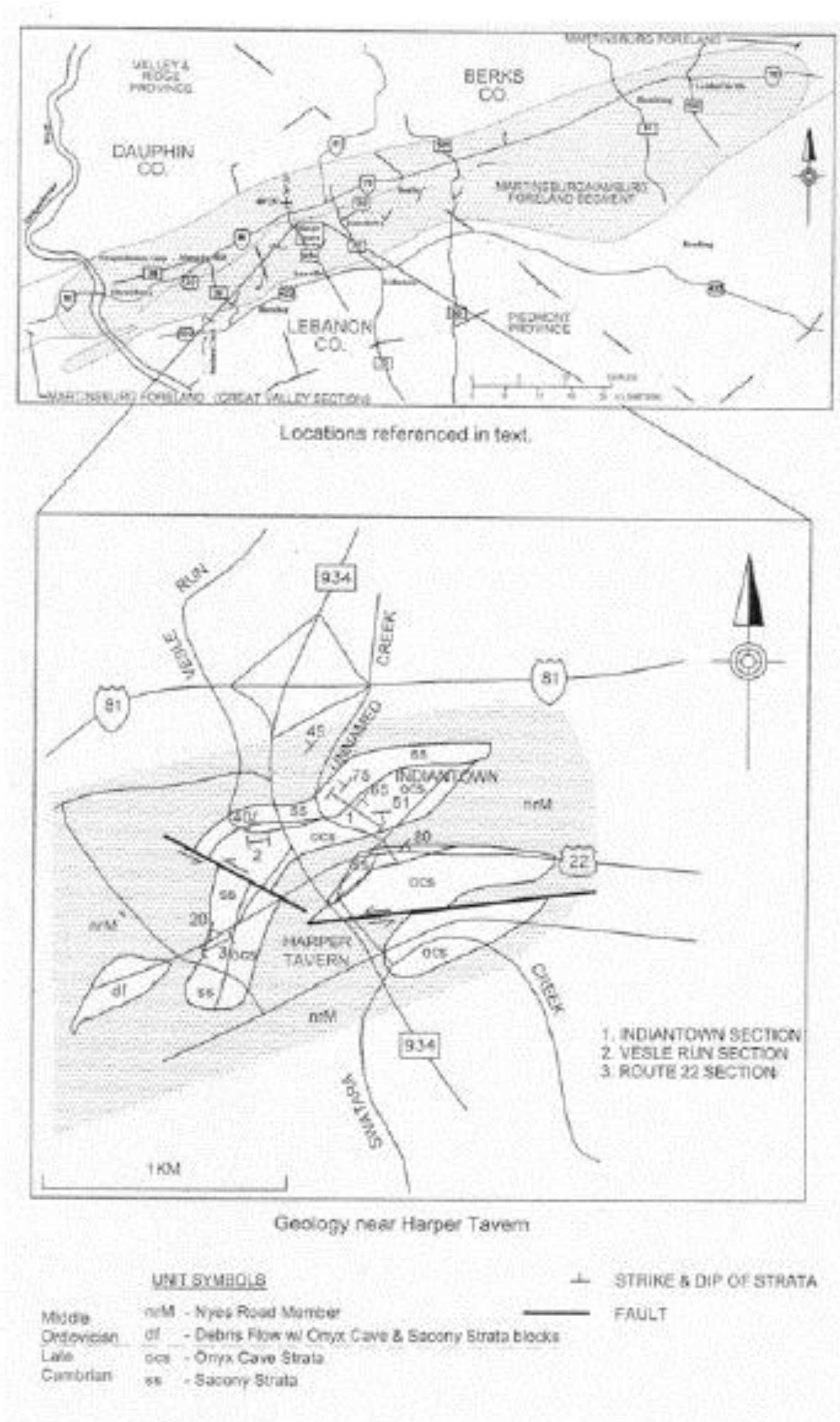


Figure 5-4: Location map for Vesle Run section (Stop 5-5, 2 on map) of a very large olistolith composed of carbonate turbidites. From Ganis (2004).

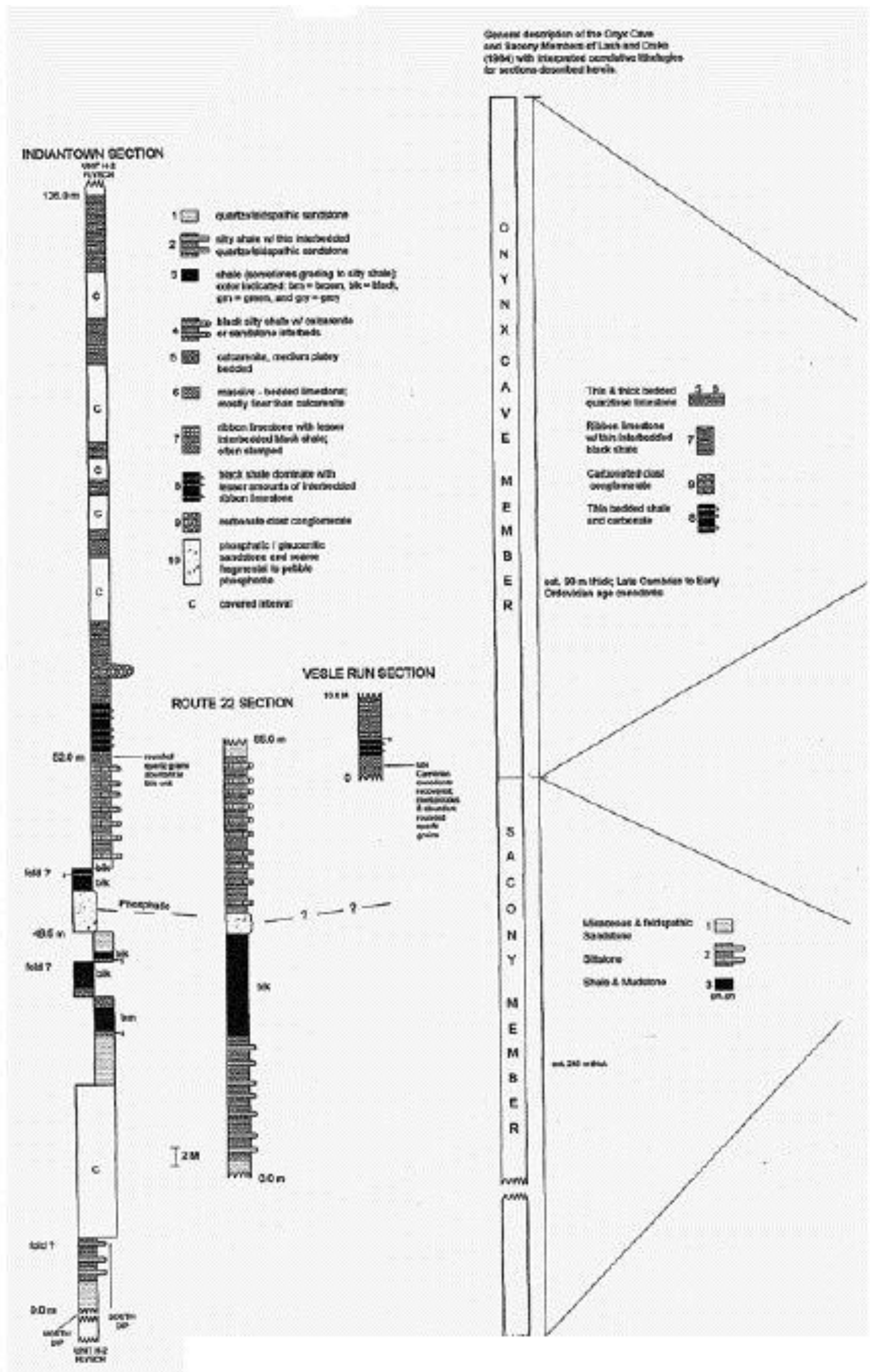


Figure 5-5: Sections referenced in Figure 5-4 (including Stop 5-5) with comparison to similar rocks described by Lash and Drake (1984). From Ganis (2004).

Stop 5-6: Martinsburg Formation cover.
Coordinates: Latitude 40° 15’ 39” N; Longitude 76° 45’ 36” W.

The Dauphin anticlinorium is cored by the allochthons of the Middle Ordovician Dauphin Formation and contains Late Cambrian to Early Ordovician olistoliths. The Dauphin Formation is sedimentologically complex with a highly variable assortment of strata. In contrast, the Dauphin Formation was covered by the relatively uniform muds of the middle Late Ordovician Martinsburg Formation flysch. Although the Dauphin/Martinsburg was severely faulted and stacked during the waning stages of the Taconic orogeny, the major fold defined by the Dauphin anticlinorium is an Alleghenian structure. We know this because Silurian rocks were infolded into the structure, surviving as a few isolated outliers. The Martinsburg Formation in the Great Valley of Dauphin, Lebanon, and Berks counties is mostly dark grey shale, invariably highly sheared and cleaved. Occasionally, the sedimentology was active enough for coarser turbidite flow. At Stop 5-6, the Martinsburg is rather uniform, highly cleaved, dark grey shale. No fossils have been found here, but this unit consistently yields graptolites in low to moderate abundance throughout its extent, where cleavage does not obscure the bedding. The basal strata of the Martinsburg Formation in this area fall in the *Climacograptus bicornis* Zone (including *C. bicornis*) and the highest on this southern limb is within the *Diplacanthograptus caudatus* Zone. The northern limb of the Dauphin anticlinorium is lithologically similar except it is massively overturned and the Martinsburg Formation extends well into the *D. spiniferus* Zone.

This stop is also described as Stop #12 in the 75th Field Conference of Pennsylvania Geologists (Ganis and Blackmer, 2010c). The Martinsburg Formation cover contact with the underlying Dauphin Formation can be seen nearby on high bankside exposures along Manada Creek.

Stop 5-7: Cocalico Formation and the Yellow Breeches Thrust at Chambers Hill.
Coordinates: Latitude 40° 15’ 38” N; Longitude 76° 45’ 36” W.

The Late Ordovician foreland subsidence affected the full extent of the carbonate bank, and the rocks we have examined thus far are only part of the Taconic fill story above that subsidence. Remnants of the more inward parts of the basin fill, now metamorphosed to greenschist grade, are found in the Cocalico Formation in Lancaster County. The Alleghenian Yellow Breeches thrust conveniently brings a portion of this “meta-fill” northwest into the Great Valley. The rocks carried on the Yellow Breeches thrust include a thick portion of the Lebanon Valley carbonate sequence as well as the Cocalico Formation; the entire sequence is massively overturned and caught up in a colossal Taconic nappe. At this stop, we will see mainly purple and red phyllites and some massive quartzitic sandstone. We invite a comparison to the rocks seen at stop 5-1 at Manada Hill. We contend that the Cocalico section here is the Manada Hill (+/-) meta-equivalent. [Note: Ganis and Wise, 2008, fig. 5, p.172, referred to the Cocalico rocks north of the Mesozoic truncation and separated from the Cocalico Formation in Lancaster County as the Cocalico Formation (North)].

This stop was Stop #9 for the 75th Field Conference of Pennsylvania Geologists (Ganis and Blackmer, 2010d).

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Chapter 6: Road Log

Note: Driving distances estimated below were prepared using functions in the MapQuest website and may include (minor) errors.

Day 1: Furongian and Ordovician units of the Shenandoah Valley, Virginia

Interval-miles	*Total miles*	
0	0	Depart from Hoffman Hall, James Madison University, Harrisonburg, Virginia, on Bluestone Parkway
0.2	0.2	Turn Left (south) onto South Main St, Route-11
0.3	0.5	Turn left (south) onto Port Republic Road
0.6	1.1	Turn left (north) onto the entrance ramp for I-81, Exit 245
45.7	46.8	Exit I-81 at Tom's Brook, Exit 291, turn right (east) onto Mt Olive Road
0.8	47.6	Turn left (north) at "T" intersection onto Route-11, Old Valley Pike
3.0	50.6	Turn left onto Battlefield Road (601 Road), This road is poorly marked. The lanes of Route-11 will separate on a descending curve. At the bottom of the hill turn left across the southbound traffic.
0.3	50.9	Cross the bridge as you ascend the hill. Park where available.

STOP 1-1 – Tumbling Run, Virginia

		Return east on Battlefield Road
3.0	53.9	Turn left on Route-11 (Old Valley Pike/Stover Ave/West King St) Enter Strasburg, Virginia
1.9	55.8	Turn Left (north) to continue on Route-11 (North Massanutten Street)
0.2	56.0	Bear left (north) onto Route-55 (John Marshall Highway)
4.0	60.0	Turn left (west) onto Back Road (623 Road). Park at intersection.

STOP 1-2 - Conococheague Formation outcrops along Route-55, Virginia

		Turn around, turn right (south) onto Route-55, cross I-81
3.5	63.5	Park in vicinity of Colley Block Road.

STOP 1-3 – Oranda Formation type section, Virginia

		Return (north) on Route-55 toward I-81
1.0	64.5	Turn right onto entrance ramp for I-81 (north), Exit 296
57.2	121.7	Arrive at the interchange between I-81 and I-70, Hagerstown, Maryland

End Day 1

Figure 6-1: A. Stop 1-1, Tumbling Run exposures of New Market Limestone from bridge; B. Stop 1-1, Tumbling Run exposures of Edinburg Formation.

Day 2: Furongian and Tremadocian platform carbonates of the Cumberland Valley and southernmost Nittany Arch

Interval- miles	*Total miles*	
		Begin travel measurement from Interchange between I-81 and I-70
		Proceed west on I-70, exit at Clear Spring, Maryland, Exit 18
9.0	9.0	Turn left (south) onto Route-68 (Clear Spring Road)
0.8	9.8	Turn right (south) onto Ashton Road
2.6	12.4	Turn left (south) onto Dam 5 Road at sharp turn in road
0.7	13.1	Turn right into parking area for Dam 5

STOP 2-0 – Conococheague Formation at C&O Canal, Dam 5, Maryland

0.7	13.8	Return to the intersection of Ashton Road and Dam 5 Road. Park.

STOP 2-1 – Conococheague Formation at C&O Canal, MP-108E and MP-107, Maryland

		Return north on Ashton Road
2.6	16.4	Turn left (north) onto Route-68 (Clear Spring Road)
0.8	17.2	Turn left (west) onto I-70, Exit 18
39.3	56.5	Proceed on I-70 West (north) to Breezewood, Pennsylvania, Exit 149
		Turn left under interstate, then right (north) onto South Breezewood Road
1.7	58.2	Turn left (west) onto US-30 (Lincoln Highway)
15.0	73.2	Turn left (south) onto PA-326 (Egolf Road) after Pennsylvania Turnpike overpass
0.7	73.9	Bear right (south), continuing on PA-326
2.6	76.5	Park as available.

STOP 2-2a Ore Hill Limestone at the Imler Quarry measured section, Pennsylvania

		Return (north) on PA-326 (Egolf Road)
2.6	79.1	Bear left to continue on PA-325
0.7	79.8	Turn left (west) onto US-30 (Lincoln Highway)
0.4	80.2	Bear right (west) continuing on US-30
1.9	82.1	Bear right onto exit ramp to I-99/US-220
0.5	82.6	Merge (north) onto I-99/US-220
8.5	91.1	Exit I-99 (US-220), turn right (east) off exit ramp
0.1	91.2	Turn left (north) onto PA-869 (Brumbaugh Road)
3.5	96.5	Turn left (north) onto PA-867 (Layfayette Road) in Brumbaugh
1.8	98.3	Turn right (east) onto Ridge Road in Layfayetteville
1.5	99.8	Turn left (north) onto Cowan School Road
1.0	100.8	Proceed past intersection with Fury Road. Park as available.

STOP 2-2b Ore Hill Limestone at the Crossroads measured section, Pennsylvania

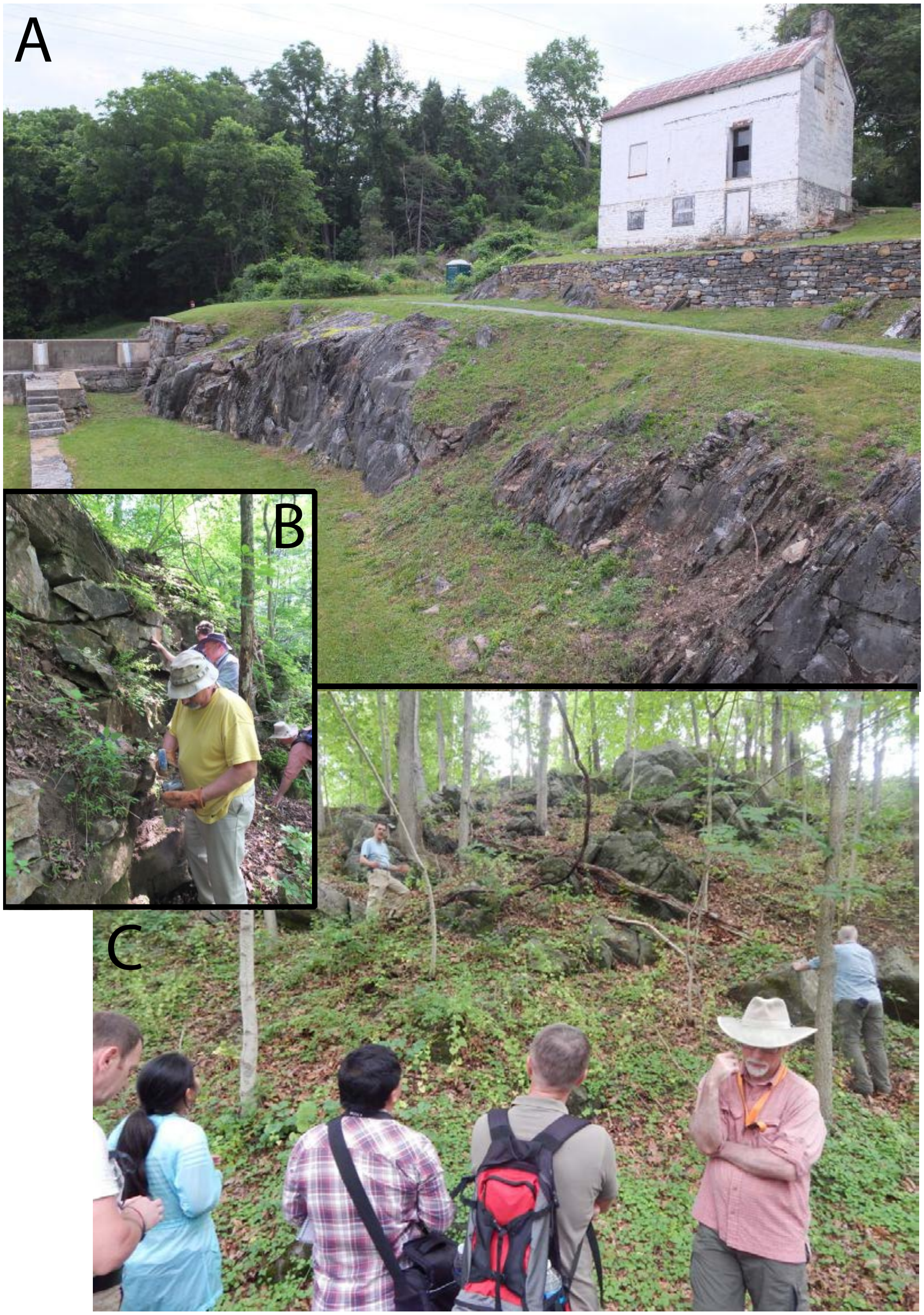


Figure 6-2: A. Exposures of the Conococheague Formation along Chesapeake and Ohio (C&O) canal at Stop 2-0; B. Exposures of the Ore hill Member of the Gatesburg Formation at Imler Quarry at Stop 2-2a; C. Exposures of Conococheague - Stonehenge formation contact along the Chesapeake and Ohio (C&O) canal at Stop 2-1.

0.0		Proceed west on Cowan School Road (Co-1032)
0.5	101.3	Turn left (north) onto PA-868 (Potter Creek Road)
2.7	104.0	Bear right (north) onto PA-867 (Lafayette Road, which becomes Bloomfield Road at the Blair County line)
6.0	110.0	Turn left (north) onto South Main St (see Figure 6-3)
0.1	110.1	Turn right (east) onto Spang St. (South Main becomes a 1-way street!)
0.2	110.3	At 5-way intersection, bear ahead to left (north) on Spang
0.4	110.7	Turn right (east) onto PA-36/PA-164
0.2	110.9	Turn left into Burger King Parking lot

STOP 2-3 Axemann Formation in Roaring Spring, Pennsylvania

		Return (west) on PA-36/PA-164
3.1	114.0	Merge onto I-99 (north)
8.0	122.0	Arrive in Altoona, Pennsylvania, at interchange between I-99/US-220 and Plank Road/Bus-220, Exit 31

End Day 2

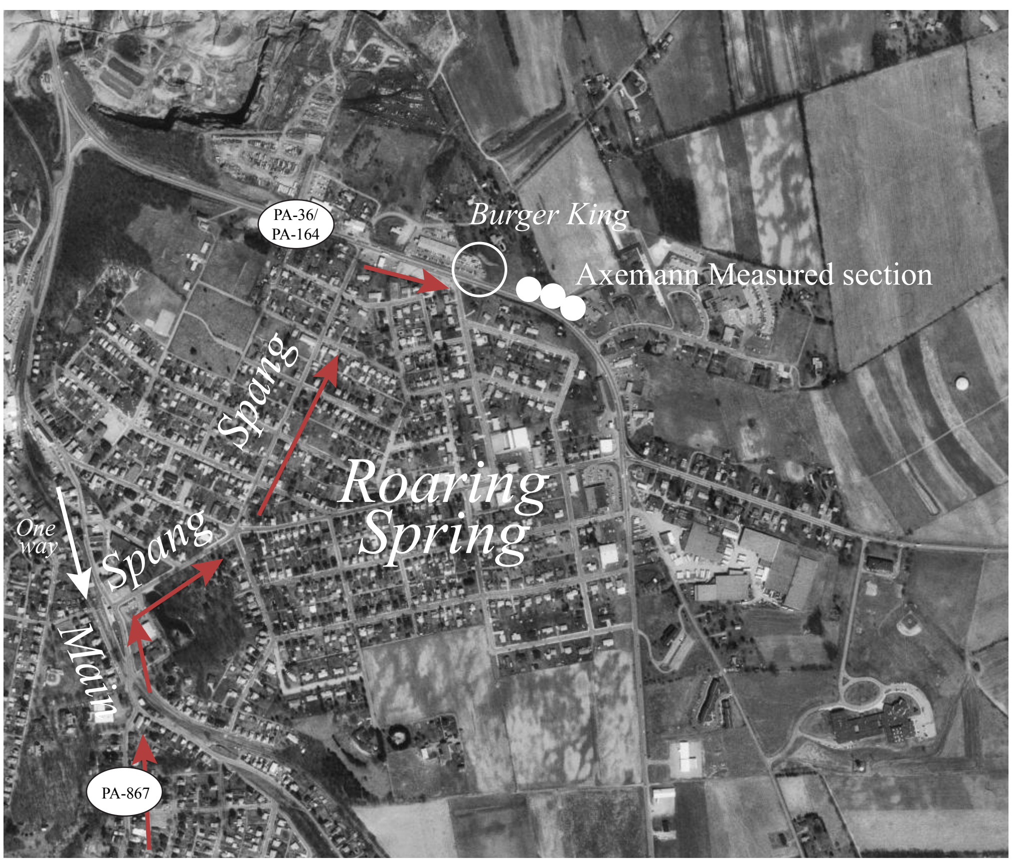


Figure 6-3: Modified Google Earth image indicating route through Roaring Spring, Pennsylvania, to arrive at Stop 2-3.

Day 3: Ordovician facies of the central and northern Nittany Arch, central Pennsylvania

Interval-miles	*Total miles*	
	0.0	Proceed northbound from I-99/US-220 Interchange, Exit 31
18.3	18.3	Exit I-99 at Tyrone, Pennsylvania, Exit 48, turn left off ramp, merge right (east) onto PA-453
4.9	23.2	Proceed east on Route-453 to Union Furnace measured section. Park where appropriate.

STOP 3-1 – Union Furnace measured section, Pennsylvania

		Return (west) on Route-453, returning toward Tyrone
2.2	25.4	Turn off at Tyrone St., entrance to Birmingham, Pennsylvania

STOP 3-2 – Birmingham Fenster, Birmingham, Pennsylvania

Figure 6-4: A. Exposure of Middle and Upper Ordovician carbonates at Union Furnace, Stop 3-1; B. Exposure of Juniata Formation within Birmingham Fenster at Stop 3-2.

		Continue (west) on Route-453
2.5	27.9	Turn right (north) onto entrance ramp to I-99/US-220
31.8	69.7	Bear onto exit ramp for Route-150 northbound (Brenner Pike) Bellefonte, Pennsylvania, Exit 78
0.4	70.1	Turn right (east) onto Rishel Hill Dr.
1.0	71.1	Turn left (north) onto Route-144 (Axemann Road)
2.2	73.3	Enter parking area, if available, on west side of road

STOP 3-3a – Stonehenge Formation in the Bellefonte, Pennsylvania, region

Note: Five measured sections (Figure 3-11) lie within 2 miles along Route-144 and additional local driving distances are omitted.

Second note: Please, be especially careful of road traffic at these stops. Route-144 is narrow, has narrow shoulders, and blind curves.

		Return (south) on Route-144
2.2	75.5	Turn right (west) onto Rishel Hill Road
1.0	76.5	Turn left (south) onto Route-150 (Brenner Pike)
0.2	76.7	Bear right (west) onto entrance ramp to I-99/US-220
5.1	81.8	Bear right to merge onto US-322, eastbound, Exit 73
84.5	166.3	Proceed (east) on US-322 to interchange of US-322 and I-81 in Harrisburg, Pennsylvania

End of Day 3

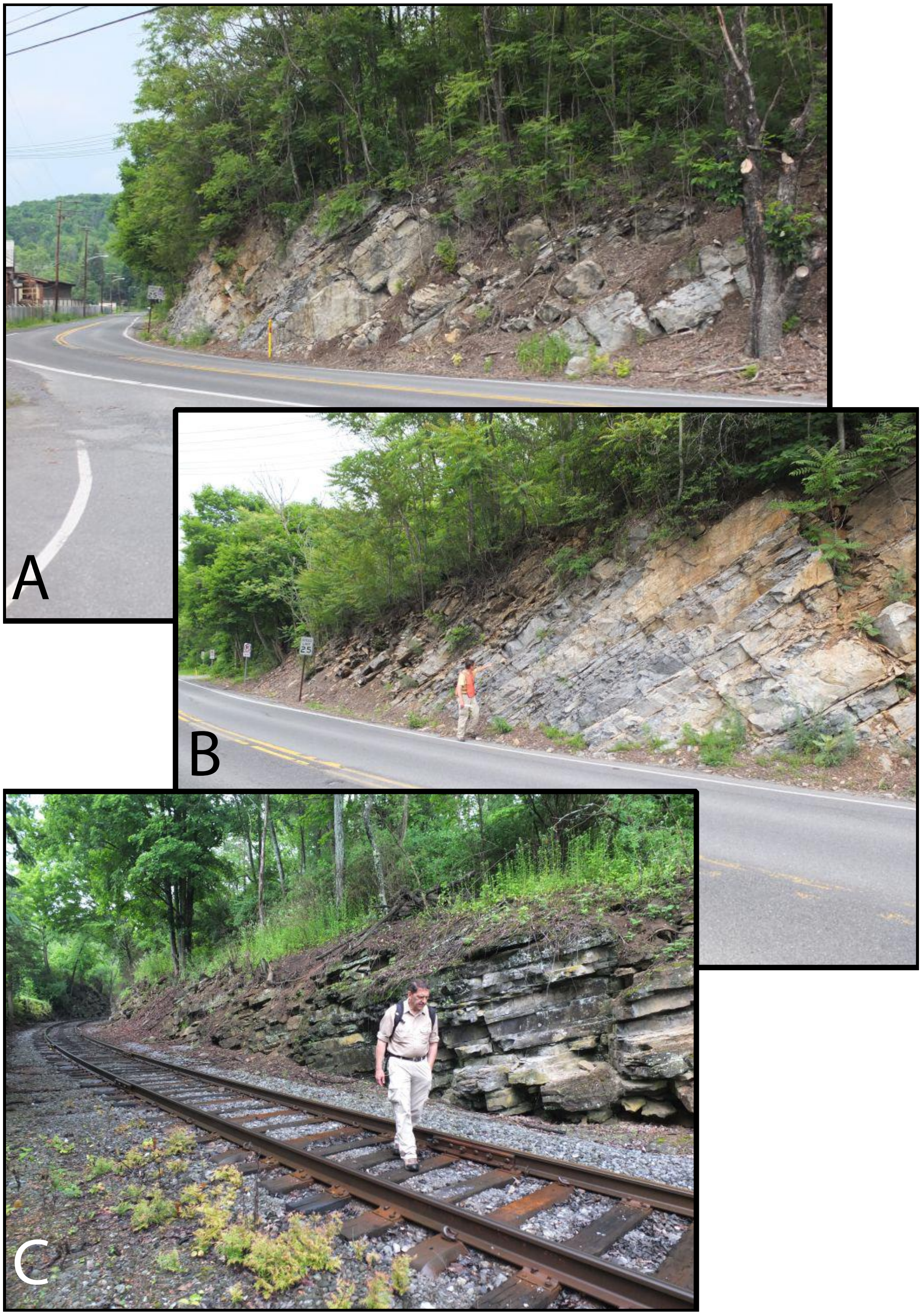


Figure 6-5: A. Exposure of basal Spring Creek member of the Stonehenge Formation at Stop 3-3a; B. JFT indicating contact between Spring Creek member (right) and overlying Graysville member (left) of the Stonehenge Formation at Stop 3-3a; C. Exposure of Logan Branch member of the Stonehenge Formation at Stop 3-4c.

Day 4: Active margin carbonates and basal Martinsburg Formation (Antes Shale) in the Northern Kishacoquillas Valley, Reedsville, Pennsylvania

Interval-Total
miles miles

	0.0	Proceed east, turning south on US-322
25.0	25.0	Exit US-322 at intersection with PA Route-655 Park where appropriate

STOP 4-1 – Nealmont, Salona, Coburn, and Antes formations at Reedsville, Pennsylvania, interchange of US-322 and PA-655

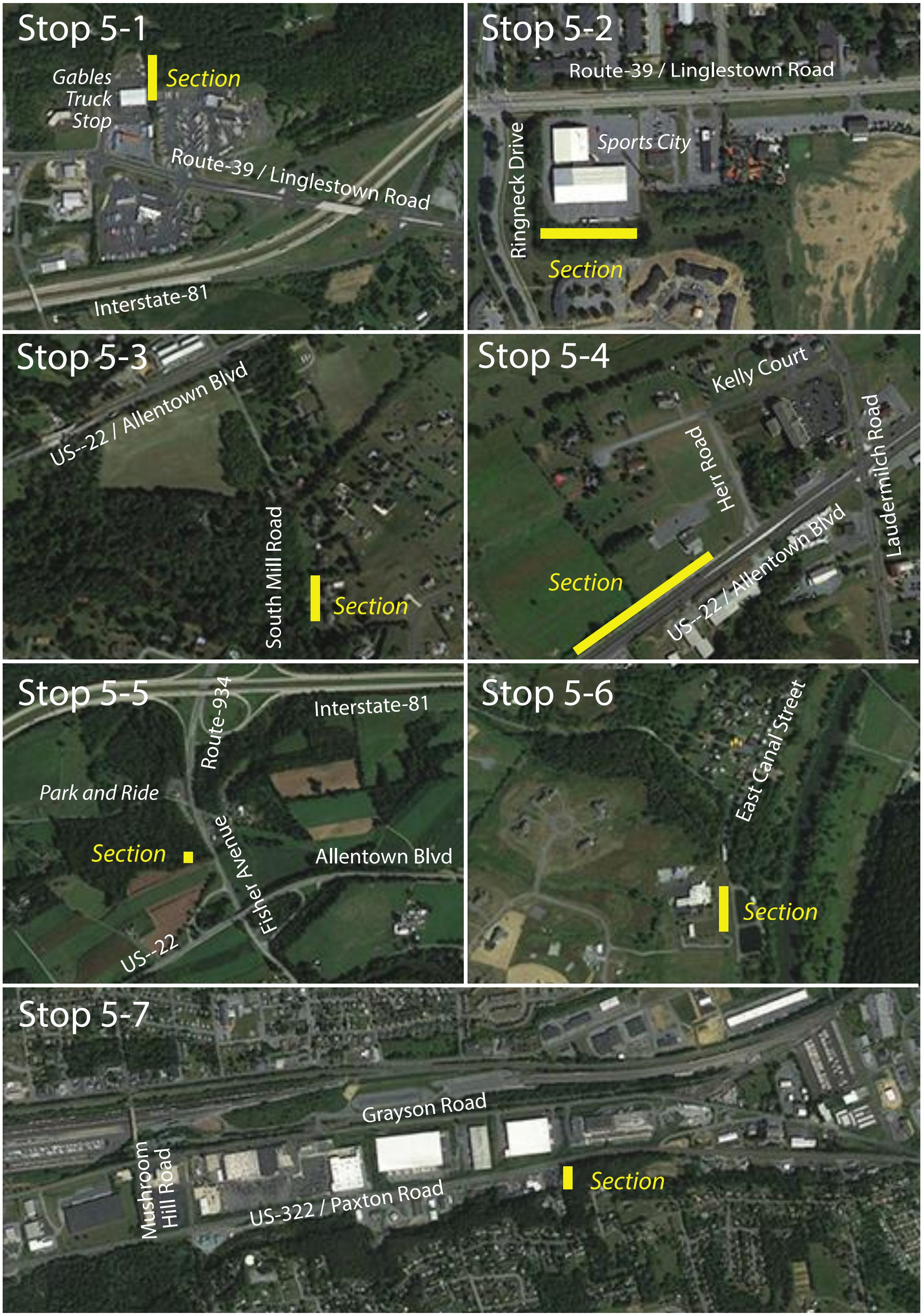
		Proceed on Route-655 (east, turning south) through Reedsville (becoming S. Main St.)
0.7	25.7	Park near intersection of S. Main and Station Hill Road Walk (south) along Station Hill Road until it rejoins S. Main

STOP 4-2 – Roadcut in Upper Ordovician clastics: Juniata and Bald Eagle formations

		Return to US-322/PA-655 interchange, enter US-322 (east/south)
60.0	85.7	Arrive at US-322/I-81 interchange

End of Day 4

Figure 6-6: Overview of road cut exposure of Nealmont and Salona formations along US-322 for Stop 4-1.


Stop 5-1
Gables Truck Stop
Section
Route-39 / Linglestown Road
Interstate-81
Stop 5-2
Route-39 / Linglestown Road
Ringneck Drive
Sports City
Section
Stop 5-3
US--22 / Allentown Blvd
South Mill Road
Section
Stop 5-4
Kelly Court
Herr Road
Laudermilch Road
Section
US--22 / Allentown Blvd
Stop 5-5
Route-934
Interstate-81
Park and Ride
Section
Fisher Avenue
Allentown Blvd
US--22
Stop 5-6
East Canal Street
Section
Stop 5-7
Grayson Road
Mushroom Hill Road
US-322 / Paxton Road
Section

Day 5: The Taconic Sequences of the Great Valley of Pennsylvania

Interval-Total miles	*miles*	
	0.0	Proceed east on I-81 from I-81/US-322 interchange
9.6	9.6	Exit I -81 at Exit 77, turn left (west) off of the exit ramp onto Route-39 (Linglestown Road)
0.4	10.0	Turn right (north) into Gables Truck Stop, just east of the Holiday Inn Express Park as appropriate; the exposure is beyond the south yard fence of Triple K Fleet services, near or at the northeast corner of the parking lot

STOP 5-1: Abyssal Pelagites; Manada Hill Member (Type locality), Dauphin Formation and the Linglestown Formation, Harrisburg, Pennsylvania

		Proceed (west) on Route-39 (Linglestown Road)
6.2	16.2	Turn left (south) into parking lot for Sports City; immediately east of junction of Route-39 and Pheasant Road (in MapQuest) or Ringneck Road (in Google Earth); Proceed to parking area in back of the building

STOP 5-2: Boulder olistostromes: Shellsville Member, Dauphin Formation

		Return (east) on Route-39
0.4	16.2	Turn right (south) onto Colonial Road
2.7	18.9	Turn left (east) onto PA Route-22 (Jonestown Road/Allentown Boulevard)
7.9	26.8	Turn right (south) onto South Mill Road
0.3	27.1	Park as appropriate south of Sycamore Lane

STOP 5-3: Submarine channel turbidites: Nyes Road Member, Dauphin Formation

		Return (north) on South Mill Road
0.3	27.4	Turn right onto Route-22 (Allentown Boulevard)
2.8	30.2	Turn left (north) onto PA Route-743 (Bow Creek Road)
0.1	30.3	Turn left (west) onto Kelly Court
0.1	30.4	Turn left (south) onto Herr Road.
0.1	30.5	Park as appropriate, before Route-22

STOP 5-4: Hemipelagites: Shellsville Member (type locality), Dauphin Formation

Facing page

Figure 6-7: Modified Google Earth images of stops for Day 5.

Figure 6-8: A. Exposure of the type locality of the Shellsville Member of the Dauphin Formation at Stop 5-4; B. View west along Vesle Run at Stop 5-5; C. Exposure of Cocalico Formation at Stop 5-7.

		Return on Herr Road/Kelly Court/Bow Creek Road
0.3	30.8	Turn left (east) onto Route-22 (Allentown Boulevard)
4.6	35.4	Bear right onto merge onto PA Route-934 (Fischer Avenue) northbound
0.3	35.7	Turn left (west) onto Mill Road. Park in Park and Ride commuter lot Walk south to Vesle Run, drop to stream level and walk west to outcrop

STOP 5-5: Carbonate turbidites: very large olistoliths

		Return (south) on Fischer Road
0.2	35.9	Turn right (west) onto entrance ramp to Route-22
4.5	40.4	Turn left (south) onto Route-743 (Laudermilsch Road)
3.2	43.6	Turn right (west) onto East Canal Road (2205 Road)
2.0	45.6	Turn left (south) onto Sand Beach Road (2015 Road)
0.3	45.9	Turn right (west) to continue on East Canal Road
0.5	46.5	Park as appropriate adjacent to water plant

STOP 5-6: Martinsburg Formation cover

		Proceed (south) on East Canal Road
0.9	47.4	Turn left (south) onto PA Route-39 (Hershey Road)
0.6	48.0	Turn right (west) to continue on PA Route-39 (Hershey Park Drive)
2.3	50.3	Merge onto US-322 (Paxton Street) westbound at PA-39/US-322/US-422 interchange
5.0	55.3	Commit U-turn at intersection with Mushroom Hill Road
0.8	56.1	Turn right into private driveway immediately east of lot for Enterprise Car Sales. Park as appropriate. Walk south and uphill along private drive to Hill Top Body Shop

STOP 5-7: Cocalico Formation and the Yellow Breeches Thrust at Chambers Hill

End of Day 5 and the end of the 12th International Symposium on the Ordovician System Post-meeting Field Trip to the central Appalachians. Thank you.