THE NATURE OF SILURIAN MOLASSE AND THE TACONIC UNCONFORMITY IN THE GREEN POND SYNCLINE, NEW JERSEY-NEW YORK, USA

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Introduction

This paper summarizes the outcrop and subsurface expressions of the Ordovician Taconic unconformity and the overlying Silurian molasse in the Green Pond syncline (GPS), an elongate belt of down-faulted Lower and Middle Paleozoic rocks in the New Jersey (NJ) Highlands and bordering the New York (NY) Hudson Highlands on the west (Figure 1). The Taconic unconformity is the erosion surface resulting from tectonic uplift during the Taconic orogeny of the present-day New England region southwestward through the NY recess and into the Pennsylvania Salient (Figure 1). The Taconic was among the first of a series of Paleozoic mountain building episodes affecting the eastern continental margin of ancestral North America (Drake et al., 1989). It is widely thought to have

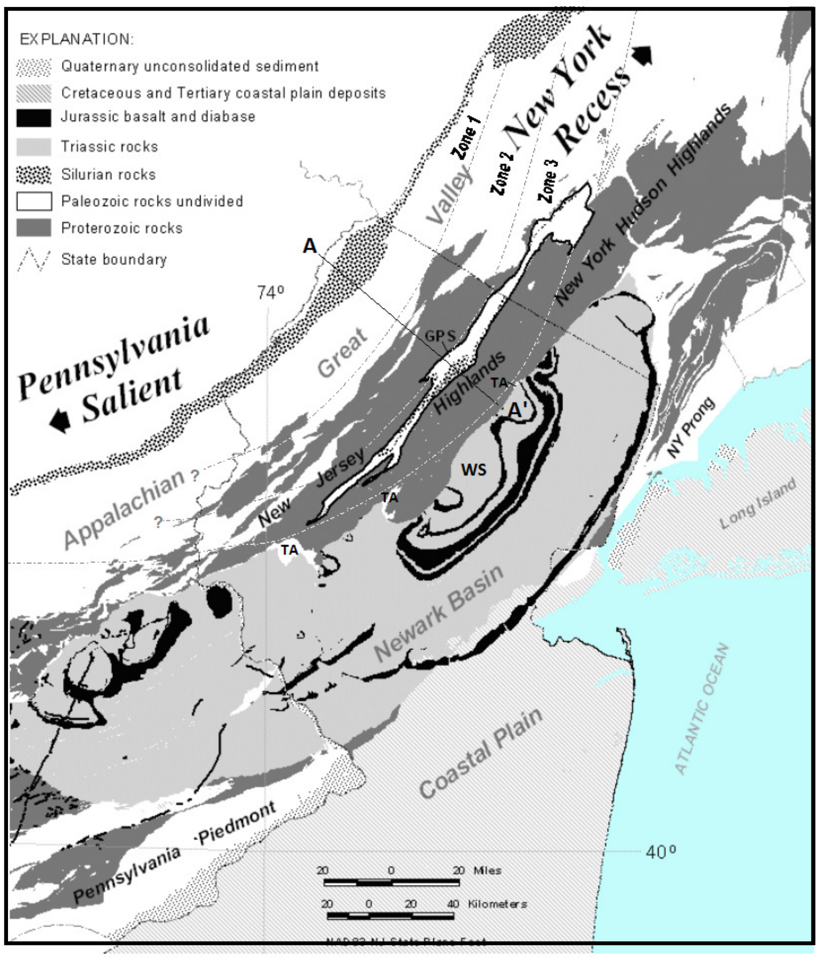


Figure 1. Generalized geology of the north mid-Atlantic region USA, showing named provinces and Appalachian terrain relative to the Green Pond Syncline (GPS). Cross section trace A-A' is coincident with parts of section A-A' of Drake et al. (1996) and Herman et al. (1997 - see Figure 2). The trace of Zones 1-3 are extrapolated southwestward into PA from New York State where Epstein and Lyttle (1987) reported increasing Taconic orogenic strains progressing southeastward toward the location of the Taconic allocthons, noted with a 'TA' along the northwest border of the Newark Basin. Fold and faults strains in each zone are detailed in the text. WS – Watchung syncline.

Herman, G.C., 2012, The nature of Silurian molasses and the Taconic unconformity in the Green Pond syncline, New Jersey-New York, *in* Harper, J. A., ed., Journey along the Taconic unconformity, northeastern Pennsylvania, New Jersey, and southeastern New York: Guidebook, 77th Annual Field Conference of Pennsylvania Geologists, Shawnee on Delaware, PA, p. 46-84.

resulted from the collision and obduction of an island arc onto the continental margin beginning in the Early to Middle Ordovician period and ending in the Late Ordovician (~443 Ma), spanning a time period of about 15-20 million years (Wise and Ganis, 2009). Evidence for the unconformity now occurs where basal Silurian quartzite and conglomerate rest on Middle Proterozoic to Middle Ordovician bedrock exposed during orogenesis. The Taconic unconformity is an angular unconformity in renowned areas along the base of Hawk Mountain, Pennsylvania (PA), Kittatinny Mountain, NJ, and Shawangunk Mountain, NY at the front of the Appalachian Great Valley where dip angles across the unconformity between Early to Middle Ordovician foredeep sedimentary rocks and the Silurian molasse vary upward to as much as 15^{o} (Epstein and Lyttle, 1987). These relationships indicate that the current area of the Great Valley was a Taconic foreland region that was mildly to moderately strained with open-upright folds and tilting during the Taconic Orogeny (Epstein and Lyttle, 1987). Evidence of rock strain of Taconic age increasing southeastward within the Ordovician flysch of the Hudson Valley led Epstein and Lyttle (1987) to define three deformation zones before encountering Taconic allocthons (Figure 1). Zone 1 is mildly strained with open, upright folding; zone 2 contains tighter, steeper folds and localized thrust faulting, and zone 3 consists of thrust faults, overturned folds, and tectonic mélange. A recent effort of constructing palinspastic cross sections through the NJ region (Drake et al., 1996) is based on balanced foreland structures within zone 1 (Herman et al., 1997) that includes a depiction of a Taconic foreland-fold sequence of Lower Paleozoic rocks cored by Proterozoic basement (Figure 2). The restored

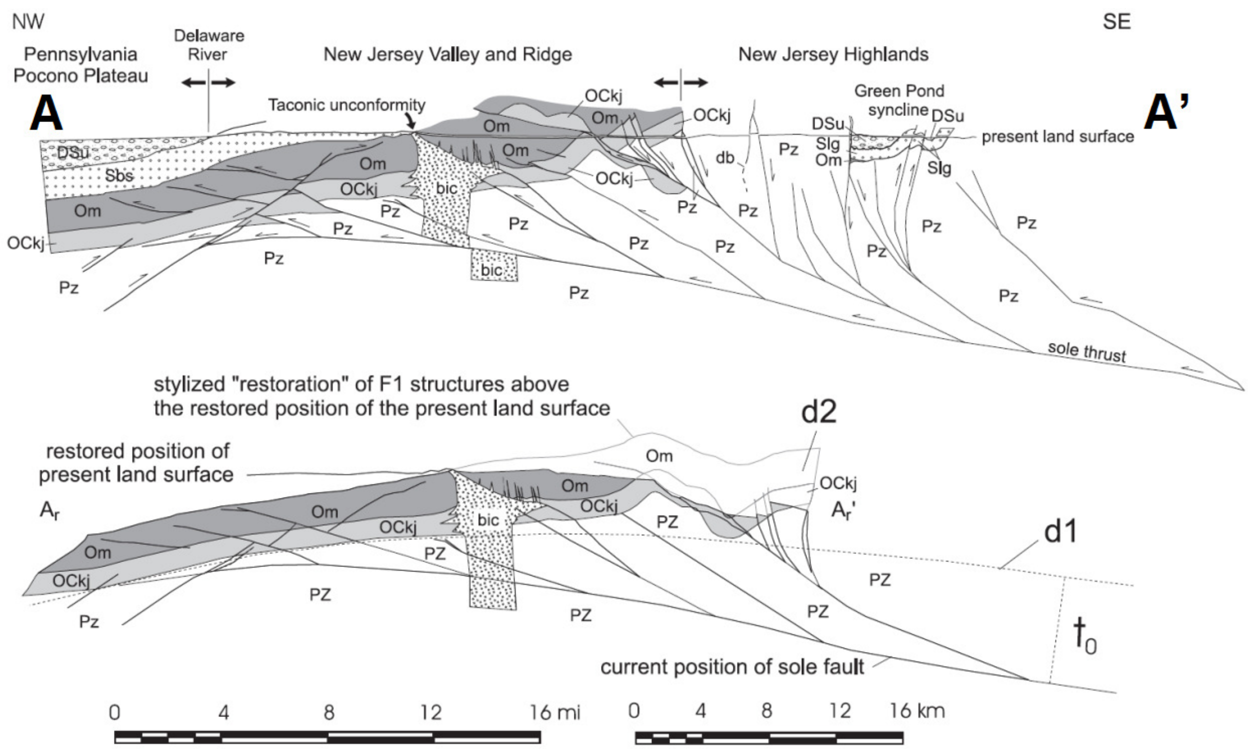


Figure 2. Details of the current (top) and palinspastic (bottom) restoration of a Taconic foreland sequence adapted from Herman et al. (1997). The section corresponds to the northwest 2/3 of A-A' of Figure 1. Abbreviations: bic—Beemerville intrusive complex; Om – Martinsburg Fm.; OCKj – Cambrian Ordvician Kittatinny Dolomite and Limestone; Pz – undivided Middle Proterzoic gneiss and granite; Sbs – Silurian Shawangunk and Bloomsburg Formations; DSu – undivided Silurian-Devonian section,; Slg Silurian Green Pond Conglomerate and Longwood Shale; d2 – restored Taconic alignment of the Cambrian-Ordvician (CO) cover sequence; d1 – restored CO base of the carbonate platform prior to sole-fault development.

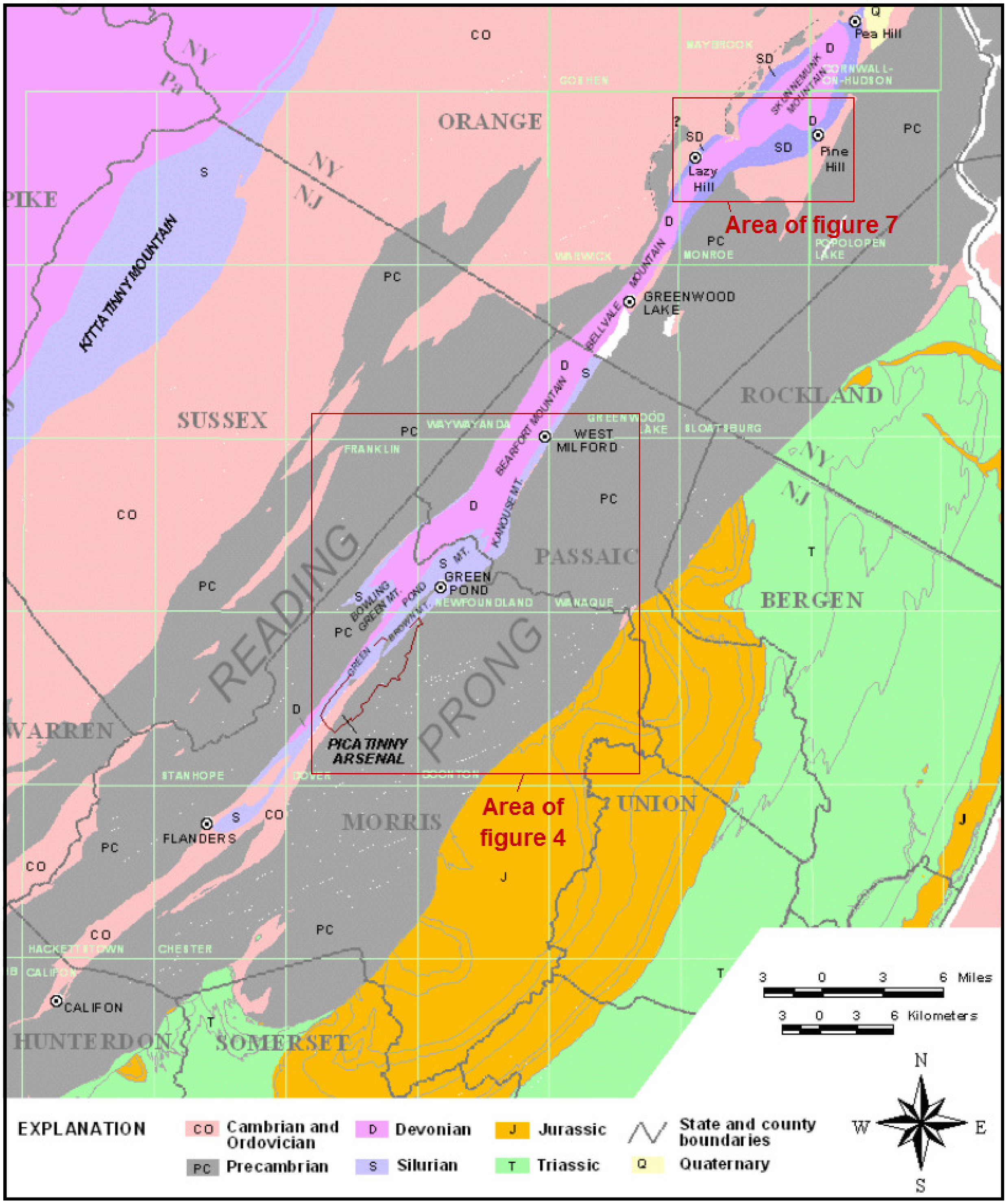


Figure 3. Generalized bedrock geology of the Green Pond Syncline. Adapted from Rickard et al. (1970) and Drake et al. (1996). Note the areas for Figures 4 and 7.

cover folds in NJ assumed a pre-Taconic, broadly arched shelf sequence for the geographic extent of the current southwest NJ Highlands, Kittatinny Valley, and Kittatinny Mountain. But the reconstructed Taconic foreland sequence doesn't reach into the northern highlands region owing to the removal of Lower Paleozoic rocks from the structural culminations of the Reading Prong (Figure 3), and thereby lacks the basis for palinspastic, balanced cross sections in those areas.

Stratigraphic and structural details of the Taconic unconformity and overlying Silurian molasse reported from previous work are reviewed as a basis to discuss their geologic nature in the GPS. Early work in NY by Darton (1894 a, b) was followed closely in NJ by Kummel and Weller (1902), who mapped and reported detailed lithological and structural relationships throughout the Green Pond Mountain region where basal Silurian sedimentary rocks rest on older rocks from Precambrian to Ordovician age. In NY however, details surrounding the nature of the unconformity are sketchier as the Green Pond Formation is restricted in its distribution and strike length at three different locations around the northeastern end of the regional syncline. Moreover, the Green Pond Formation in NY is mapped using different names in different locations, and there is a lack of detailed, uniform mapping that could otherwise shed some light on the stratigraphic variations and structural complications seen in that area. Currently, Green Pond Conglomerate is mapped on the east side of the syncline (Dodd, 1965) whereas Shawangunk Formation is mapped on the west side (Jaffe and Jaffe, 1973). These stratigraphic units are of the same age, and part of the same depositional sequence, but are mapped as separate units because of contrasting matrix color and clast composition when moving from one side of the syncline to the other. These differences are briefly noted as part of a discussion on the formation nomenclature and why the name 'Green Pond Formation' is generally used herein.

A recent trip to Orange County, NY, was made in order to visit the two locations mentioned above on different sides of the syncline where the nature of the Silurian molasse differs in outcrop. The lithological differences seen in this area are compared and contrasted with those occurring elsewhere in the GPS. A new subsurface photo of the unconformity stemming from a borehole televiewer survey of a water well from the central part of the NJ Green Pond Mountain region is also documented. This is the first subsurface record of the stratigraphic contact in NJ, and the only known record of the unconformity in the GPS besides that mentioned by Kummel and Weller (1902), which has not been corroborated. Aspects of the unconformity and overlying molasse are added from other referenced sources to help gain perspective for a palinspastic stylization of the NJ Highlands. This stylization builds on the northernmost palinspastic section from Herman et al. (1997) showing a mildly strained Cambrian-Ordovician carbonate platform and overlying Middle Ordovician flysch, both of which are arranged in open, upright folds of Taconic age. The section is extended southeast to depict the strain profile of a Taconic fold and thrust belt, an erosional unconformity, and covering molasse.

Geologic Setting

The GPS is the largest Paleozoic Valley in the Reading Prong and lies at the juncture between the central and northern Appalachian region (Figure 2). It's about 75 mi (121 km) long and up to 6 mi (10 km) wide, with about two-third's lying in NJ and one-third in NY (Figure 2). The Paleozoic sedimentary rocks in the GPS border the NY Hudson Highlands on the west (Figure 1), but are faulted and folded within the Reading Prong in NJ and PA (Figures 1 and 2). In a structural sense, the "syncline" is more formally a regional, northeast-plunging synclinorium with folded and faulted Lower Paleozoic (Cambrian-Ordovician) at the surface in the southwest and Middle Devonian rocks coring large, closed synclines at the surface in northeastern NJ and into NY (Figure 4). It's unique among Reading Prong Paleozoic valleys because it contains Middle Paleozoic (Silurian-Devonian) units of stratigraphic affinity with those cropping out northwest of the Great Valley, beginning with Kittatinny and Shawangunk Mountains over 15 mi (24 km) distance to the northwest (Figures 2 and 3).

Paleozoic rocks in the GPS range in age from Early Cambrian to Middle Devonian. As many as two to three marine cycles shape the stratigraphic column, including a Lower Paleozoic (Cambrian-Ordovician) marine transgression followed by a series of Middle Paleozoic events, including: an Early Silurian regression, a Middle- to Late Silurian transgression, and a Middle-Devonian regression (Herman and Mitchell, 1991). It is a widely held view that these Lower Paleozoic rocks sustained at least three tectonic phases of uplift and erosion including: (1) early Ordovician; (2) Late Ordovician Taconic orogeny; and (3) Late Paleozoic Alleghanian orogeny (alternatively known as the Allegheny or Appalachian orogeny).

Prior and New Work on the Nature of the Unconformity and the Silurian Molasse

The focus here is on the unconformity and nature of rocks bracketing the erosional surface resulting from the Early Silurian regression and the Middle to Late Silurian transgression in the GPS. The outcrop expression of basal Silurian strata defines the nature of Taconic unconformity, which is mapped in the NJ Green Pond Mountain region (Figures 4, 5, and 6) and three locations in Orange County, NY, near the northeast end of the GPS (Figure 3).

A Note on the Nomenclature of the Green Pond Formation

The basal, Lower Silurian unit in the GPS consists of a mixture of pebble to cobble conglomerate, quartzose and subgraywacke sandstone, quartz siltstone, and shale. Its thickness, composition, color, and texture vary by location in the syncline. Accordingly, it has been called many different names. Rogers (1836) first described the 'Green-pond-mountain conglomerate' but miscorrelated it with Triassic border-fault conglomerate (Thomson, 1957). Early miscorrelation with Devonian Skunnemunk Conglomerate by many others in the region was resolved by Darton (1894a) who found Devonian Helderberg limestone between them. Ries (1895) called it the Medina formation (Lower Silurian) in NY. Kummel and Weller (1902) and Southard (1960) preferred Green Pond Formation, but more recent workers have used Green Pond Conglomerate (Thomson, 1957; Herman and Mitchell, 1991; Drake et al., 1996) or Shawangunk Formation (Barnett, 1976; Jaffe and Jaffe, 1973). In this report, the unit is referred to as the Green Pond Formation. The decision to use "Formation" here rather than "Conglomerate" is based on the consideration that conglomerate locally constitutes less than half of the formation gross lithology, with one comprehensive measure indicating 49% sandstone, 42% conglomerate, 6% shale, and 3% siltstone (Thomson, 1959). The term "conglomerate", or "conglomerate of the Green pond Formation", or more informally "Green Pond conglomerate", is sometimes useful when describing the distribution of conglomerate with respect to specific locations in the syncline. The use of "Formation" is consistent with the

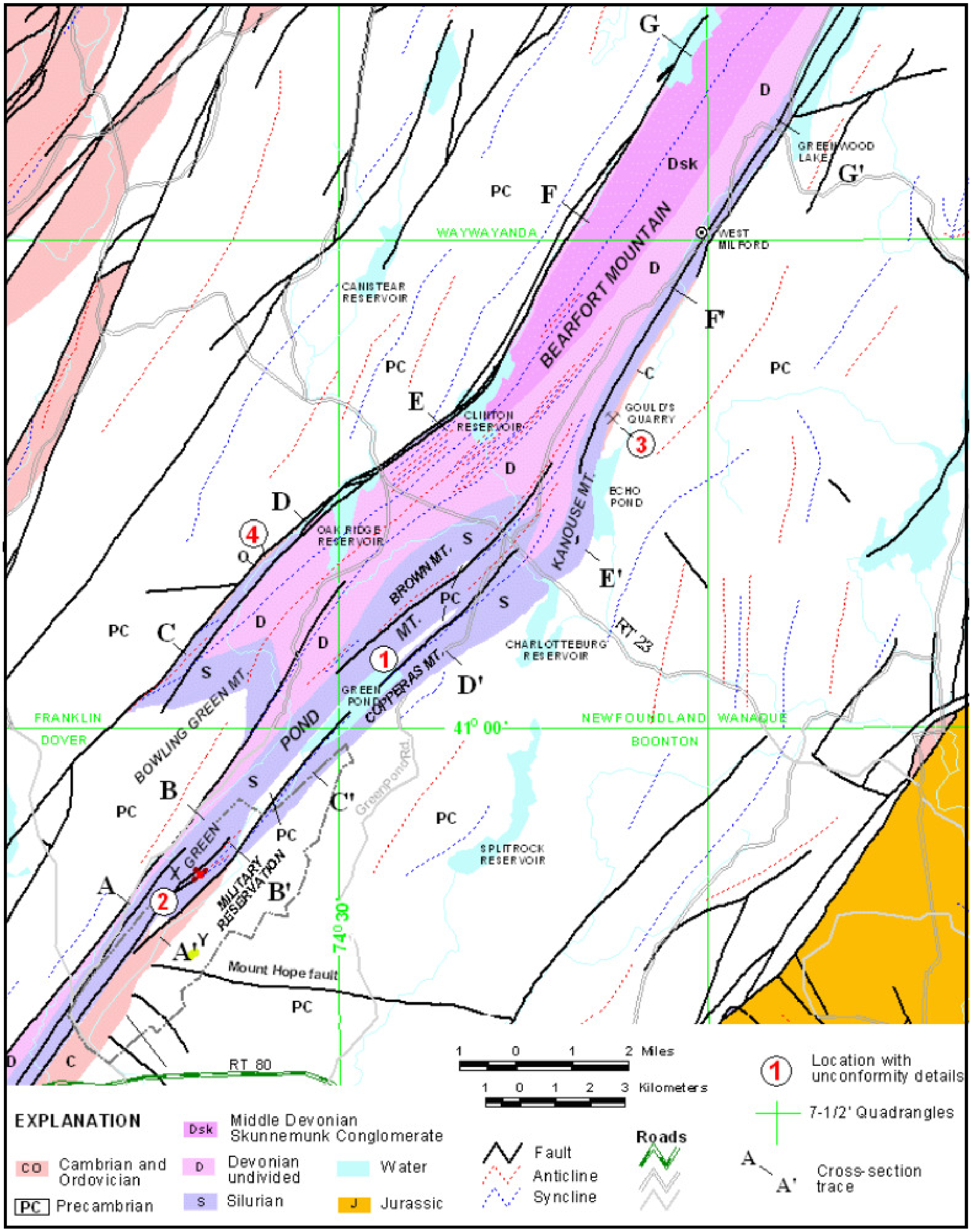
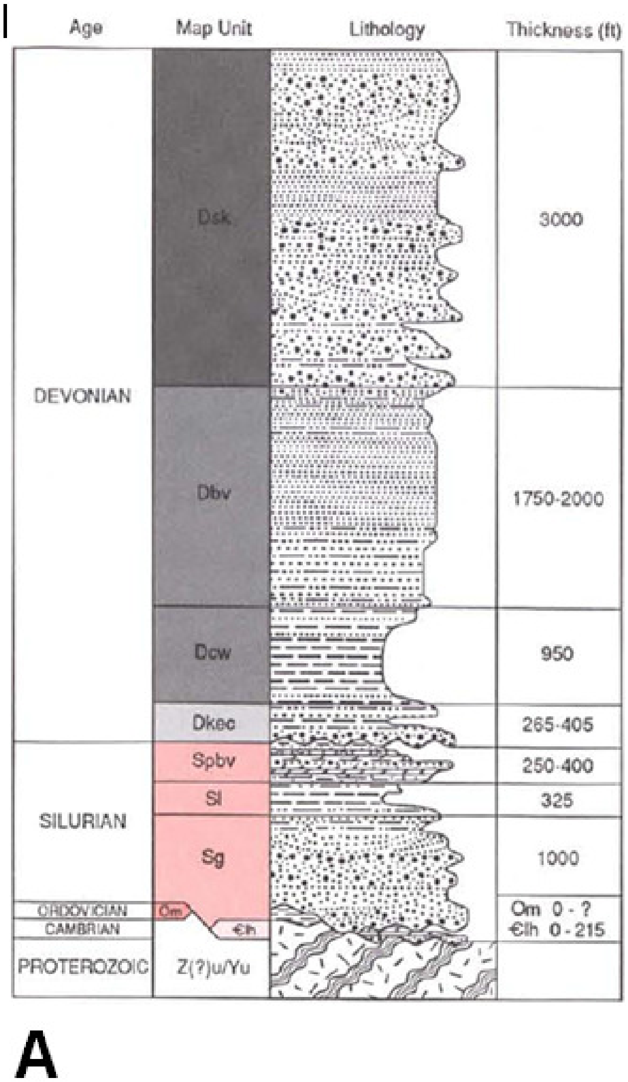


Figure 4. Generalized bedrock geology of the Green Pond Mountain region. Adapted from Herman and Mitchell (1991) and Drake et al. (1996). Note the location of section traces A through G (shown in Figure 5B). Details of the Taconic unconformity are discussed in the text for locations 1 to 4.



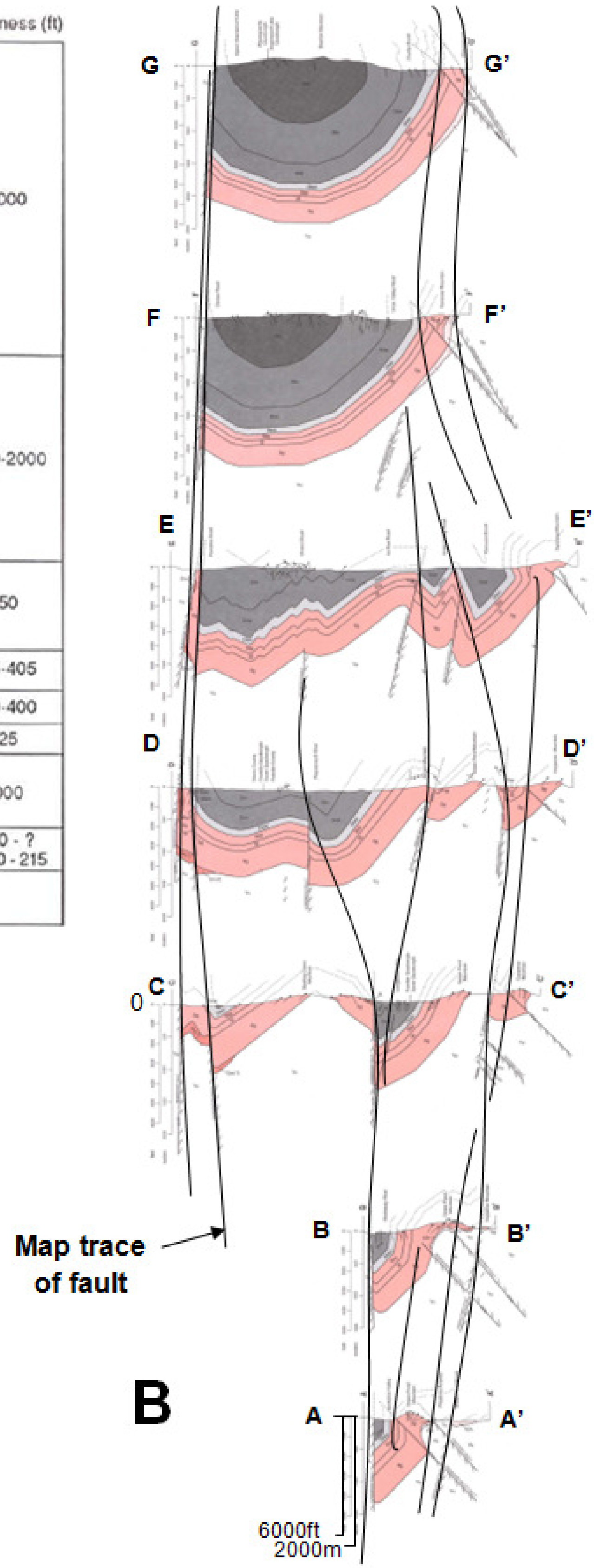


Figure 5. A stratigraphic column (A) and serial cross sections (B) for the NJ Green Pond Mountain region (Herman and Mitchell, 1991).

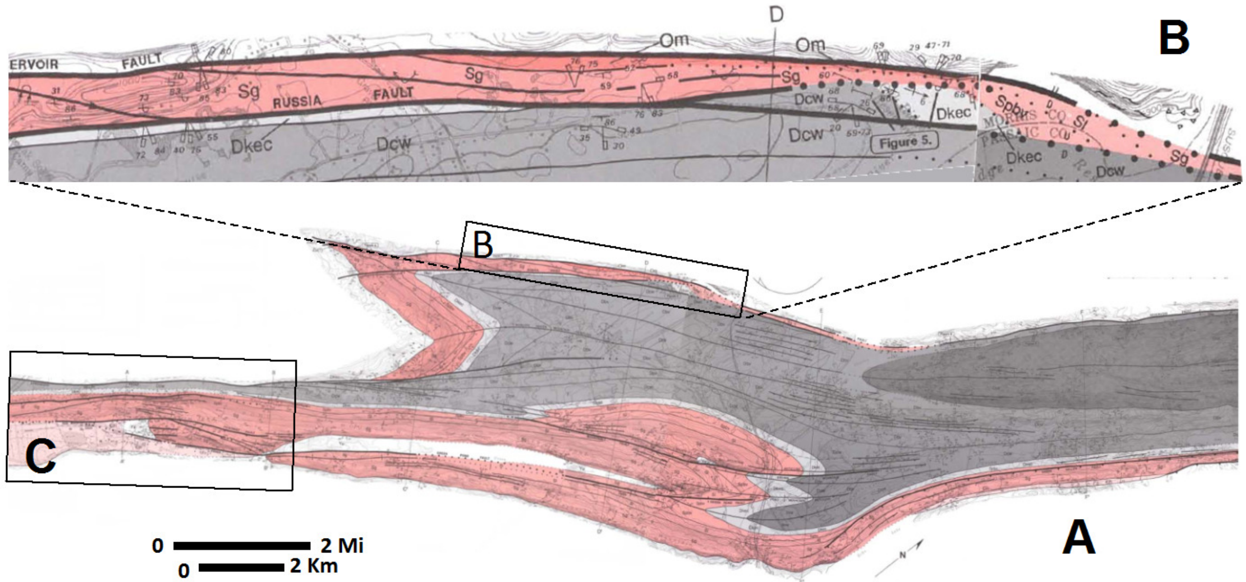


Figure 6. A. Geologic map of the central part of the Green Pond Mountain region adapted from Herman and Mitchell (1991). B. Inset map showing details along part of the northwestern boundary of the GPS where the Green Pond and Martinsburg Formations are mapped in a steeply northwest-dipping fold limb between two high-angle faults in the Reservoir fault system. The steeply-dipping limb contains is overturned steeply southeast just a short distance along strike to the west. The two shale occurrences mapped as Martinsburg are indicated by Om labels and leaders (top center of B.) C - Area C is shown in detail later in this report for the area of the US ARMY Picatinny Arsenal.

naming of the Shawangunk Formation, its stratigraphic equivalent in the Ridge and Valley Province that also contains abundant pebble conglomerate and varied alluvial-fluvial facies.

The Green Pond Mountain Region of New Jersey

The NJ part of the GPS historically has been referred to the Green Pond Mountain region and has been mapped over three time periods including the turn of the twentieth century (Kummel and Weller, 1902), around 1970 (Barnett, 1976), and again in the mid 1980s (Herman and Mitchell, 1991). The pioneering work of Kummel and Weller (1902) provides abundant stratigraphic and paleontological details, including observations of local strains such as fault attitude and slip motion.

The following excerpts are cited directly from Kummel and Weller's (1902) report on the geology of the Green Pond Mountain region:

> "The Green Pond Formation . . . consists of coarse, siliceous conglomerate, interbedded with and grading upward into quartzite and sandstones. The pebbles of the conglomerate range from one-half to three inches in diameter, and are almost entirely white quartz, but some pink quartz, black, white, yellow and red chert, red and purple quartzite and a very few red shale and pink jasper pebbles occur. The white quartz pebbles have frequently a pink tinge on their outer portion.
>
> "The quartzite . . . is interbedded in the upper portion of the conglomerate and rests upon it. It is in general a purple-red color, but presents various shades of pink,

yellow, brown and gray. Some of these beds are massive and show no laminae, but in others the thin stratification planes can be readily made out. The conglomerate beds are often very thick, with but slight trace of any bedding. In the southwestern part of the area, in the isolated hills southwest of the Rockaway River, the rock is much softer than farther north, and is friable sandstone rather than a quartzite. So completely disintegrated are some of these beds that they have been dug for sand and gravel for many years. This friable sandstone phase is well shown in the white rock cut on the D. L. & W. Railroad west of Port Oram and at the sand-pits in the vicinity of Flanders . . . The relationships of the conglomerate and quartzite to the older formations are not exposed in the isolated hills in the southwestern portion of the area."

"The relation of this formation to the overlying beds is simple. It passes upward somewhat abruptly into a soft red shale. Nowhere in NJ have the two been seen in actual contact, but they are frequently exposed in such close relationship as to render this conclusion a safe one."

"Various estimates have been made of the thickness of this formation. These range from 400 to 650 feet. All of these estimates, however, are believed to come far short of the actual thickness. In some cases they manifestly take into account only that part of the formation exposed in the steep eastward facing cliffs which characterize these ridges, and take no account of the higher beds which outcrop with steep dips on the back slopes of the mountain, and which add greatly to the thickness. In some cases, too, the small estimates may be due to an assumption that the ridges are formed by closely compressed folds. Our own estimates, measured on numerous section lines across the ridges, where at least the approximate portion of the enclosing formations were determined, and based on frequent observations of the angle of dip, indicate that the thickness of this formation is probably not less than 1,200 feet and locally it may be 1,500 feet. It is not asserted, however, that this entire thickness is exposed at any one locality, but we believe that these figures represent the thickness of the formation as developed along the greater portion of Green Pond and Copperas mountains. Toward the northern end of Kanouse mountain the thickness apparently diminishes somewhat; yet owing to the thick deposits of drift which conceal both the basal and upper portions, estimates of the thickness there may be somewhat in error. In the previous discussions of this region published in the Reports of the Survey, the conglomerate which occurs along Bearfort mountain was assumed to be the same as of Green Pond and Copperas mountains. Mr. Darton was the first to point out that this was an error, and the same conclusion was announced about the same time by Mr. Walcott. Our work corroborates completely the conclusions of these investigators in this respect. Although the conglomerates of Bearfort and Green Pond mountain resemble each other somewhat closely, yet critical examination of the two discloses at once marked lithological differences. These will be pointed out in connection with the description of the Bearfort conglomerate. Since the Green Pond formation rests unconformably in places upon the Lower Cambrian limestone, and perhaps upon Hudson River slate, and is overlain conformably by a red shale, which, as will be shown later, passes upward into a siliceous limestone containing Niagaran fossils, the correlation of the Green Pond formation with the Oneida conglomerate exposed in

Kittatinny mountain is probably correct. The lithological differences between the two are not so great as has been assumed by some observers. The lower beds of the Green Pond conglomerate are not infrequently of the same grey color and in almost every way identical with the conglomerate of Kittatinny mountain. Moreover, reddish conglomerates so common in the Green Pond rocks are not infrequent in the Kittatinny mountain beds. Although lithological resemblances and differences are not always safe guides for correlation, particularly in a formation which is so subject to variation as a conglomerate and sandstone, yet the structural position of the two is practically the stone, and there can be no question as to the correctness of this correlation, which was first announced by Merrill. He, however, included the conglomerate of Bearfort mountain as a part of the Green Pond formation."

Specific occurrences where the Green Pond Formation crops out in close proximity to older rocks in NJ are discussed below with respect to locations identified in Figure 4. The following details mostly stem from Kummel and Weller (1902) but are supplemented by work of Herman and Mitchell (1991).

Green Pond Formation over Middle Proterozoic crystalline basement (Figure 4, locations 1 and 2 for Copperas, Green Pond, Brown, and Bowling Green Mountains). – From Kummel and Weller (1902):

"The relation of this formation to the underlying rocks is readily determined, although only in one place has the actual contact been seen. Throughout the entire extent of Copperas mountain it rests unconformably upon the eroded surface of the crystallines, which form the lower part of the southeastern face of the mountain. At the mines opposite Green Pond the two formations are frequently exposed within twenty five or thirty feet of each other, although not in actual contact. Here the lowest conglomerate bed is rather gray in color and resembles closely the conglomerate of the Kittatinny and Shawangunk mountains. Along this face of the mountain the contact can be located definitely at an elevation of about 1,100 feet, or 225 to 250 feet below the crest"

"At Middle Forge, in the quarry west of the road (near location 2, fig. 4), the conglomerate of the Green Pond mountain apparently rests upon the Kittatinny limestone, but northward a quarter of a mile the conglomerate and gneiss are apparently in contact. West of the pond a fault evidently separates the high cliff of conglomerate from the Kittatinny limestone exposed in the quarry on the shore, both formations showing strong evidence of shearing and drag at outcrops nearest the hidden contact. Elsewhere along this mountain the conglomerate apparently rests upon the gneiss, and, although this contact is nowhere exposed, yet the two are shown in close proximity to each other at many places along the wild and narrow gorge of Green Pond brook, up which the gneiss can be traced continuously to about one-quarter of a mile southwest of the end of the pond where it is lost in the swamp. However, it reappears again a mile and a half east of the upper end of Green Pond forming a narrow bench fifty yards in width and several hundred yards long, immediately below the prominent summit of Green Pond mountain. Toward the lake the ledge becomes buried beneath the drift and to the northeast it disappears beneath the great blocks of talus, the dip of its contact with the overlying conglomerate and quartzite being such as to carry it beneath the surface within a short distance."

"The conglomerate is also seen to rest upon the gneiss in the offset of Green Pond mountain, southwest of Newfoundland, which is known locally as Brown's mountain. In Bowling Green mountain the conglomerate is wrapped around the northward end of a ridge of gneiss, and probably rests directly upon it; but the contact has not been seen, and nowhere have the rocks been found in such close proximity to each other as to eliminate beyond a doubt the possibility of a narrow strip of older sedimentary rocks between them."

Herman and Mitchell (1991) mapped Middle Proterozoic crystalline rocks with metamorphic layering dipping moderately to steeply southeast along the unconformity in the southeast-central and northeast part of the Green Pond Mountain region, whereas the Green Pond Formation dips moderately to steeply northwesterly. They also note that the contact of the conglomerate with the underlying basement rocks is not observed and is locally obscured by as little as 3 ft (0.9 m) of cover. The lack of pervasive tectonic strain fabric along the southeast syncline limb precludes a major structural contact, although limited shear strain associated with cover-layer folding is expected. These regional relations indicate that the Taconic unconformity is most pronounced in this area where the entire Lower Paleozoic section was eroded.

The basal conglomerate is coarsest to the east at Green Pond, Brown, and Kanouse Mountains where angular cobbles of shale and quartz are common, with some shale clasts measured up to 18 in (46 cm). To the west, at Bowling Green Mountain, the basal conglomerate contains mostly subangular to subrounded quartz-pebbles and is interbedded with quartzitic arkose and orthoquartzite.

Green Pond Formation over Cambrian-Ordovician Middle Proterozoic crystalline basement Gould's Quarry (Figure 4, Location 3). – From Kummel and Weller (1902):

"At Gould's quarry, large masses of the underlying limestone are included in a conglomerate, which is believed to be the basal layers of this formation. The matrix is comprised of quartz sand, is vitreous in texture and generally of a dull red color, but white, gray and greenish strata frequently occur, particularly in the basal portion, so that the formation is not so exclusively red as implied in most of the earlier reports. The beds are almost uniformly quartzitic in texture, and, on account of their hardness, form the long, narrow, steep-sided mountain ridges characterizing this region. Locally, however, the basal portion of the conglomerate is apparently quite friable and disintegrates readily, due probably to a greater or less amount of calcareous material derived from the limestone on which it rests in places. A good instance of this was found about 2 mi (3 km) north of Macopin lake, where the basal beds are so disintegrated that they have been dug for gravel".

Herman and Mitchell (1991) show bed strike in both the Lower and Middle Paleozoic units here are the same, but bedding dips more steeply (60^{o} to 70^{o} northwest) in units below the unconformity in comparison to those above (42^{o} to 56^{o} northwest).

Green Pond Formation over Middle Ordovician Martinsburg Formation along the Reservoir Fault (Figure 4, Location 4). – From Kummel and Weller (1902):

> "The outcrops of this formation southwest of Oak Ridge reservoir apparently rest upon a black shale, which may belong to the Hudson River formation, but no positive assertions can be made. Farther to the southwest they apparently abut against the crystallines and in the fault plane."

Barnett (1976) reports Ordovician brachiopods in this shale, resulting in his mapping them as Middle to Upper Ordovician Martinsburg Formation. There are two shale outcrops that are bounded on the southeast by fault slices of Green Pond pebble conglomerate (Figure 6). Worthington (1953) reported another occurrence of the Martinsburg Formation along the Reservoir fault farther southwest where the Green Pond Formation pinches out between Holland and Bowling Green Mountains. However, the black phyllite he described differs from the tectonized shales at Oak Ridge, and occurs with other anomalous rocks of uncertain affinity. Other tectonized sedimentary rocks that crop out along the trace of the Reservoir fault directly west of the Green Pond conglomerate show abundant stretched quartz grains included within a dark greenish-gray to dark reddish-brown phyllonitic matrix. Immediately to the southwest, and southeast across the trace of a subsidiary fault, the Green Pond Formation unconformably overlies a patchy strip of very low-grade metamorphic arkose and quartzite unlike other Middle Proterozoic basement rocks in the region. These rocks are similar to the Chestnut Hill Formation of Late Proterozoic (Z) age reported in the southwest NJ Highlands (Drake, 1984).

The Green Pond Formation in Orange County, New York

The Green Pond Formation Is mapped in three areas in Orange County, NY, covered by the Monroe, Lake Popolopen, and Cornwall-on-Hudson 7-½ minute quadrangles (Figures 2, 3 and 7). These locations are specifically discussed below with respect to Lazy Hill, Pine Hill, and two bedrock ridges near Pea Hill, respectively (Figure 2). Lazy Hill lies about 2 mi (3 km) west of Monroe on the western side of Bellvale Mountain, and the western limb of the syncline (Figures 2 and 7). Pine Hill lies immediately east of Highlands Mills, NY on the east side of the syncline where one long, northeast-striking, thin bedrock ridge rises about 200 ft (61 m) above base elevations along Skyline Drive (Figure 7). The ridges near Pea Hill are more than 1 mi (1.6 km) west of Cornwall, NY within the Cornwall-on-Hudson quadrangle and at the very northeast tip of the GPS. These are a little less conspicuous, rising only about 120 ft (37 m) above base elevations.

Lazy Hill and Fault Blocks in the Monroe Quadrangle

The bedrock geology map of the Monroe quadrangle provides the only record of detailed structural readings of strata bracketing the unconformity in the NY part of the GPS (Jaffe and Jaffe, 1973 and Figure 7). Basal Silurian conglomerate and quartzite are mapped just west of Monroe in a series of fault blocks that are referred to here as south, central, and north (Figure 7). The south and central blocks flank Bellvale Mountain, whereas the north block flanks Schunemunk Mountain (Figure 3). The unit is mapped as Shawangunk Formation, and is described as green-gray to white and buff-colored orthoquartzite (25%) and conglomerate

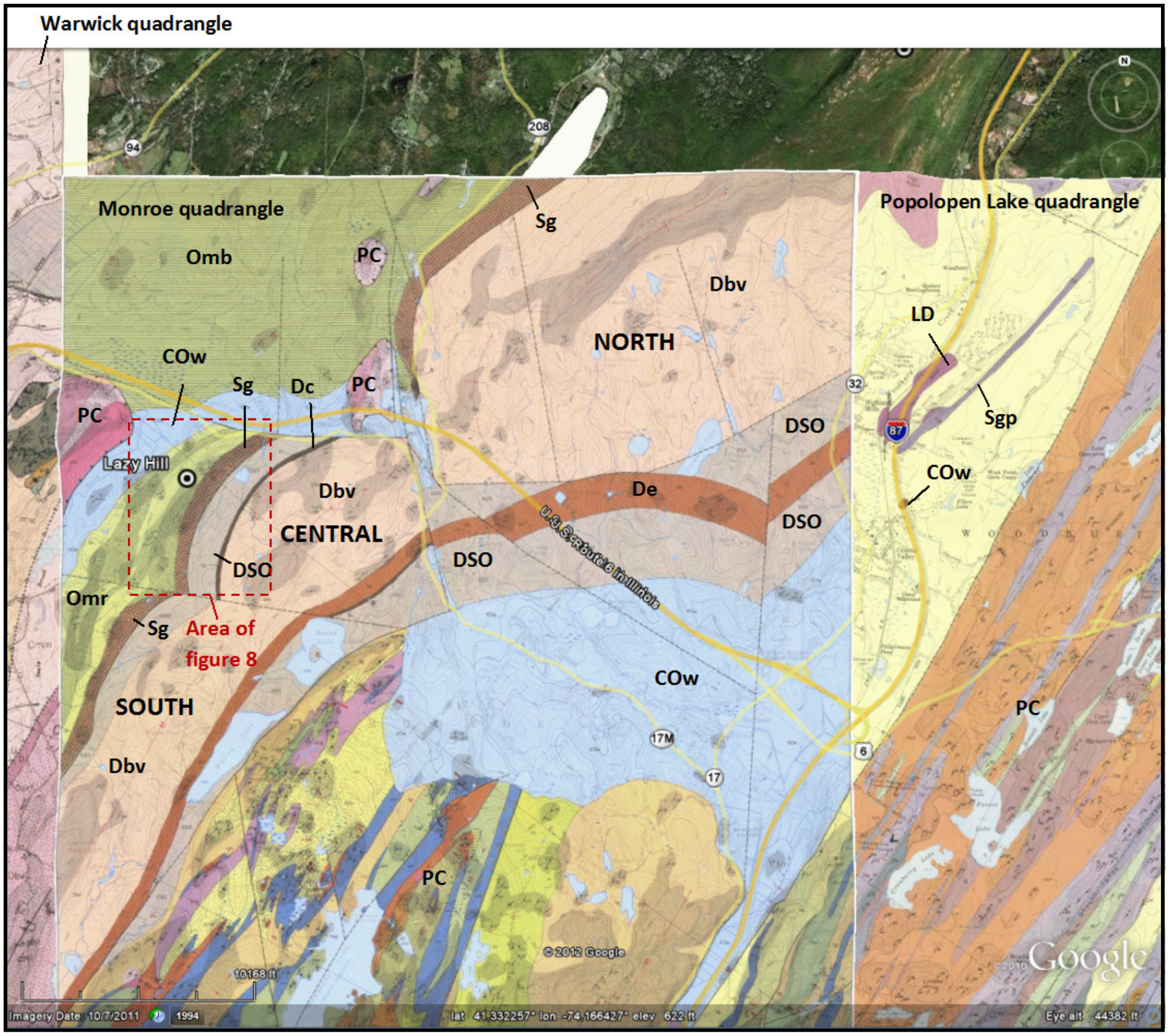


Figure 7. Composite display of three bedrock geology maps (Offield, 1967—left; Jaffe and Jaffe, 1973—center; and Dodd, 1965— right) registered in Google Earth that cover parts of the Green Pond Syncline in New York State. The Shawangunk Formation (Sg) is mapped to the west whereas the Green Pond Formation (Sgp) is mapped to the east. The Shawangunk is extended north of the Monroe quadrangle boundary based on the topographic expression of the associated hill. The relationship of the Taconic unconformity on the west side of the syncline is discussed in the text with respect to south, central, and north fault blocks in the Monroe quadrangle. Abbreviations: Dbv—Devonian Bellvale Formation; COw – Cambrian-Ordovician Wappinger Group (dolomite); Dc – Connelly Conglomerate; De – Esopus Formation; DSO - concealed Silurian, Devonian, and Ordovician strata; LD – Lower Devonian sedimentary rocks; Omr – Ordovician Martinsburg calcareous shale and quartzite; PC – Precambrian rocks.

(75%) consisting of coarse white pebbles of milky vein quartz in a matrix of fine pebbles and grains of rounded quartz.

According to Jaffe and Jaffe (1973):

> "A 10-meter section measured across the top of Lazy Hill, shows from west to east; about 1 meter of gray-buff orthoquartzite, 2.5 meters of coarse white pebble conglomerate, 4.5 meters of white orthoquartzite with ripple marks on bedding planes, and 1.25 meters of finer white quartz pebble conglomerate . . . Toward the

eastern edge of Lazy Hill scarp, the conglomerate carries some coarse orthoclase pebbles and unit grades into a red arkosic conglomerate below the ridge top . . . Small slabs of red argillaceous sandstone were found at localities near the base of the eastern edge of lazy Hill scarp and suggest a gradation to the Longwood Shale."

Pebbles in the conglomerate are about 0.5 to 4 in (1.3 to10 cm) long, and are strongly elongated (stretched) parallel to the syncline fold axes. The rocks are reported as being shattered, sliced, and veined. They map Shawangunk Formation overlying calcareous shale and quartzite of the Martinsburg Formation, thereby having the same stratigraphic relationships as seen about the Taconic unconformity at Kittatinny and Shawangunk Mountains about 15 mi (24 km) across the Great Valley to the northwest. But the Martinsburg at Lazy Hill is comparatively more deformed than its counterpart to the northwest, with local, southeast-verging asymmetric folds and steep, northwest-dipping faults (Jaffe and Jaffe, 1973). The Shawangunk designation was used for these rocks because they closely resemble those in Shawangunk Mountain where they are white- and buff-colored rather than the grayish-purple to grayish-red color of Green Pond Formation on the eastern side of the syncline at Pine Hill, NY (Figure 7) and in the central Green Pond Mountain region of NJ. The unit thickness in the Lazy Hill area is portrayed by Jaffe and Jaffe (1973) as about 400 to 600 ft (122 to 183 m) thick based on their cross-section interpretations and calculations based on their outcrop widths and dip angles. The Shawangunk Formation of Jaffe and Jaffe (1973) will be referred to as the Green Pond Formation for the remainder of this report in accordance with the nomenclature discussion above.

In the southern and central fault blocks, the Green Pond Formation forms ridge scarp peaking at 700 to 800 ft (213 to 244 m) elevations in comparison to 900 ft (274) crest elevations of nearby Bellvale Mountain to the east. The scarps are shown as being cut by concealed cross faults striking about N95^{o} E, having little offset of cross-cut Ordovician through Devonian strata, and are thus not included on the regional maps compiled here (Figures 1 and 2). In the southern fault block, the Green Pond Formation is mapped as overlying Martinsburg Formation calcareous shale dipping north-northeast to south-southeast at 20^{o} to 50^{o}, but there are no structural readings mapped close to the unconformity, and the angular relationship between the two units here is unknown. However In the central fault block, the Green Pond is mapped near outcrops of Ramseyburg calcareous quartzite (Figure 8), and the angular unconformity is characterized along two traverses across the crest of Lazy Hill (Figure 8). Both formations strike parallel (northeast-southwest), but the Martinsburg dips gently eastward 25 to 16^{o} beneath the Shawangunk, that is mapped having moderate eastward dips of 52^{o} to 40^{o}. Along the northern traverse, there is about a 10^{o} difference in northeast-southwest strike, but the formation dips are the same (60^{o} southeast).

The Green Pond Formation crops out sparingly in the North block on the westward-facing hillslope at about 600 ft (183 m) elevation, with peak elevations of Schunemunk Mountain in the 1,300 to 1,400 ft (396 to 427 m) range. In all three blocks, it's mapped as being fault-bounded on the eastern side. For the south and central blocks, undivided and concealed rocks of Ordovician to Devonian age are mapped directly east of the bounding fault. The Lower Devonian Connelly Conglomerate is mapped about 1,300 ft (396 m) to the east of the Green Pond Formation, and adjacent to the concealed unit in the central block. It is also mapped as a fault sliver at the southern end of the ridge scarp in the north fault block (Figure 7) where Middle Devonian Bellvale Sandstone is otherwise mapped directly east of the bounding fault.

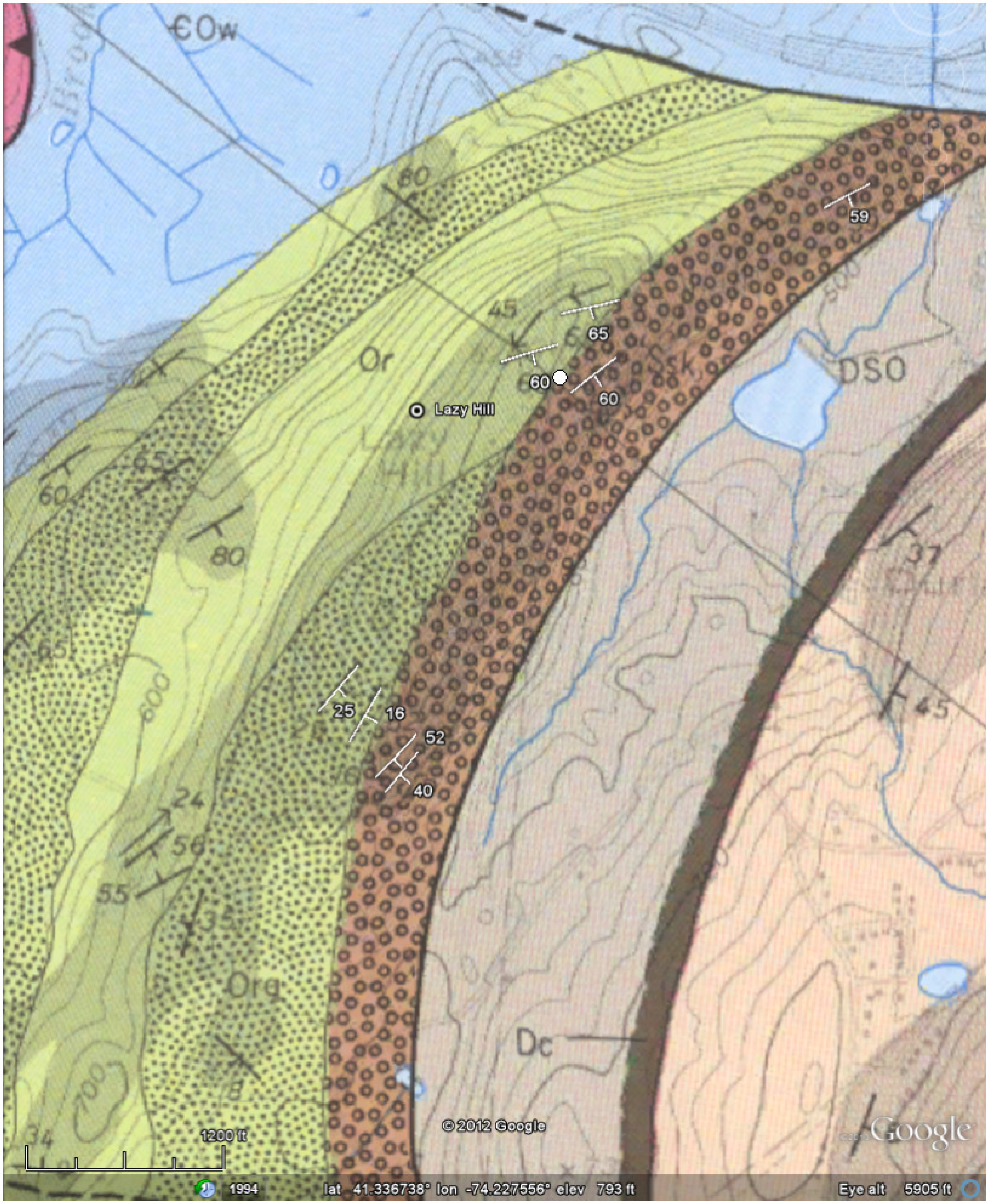


Figure 8. Structural details in the central fault block on the western limb of the GPS where the Taconic unconformity is mapped by Jaffee and Jafee (1973). Map location shown in Figure 7. Bedding strikes and dips for the two traverses across Lazy Hill are emphasized. SSk - Shawangunk Formation (referred to in the text as the Green Pond Formation), COw – Cambrian-Ordovician Wappinger Group (dolomite), Dbv – Devonian Bellvale Formation, Dc – Connelly Conglomerate, De – Esopus Formation, DSO – concealed Devonian, Silurian, and Ordovician sedimentary rocks, LD – Lower Devonian sedimentary rocks undivided, Omr – Ordovician Martinsburg calcareous shale and quartzite, PC – Precambrian rocks. Location of pictures on Figure 8 indicated by the solid white dot.

This distinction is interesting because there is enough distance between the Green Pond Formation here and the superjacent Middle Devonian Bellvale Formation to accommodate the sequence of Middle Silurian strata mapped above the Green Pond Formation elsewhere in the GPS. In NJ, the combined stratigraphic thickness of the Middle and Upper Silurian units occurring between the Green Pond Formation and the Connelly Conglomerate is about 800 ft (244 m) (Herman and Mitchell, 1991). The concealed interval in the central fault block can accommodate an 800-ft. section dipping at about 40^{o}. The closest Green Pond outcrop dips 59^{o} and the closest Connelly outcrop dips 32^{o} for an average of about 45^{o}. It is therefore possible that the Green Pond Formation is not fault-bounded on its eastern side, and for that matter, may not be fault-bounded along its entire length west of Schunnemunk Mountain where outcrops are seemingly scarce and the questionable interval is concealed by thick surficial deposits (Jaffe and Jaffe, 1973).

Don Monteverde, Jack Epstein, and I travelled to the central fault block on the west limb of Bellvale Mountain on June 28, 2012 with the hope of documenting the unconformity based on the mapping of Jaffe and Jaffe (1973). We targeted the northernmost of two traverses that they mapped across Lazy Hill in the central fault block where a power-transmission line provides access off NY Rt 17M at the base of Lazy Hill up to its crest (Figure 8). We hiked up approaching from the north, passing over pavement outcrops showing rhythmic cycles of shale, siltstone, and greywacke sandstone of the Martinsburg formation. At the location of the northernmost traverse of Jaffe and Jaffe (1973; Figure 8), there’s a prominent ridge of white pebble conglomerate cropping out immediately east of the transmission line that overlies a quartzite that is about 3.3 ft (1 m) thick along the western base and southern tip of the ridge (Figure 9). Here, white pebble conglomerate sits atop siliceous, light-brown to gray, medium- to coarse-grained uartzite that is lcally thin-bedded. It was nonreactive with dilute hydrochloric acid on fresh surfaces, and it was difficult to tell if we we're looking at or Martinsburg well-cemented subarkosic sandstone or Green Pond quartzite, because both units are penetratively strained and cut by slickensided shear planes that locally offset and complicate their contact (Figure 10). But underneath a small overhang at the southern tip of the

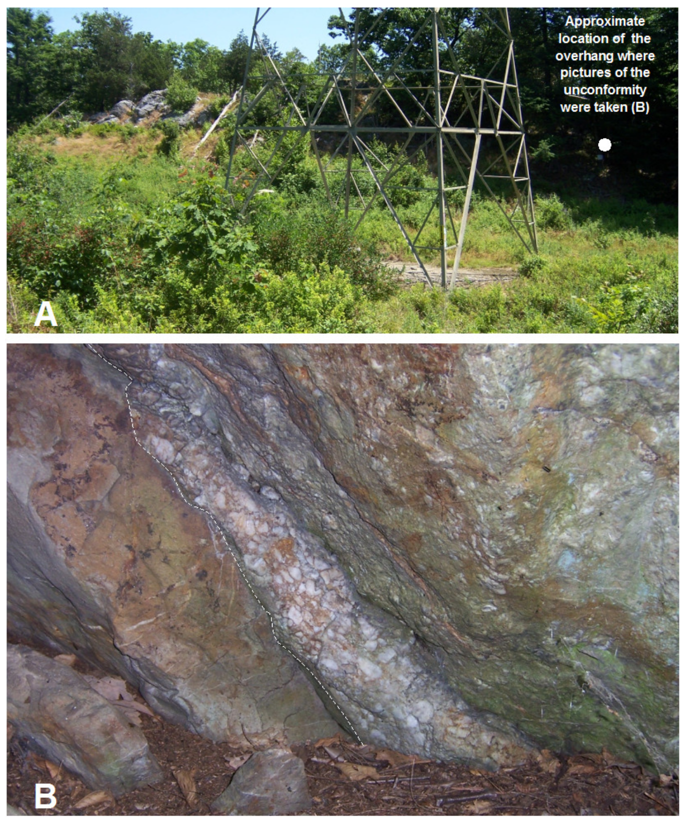


Figure 9. View of the Shawangunk Formation cropping out on a ridge atop Lazy Hill. See Figure 8 for the picture location. Photograph A is a southeast view from the trail towards the spine of the Hill. The solid white dot on the right side is the approximate location of the overhang where the unconformity crops out. Photograph B shows the overhang outcrop where white-pebble conglomerate of the Shawangunk Formation lies atop a subarkose sandstone that may be the Martinsburg Formation. Some of the strain features associated with these rocks are detailed in Figure 10, and discussed in the text. Photographs by Jack Epstein.

ridge, white pebble conglomerate sits directly on the quartzite, with very little divergence in strike and dip between the two units; the average strike/dip for the sandstone was N60^{o}E/18^{o}S compared to N73^{o}E/24^{o}S in the superjacent conglomerate. We walked the contact between the quartzite and conglomerate along strike for about 20 ft (6m) at the base of the ridge heading northeast from the overhang. The conglomerate closely resembles Green Pond conglomerate mapped along the Reservoir fault in NJ (Herman and Mitchell, 1991). In both places it contains milky-white, subangular to subrounded, vein-quartz pebbles ranging from an averaging diameter of about 1 to 2 in (2.5 to 5 cm), up to about 6 in (15 cm). The rocks along the Reservoir fault are more highly stretched and fractured in comparison to those here, but the abundance of mineral veins and stratigraphic slip and wedging at this location indicates significant Alleghanian strains here as well. The Martinsburg Formation appeared to coarsen upward towards the upper contact, but there was a significant covered interval between the Martinsburg outcrops near the trail and the base of the ridge. It is likely that the lower quartzite here is the 3-ft (0.9-m) thick quartzite at the base of the Green Pond (Shawangunk) Formation mentioned by Jaffe and Jaffe (1973). The search for the unconformity at the more southerly traverse (Figure 8) was not attempted due to time restrictions.

Pine Hill, Lake Popolopen Quadrangle

After hiking down Lazy Hill, we drove to the base of the ridge east of Highlands Mills, NY, along the base of Pine Hill in the Lake Popolopen quadrangle where the Green Pond Formation was mapped by Dodd (1965 and Figure 7). We drove into a new housing tract being built along the east side of the ridge base, and we stopped to inspect nearby boulders. The Green Pond here is the same polymictic, grayish purple and grayish red conglomerate that crops out in the eastern and central parts of the NJ Green Pond Mountain region. It has varicolored sedimentary gravel and cobbles along with abundant white, vein-quartz pebbles. The nature of the lower contact here is unknown, and it’s difficult to tell whether this ridge is bounded by a fault on the east, as the ridge is separated from outcrops of Cambrian-Ordovician Wappinger Dolomite to the southeast by a large expanse of alluvium (Dodd, 1965). No description of the Green Pond is provided by Dodd (1965) as their primary focus was on the Precambrian geology. But this sequence was studied by Southard (1960) as part of a senior thesis that provides details of the lithological facies here and in the ridges near Pea Hill (Figures 3 and 11). He reports that the Green Pond Formation is nonfossiliferous and therefore of uncertain age, but probably the stratigraphic equivalent of the Shawangunk conglomerate to the west. He divided the Green Pond Formation into five subunits, four of which are quartzite that occur mostly in the eastern section. At Pine Hill he recognized an upward sequence of conglomerate, quartzite, and sandstone that is about 400 ft (122 m) thick. The conglomerate is about 300 ft (91 m) thick and is coarsest at its base where the largest pebbles (4.5 in [11 cm] in diameter) fine upward to white-quartz pebbles 1 to 2 in (2.5 to 5 cm) in diameter. The conglomerate matrix is coarse to very coarse sand that is red and yellow in color. Conglomerate bed thickness ranges from 0.5 to 15 ft (0.15 to 5 m). Conglomerate beds contain sandstone intervals that are less continuous along bed strike where they pinch and swell. The quartzite units are medium- to thick bedded, with varieties ranging in color from light-red to white, and totaling about 55 ft (17 m) thick. The upper sandstone units are more poorly exposed, range in thickness from about 5 to 15 ft (1.5 to 5 m), and show a variety of lithological textures and color variations. Red sandstone units contain minor red shale and siltstone, cross-bedded, and laminated varieties that range in

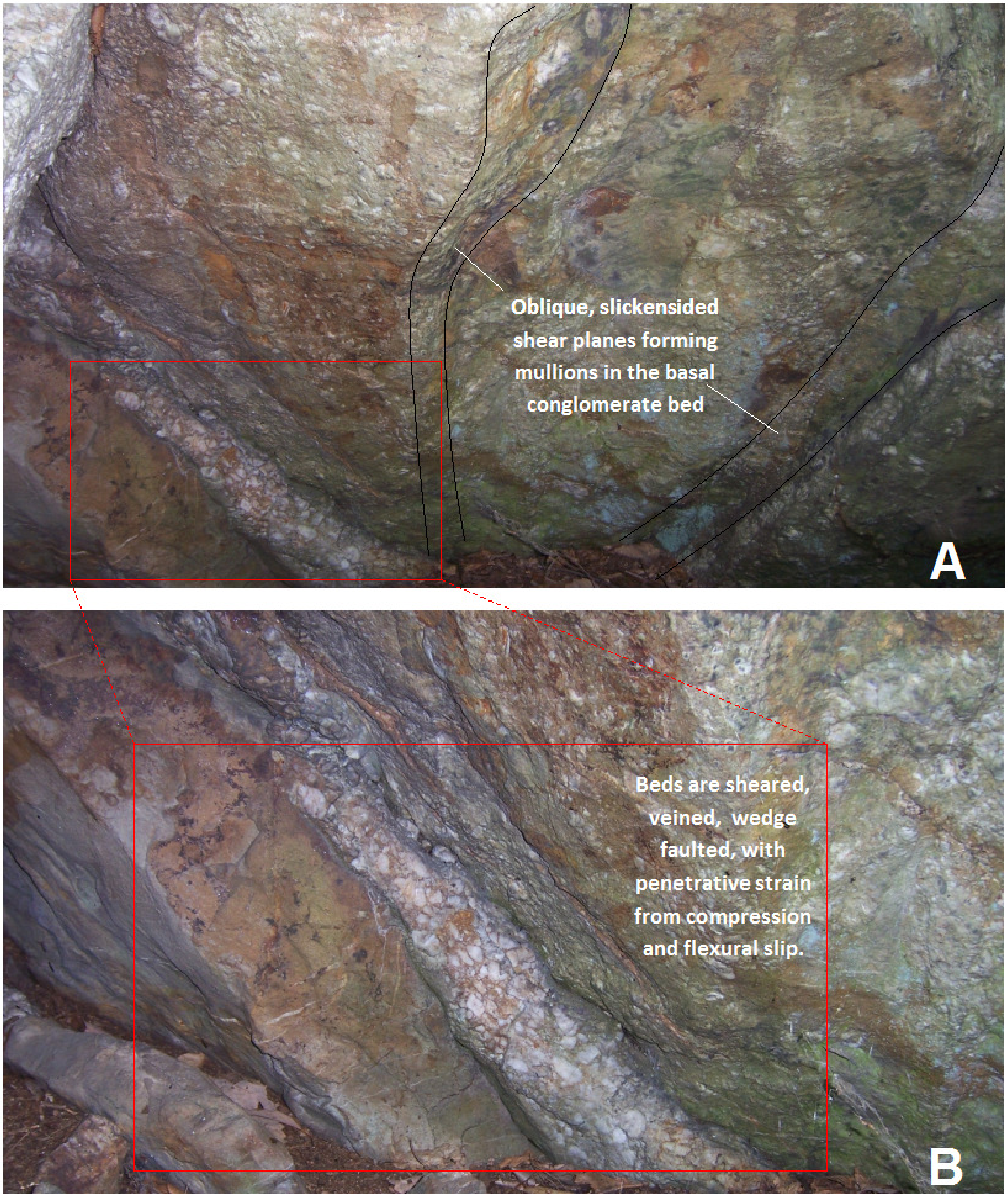


Figure 10. Detailed views of the rocks near the Taconic unconformity atop Lazy Hill. Photograph A is a northeast view of beds beneath an overhang. Beds dip left-to-right at about 20°-25° E. Slickensided shear planes form mullions (Epstein and Lyttle, 1987) at the base of a conglomerate-bed. Photograph B shows details about a contact between gray quartzite (left) and the suprajacent white-pebble conglomerate. Mineral-vein arrays and small faults locally offset the contact. The beds are penetratively strained and sheared along contacts. Photographs by Jack Epstein.

color from purplish white to purplish red and locally contain rip-up clasts, and ripple marks. This sequence at Pine Hill was also mentioned in earlier work of Darton (1894a) and Ries (1895). At that time, Ries (1895) referred to the Green Pond Formation as the Medina formation, including Oneida conglomerate at its base, with the quartzite and sandstone as upper members of the Medina formation.

The Ridges near Pea Hill, Cornwall-on-Hudson Quadrangle

At the northern end of the GPS just west of Cornwall, NY, Darton (1894a) reported conglomerate overlying Hudson Shale (Martinsburg Formation). He depicts their arrangement in a moderate- to steeply-northwest-dipping succession of Silurian to Devonian strata with Oneida conglomerate along its eastern face. Southard (1960) also studied this sequence where he reports basal conglomerate and quartzite units like those at Pine Hill, but lacking the upper sandstone unit. Ries (1895) described the east side of the eastern ridge as being formed by "coarse-grained red siliceous conglomerate (Oneida), with red sandstones and shales of Medina age". Darton (1894a) reported about 25 ft (8 m) of conglomerate and sandstone here.

The ridge locations near Pea Hill are tentatively mapped in Figure 11 based on Darton's (1894a) mapping as reported by Ries (1895). The Green Pond Formation was sketched in Google Earth as a pair of polygons corresponding to conglomerate noted on Darton's map (Figure 11B). Registration of the image proved challenging because the map is old, and contains sketched roads, railways, and a stream. The proposed alignment primarily uses two, linear topographic ridges and Pea Hill as reference features in Google Earth (Figure 11). Darton (1894a) depicted the structure and stratigraphy associated with the Green Pond (Medina formation) in the eastern ridge, but no details surrounding the western ridge were given. It is possible that the ridges may define a southwest plunging syncline axis of the GPS near its northeastern tip, but more detailed mapping is needed to verify it.

A New Subsurface Record of the Unconformity in the Green Pond Mountain Region from Picatinny Arsenal

A subsurface stratigraphic contact interpreted to be the Taconic unconformity was recently photographed as a digital borehole televiewer (BTV) optical image collected within the U.S. Army military reservation in Morris County, NJ, known as Picatinny Arsenal (Figures 3, 4, 12, and 13). In 2010 and 2011, the NJ Geological Survey was asked by Mr. Joseph Marchesani of the NJ Department of Environmental Protection Site Remediation Program to review optical BTV data collected by geophysical companies contracted by the US Army as part of on-going site characterization and remediation work at two groundwater-investigation (GWI) sites within the reserve (Figure 12). The 600 Area GWI site is underlain by the Green Pond Formation, whereas the Mid-Valley GWI site is underlain by Precambrian gneiss and granite lying immediately southeast of the GPS (Figures 4 and 13). The BTV surveys were provided as paper reports and used primarily used to determine the orientation of permeable stratigraphic layering and secondary brittle structures (fractures and faults) penetrated by the wells. The details of the BTV study of the Proterozoic rocks is beyond the scope of this work, but the orientation of metamorphic layering and folding geometry determined from a structural analysis of Mid-Valley area is incorporated into a cross-section interpretation below.

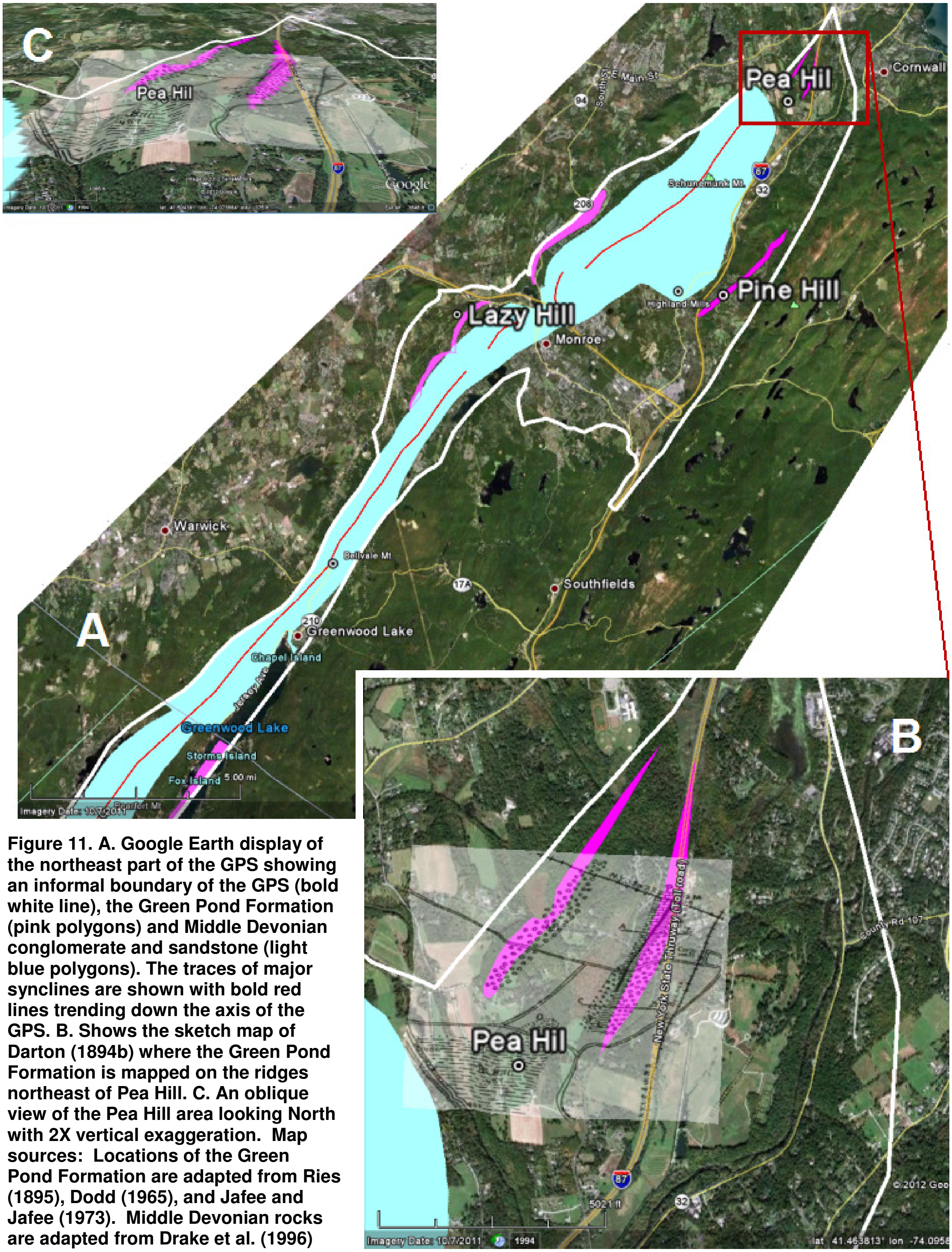


Figure 11. A. Google Earth display of the northeast part of the GPS showing an informal boundary of the GPS (bold white line), the Green Pond Formation (pink polygons) and Middle Devonian conglomerate and sandstone (light blue polygons). The traces of major synclines are shown with bold red lines trending down the axis of the GPS. B. Shows the sketch map of Darton (1894b) where the Green Pond Formation is mapped on the ridges northeast of Pea Hill. C. An oblique view of the Pea Hill area looking North with 2X vertical exaggeration. Map sources: Locations of the Green Pond Formation are adapted from Ries (1895), Dodd (1965), and Jafee and Jafee (1973). Middle Devonian rocks are adapted from Drake et al. (1996) and Rickard et al. (1970)

The unconformity was penetrated by the AWDF well within the 600 Area (Figure 14) at about a depth of about 419 ft (128 m) after passing through Green Pond conglomerate, sandstone, siltstone and shale. Below the unconformity, higher reflective, indurated, and fractured beds are interpreted to be the Cambrian Hardyston Quartzite (Figure 14). The contact between the two units is unremarkable and somewhat diffuse, but is picked at a depth of 418.65 ft (127.6 m) below ground surface (Figure 14). Figure 15 shows a statistical analysis of beds

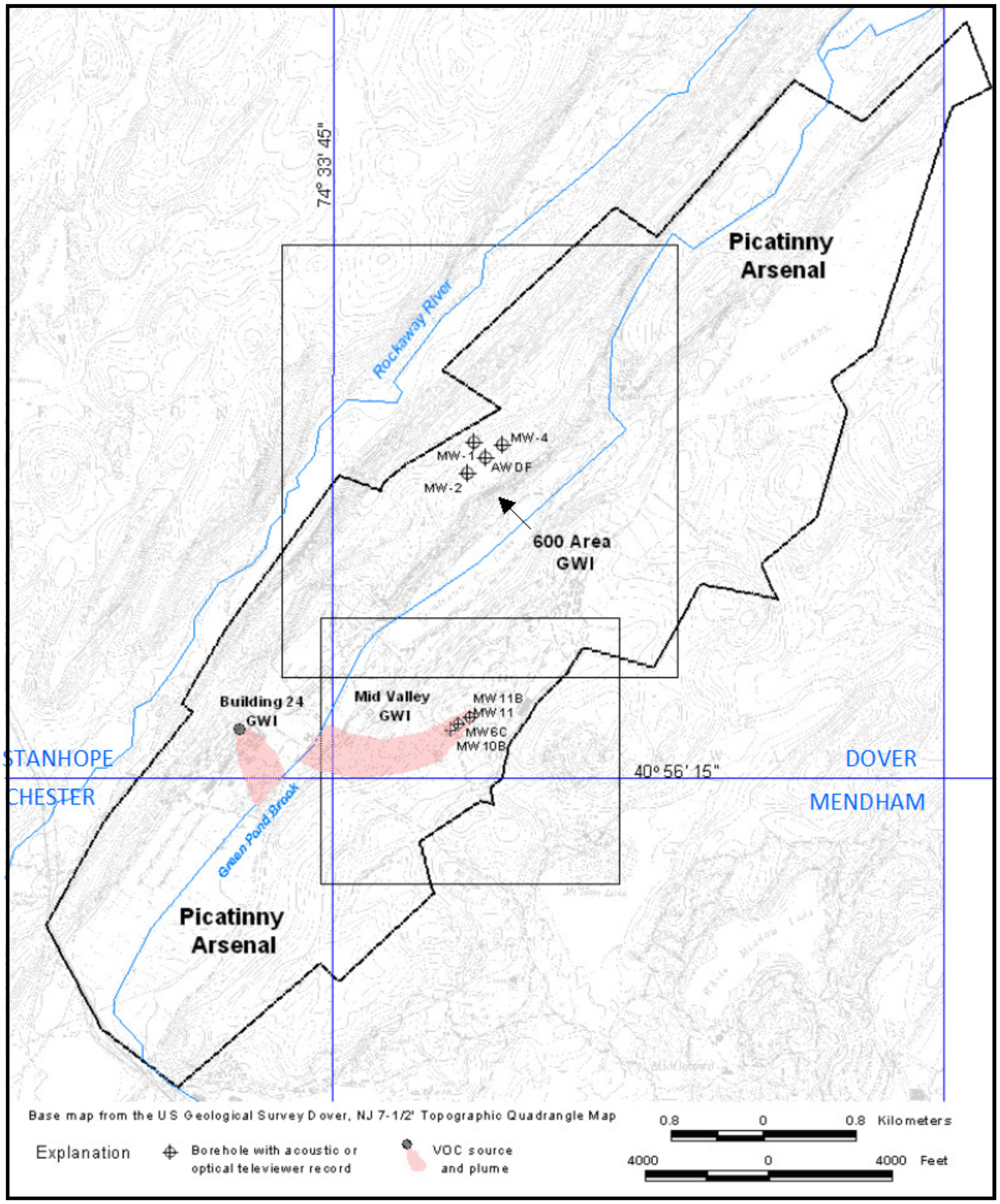


Figure 12. Location map of Picatinny Arsenal showing the locations of three groundwater investigation (GWI) sites and four USGS 7-1/2' topographic quadrangles. This paper focuses on the 600 Area GWI. The boxes correspond to the coordinate limits of digital elevation model (DEM) grids that were generated for two groundwater investigations. The unconformity was penetrated at a depth of about 419 ft (128 m) in well ADWF.

and fractures bracketing the unconformity. Figure 16 summarizes the well depths and average bed dips determined for each well from the BTV records.

The BTV images show the Green Pond Formation as a heterogeneous mix of olive green and grayish brown pebble conglomerate, sandstone, siltstone, and shale. The rock colors are described as they appear in the paper report and should be regarded with caution as they probably don't capture true colors, and the type of borehole imaging tool and data acquisition and processing parameters are unknown. But compositions and textures seen in the borehole photos facilitate distinction between conglomerate, sandstone, siltstone, and shale. The reports were only available for a brief time during the file review, which was more focused on the structural interpretation than on the stratigraphic characterization. Consequently, only a general stratigraphic review of the record was conducted and not a detailed lithological summary. As noted in the bureau review conducted then, the coarsest conglomerate beds reach 4 to 6 ft (1.6 to 1.8 m) thick, whereas the shale beds are less than 1 ft (0.3 m) thick. Sandstone beds commonly range in thickness from less than 1 ft (0.3 m) to about 2 ft (0.6 m). Beds in the basal part of the Green Pond Formation are generally finer grained than beds higher in the section (Figure 14). The Hardyston is composed of tan, brown and bluish-white, thin-to medium bedded, fine to coarse sandstone or quartzite. This unit is not folded and lacks the metamorphic and igneous textures that are seen elsewhere in Middle Proterozoic rocks. However, this lower unit may have an affinity with other anomalous metasedimentary rocks of probable Late Proterozoic age like those mentioned earlier along the Reservoir fault (Herman, and Mitchell, 1991).

Some beds in the Green Pond Formation are highly fractured whereas others are not. Bed-parallel fractures are common, as are steeply-dipping extension fractures that locally show complex banding, and therefore multiple generations of tensile opening and mineralization. Some of the steeply-dipping extension fractures show normal dip-slip movement. Most of the fractures show alteration rinds and adjacent staining of the unit matrix by groundwater infiltration and movement. The chemistry of the fracture and matrix alteration and staining is unknown. Shear fractures seem to be more common in the finer-grained beds where local wedges in the strata probably reflect bed-parallel shear strain.

The BTV data were also used to refine the bedrock geology map (Figure 16) and to construct a new cross section through the area (Figure 17). The central part of 600 Area lies between the Green Pond and Picatinny reverse faults (Figures 13, 16 and 17). Herman and Mitchell (1991) show the Picatinny fault dipping steeply southeast and the Green Pond fault dipping steeply northwest. The BTV analyses confirm that the beds near wells MW-2 and AWDF straddle a southwest gently plunging, upright, and open anticline with limbs that dip gently northwest and southeast (Figures 15 to 17). The stratigraphic interpretation of the unconformity agrees with the existing cross section interpretations that depict a thin veneer of Hardyston Quartzite overlying Precambrian basement and underlying the Green Pond Formation (Herman and Mitchell, 1991).

3D diagrams of well-field components and bedding and fracture planes for the 600 Area wells were also produced as part of the file review. Some of these diagrams are included here to further convey the subsurface BTV results (Figures 18 and 19). The maps and 3D diagrams were generated and displayed using ESRI ArcView 3.2a software. The ArcView Spatial and 3D Analyst extensions were used for clipping digital elevation models (DEMs) and the 3D Analyst extension was used with the NJGS 3D well field visualization extension to generate and

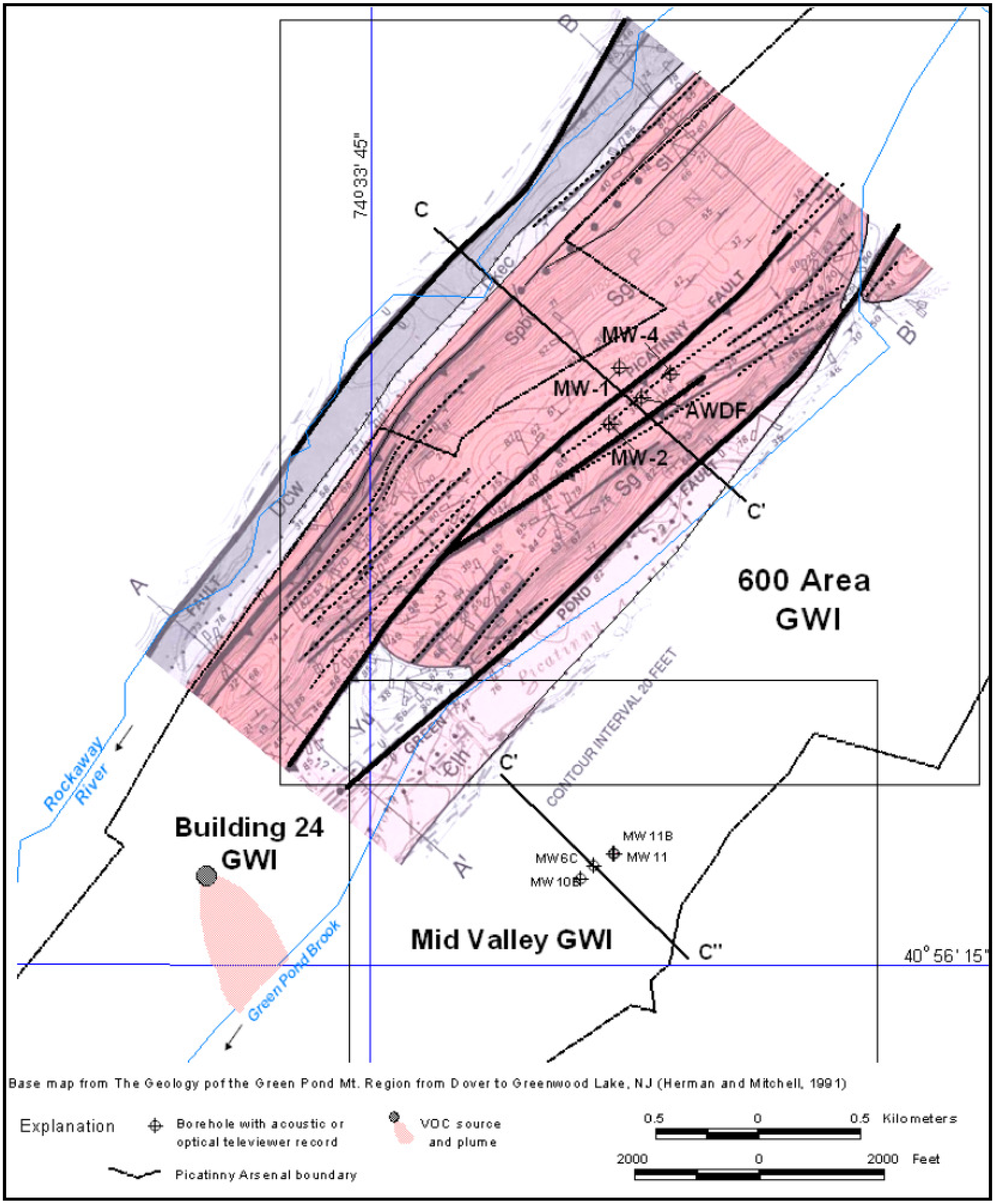


Figure 13. Part of a bedrock geological map covering the 600 Area GWI (Herman and Mitchell, 1991) was scanned and georegistered in ArcView GIS in order to refine the structural interpretation near the 600 Area based on the BTV data. The cross section interpretation C-C" is shown in Figure 17. The northwest part (C -C') lies between sections A-A' and B-B' " and edge matches to the section through the Mid Valley are (C'-C"). Note that the fault locations remain the same, but folds axes in the 600 Area have been slightly modified from those of Herman and Mitchell (1991) based on the BTV data.

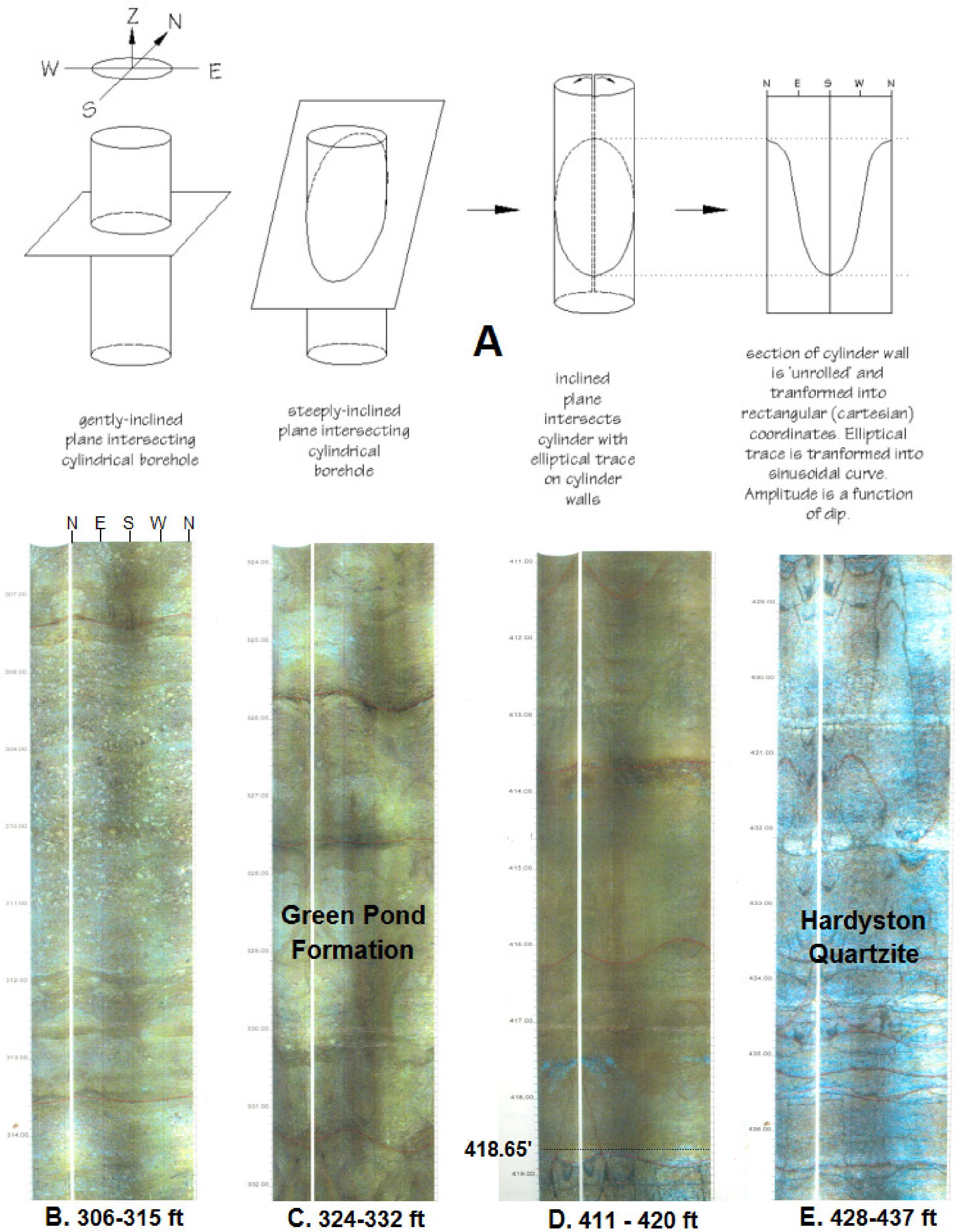


Figure 14. A. Schematic diagram illustrating how BTV images are "unrolled" and flattened for display and interpretation. B through E are optical BTV records of specific depth intervals in the well that were digitally scanned from a report by Mid-Atlantic Geoscience, LLC. Each BTV record includes a wrapped virtual core on the left showing just a sector of the well from a specific viewpoint, and a flattened, unwrapped image on the right showing the unwrapped borehole wall. Images B and C show pebble conglomerate and coarse to medium sandstone in the Green Pond Formation. Image D shows a stratigraphic contact between the Green Pond Conglomerate and the subjacent Hardyston Quartzite at about 419' depth. Image E shows a section of the Hardyston Quartzite starting about 10 ft (3 m) below the contact.

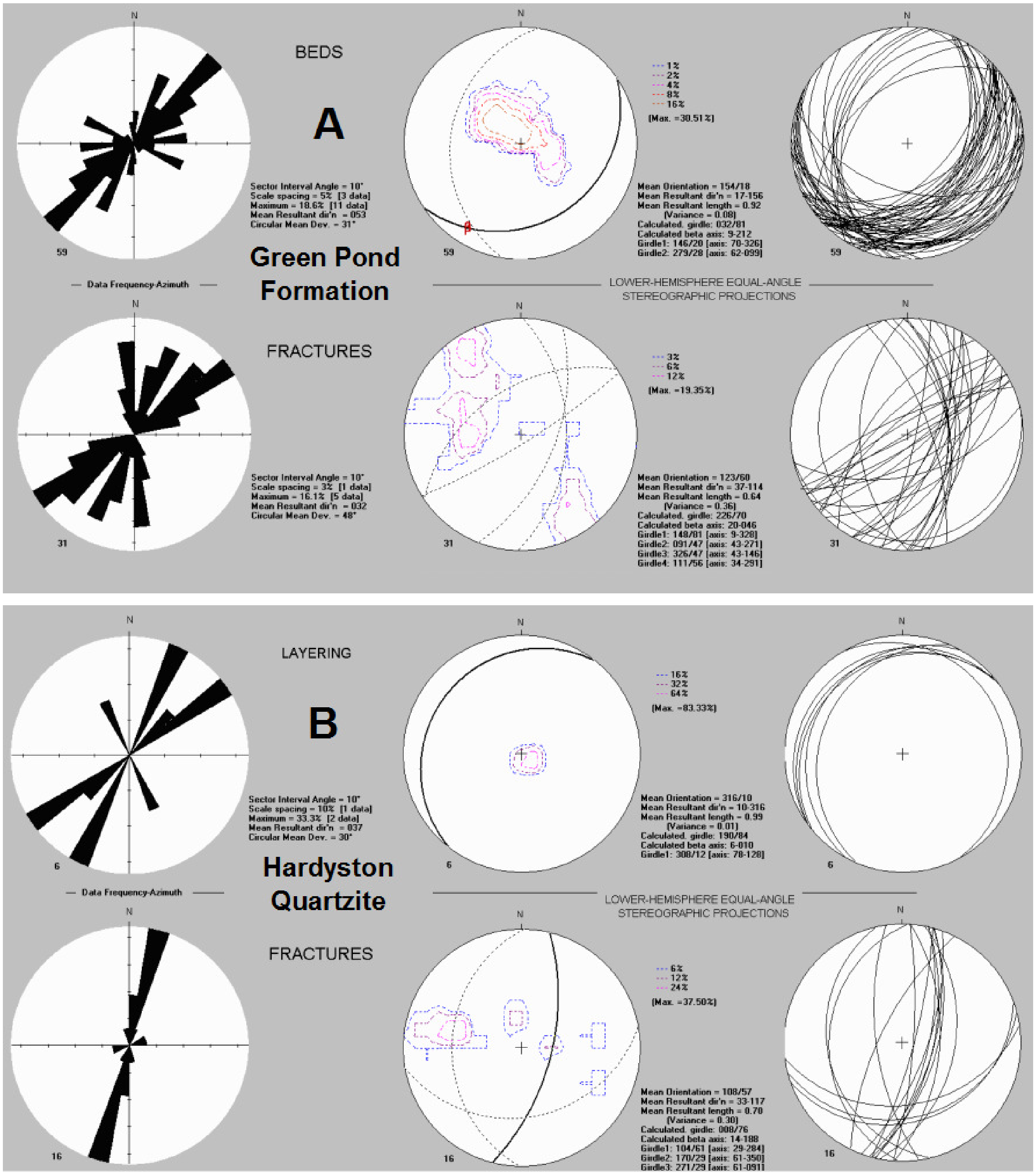


Figure 15. Structural analyses of interpreted BTV record of the AWDF well showing the orientation of beds and fractures bracketing the unconformity. A. Structures in the Green Pond Formation. B. Structures in the Hardyston Quartzite.

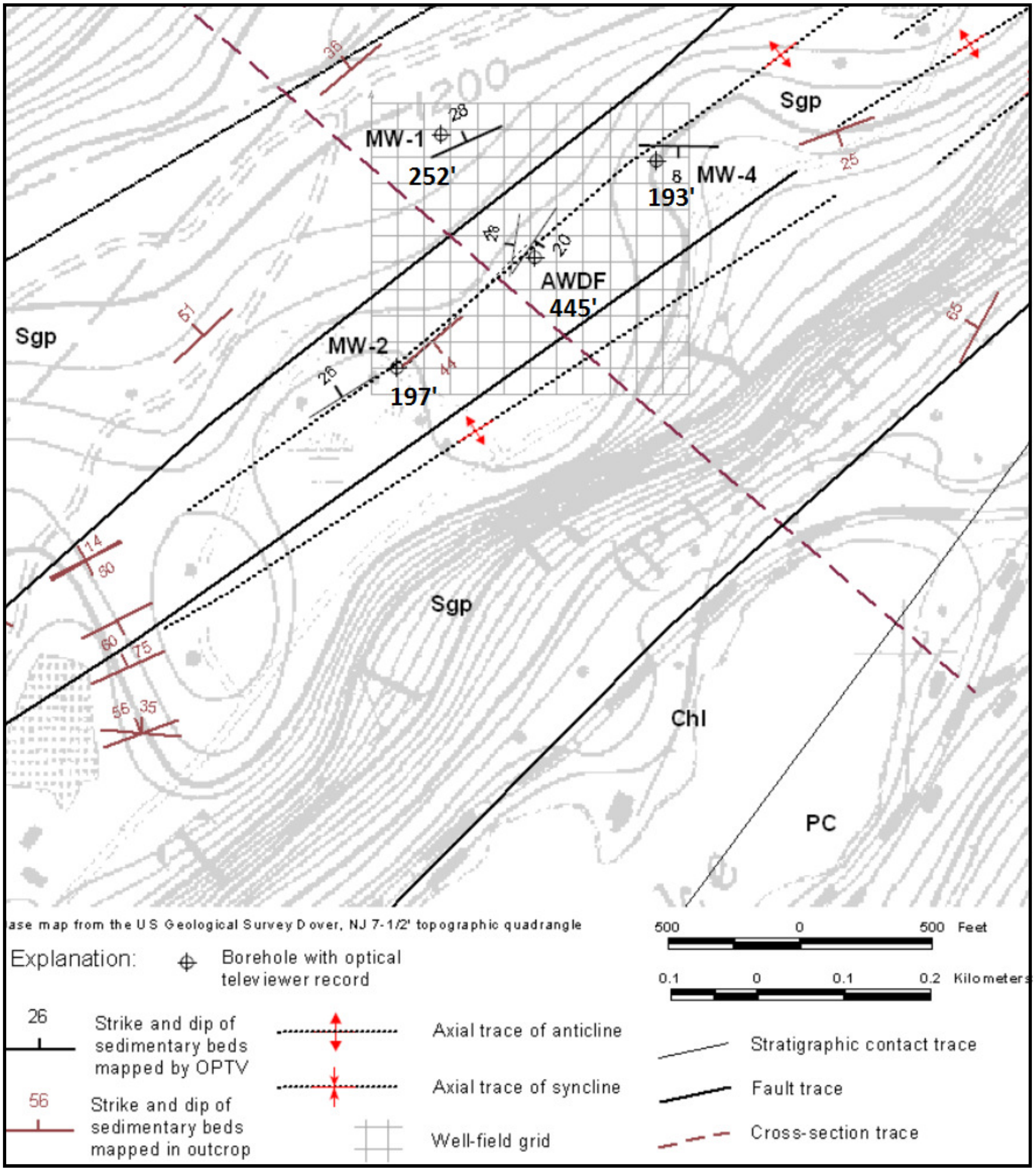


Figure 16. Geologic map near the 600 Area GWI showing a well-field grid. The AWDF well penetrates two limbs of an open, upright anticline in the Silurian Green Pond Formation before encountering the Taconic unconformity and Cambrian Hardyston Quartzite at 419 ft (128 m).

visualize 3D shapes of the boreholes, oriented structural planes, and well-field grid based on the BTV survey (N.J. Geological Survey, 2001). The borehole shapes used well-location and construction parameters taken from the consultant's report. The well and plane shapes were generated using a vertical borehole alignment because no borehole-deviation information was included in the reports.

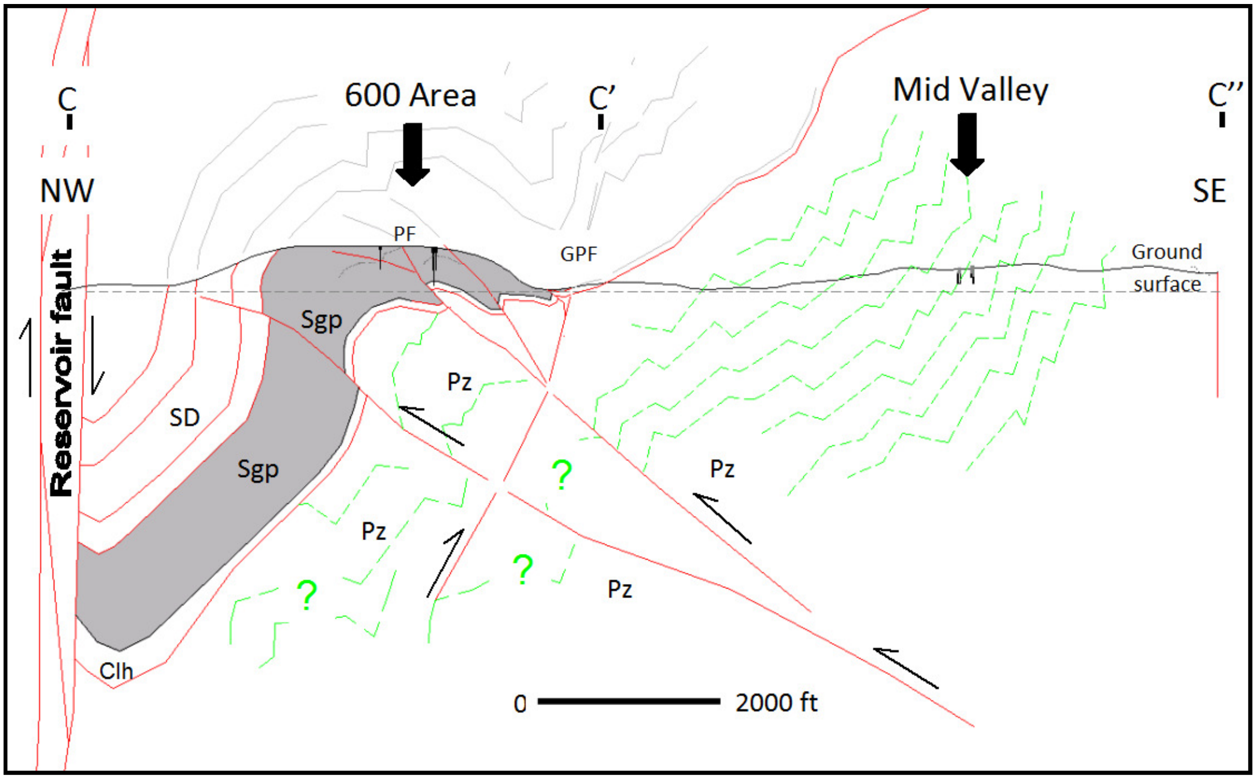


Figure 17. Cross section C-C-C" is based on earlier sections of Herman and Mitchell (1991) and the BTV analyses at the 600 Area and Mid-Valley sites (Figures 12 and 13). The section traces are shown on Figure 12. Abbreviations: Clh – Cambrian Leithsville and/or Hardyston Quartzite, Pz –Proterozoic gneiss and granite, Sgp – Silurian Green Pond Formation, SD – Undivided Silurian and Devonian rocks. GPF – Green Pond fault, PF – Picatinny fault.

Figure 18 shows that the upper beds of the Green Pond Formation in well AWDF dip gently to moderately southeast, whereas the deepest Green Pond beds dip gently (< 30^o) northwest , and a little more steeply than those of the underlying Hardyston Quartzite (~10^o northwest; Figure 15B). Beds close to the unconformity strike about the same. The histogram plot of dip azimuth for the lower set of Green Pond is interpreted here to reflect cross bedding (Figure 18C) that shows western and southern sedimentary dispersion.

A fault zone seen in the BTV record of MW-1 occurs at a depth of about 235 ft (72 m) (Figure 18A). The zone is a gently-dipping mineralized interval consisting of about 6 in (15 cm) of anastomosing light and dark vein-fill material. This horizon is interpreted as a reverse fault that is a subsidiary splay fault to the Picatinny reverse fault (Figure 17), and that separates beds of varying strike and dip. Upper beds in the Green Pond Formation in MW-1 dip gently northwest, and then become steep northwest deeper in the well and closer to the fault. Beneath the fault, bedding returns to dipping gently northwest.

The resulting well-field features were displayed relative to a DEM and a digital version of the cross section to examine the spatial relationships of the measured features from different viewpoints. Figure 19 shows the bedrock structures based on the BTV data relative to a DEM covering the 600 Area (Figure 10A) and a 3D display of the cross section C-C'-C".

DISCUSSION

A stylized, cross section across the Reading Prong in NJ (Figure 20) was constructed to help summarize and integrate different aspects of we know about the Taconic unconformity in the GPS region, and to facilitate discussion on some of the more speculative aspects with respect to its stratigraphic variability and probable connection with the Shawangunk Formation across the Great Valley (Figures 1 and 19). The section is pinned in the foreland by the Late Ordovician Beemerville intrusive complex (Ghatge et al., 1992) and uses the restored and balanced Lower Paleozoic cover sequence depicted in section A-A' of Herman et al. (1997). Their A-A' is extended southeast toward the Taconic hinterland roots to depict a "restored" Taconic foreland cover-fold sequence that arches over the current crystalline roots of the Reading Prong. The cover is folded above crystalline basement, with northwest verging folds

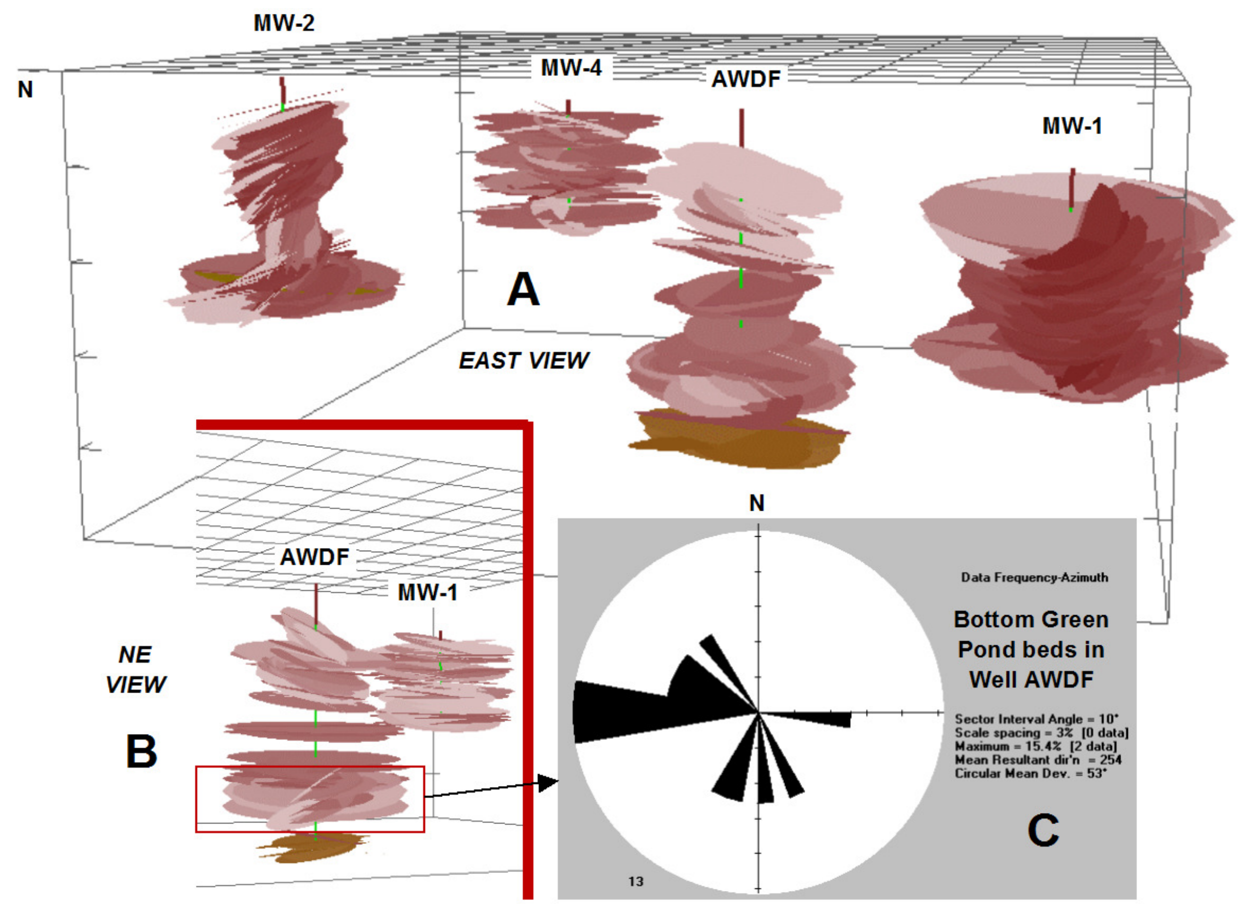


Figure 18. 3D graphic displays of the 600 Area well field and a circular histogram analysis of bed dip azimuth in the lower part of the Green Pond Formation in well AWDF. Image A is an east view showing a 3D well-field grid with 50-ft (15-m) divisions, ellipses oriented parallel to measured beds (pink polygons), and well parts including cased (upper, dark red) and open (lower, light green) well parts. Bed ellipses were generated at BTV record depths using 300 ft (91 m) major axes and 150 ft (46 m) minor axes. The pink planes are Green Pond Formation whereas the deepest beds in well AWDF (brass colored) are Hardyston Quartzite. Image B is a northeast view of wells AWDF and MW-1 showing the variability in bedding dip in well AWDF, and cross beds in the lowest part of the Green Pond Formation. Image C is a circular histogram analysis of bed dip azimuth of bottom beds in the Green pond formation from the AWDF well interval 331 to 373 ft (114 m) below land surface. The histogram and 3D display shows that the bottom beds are cross-stratified with S and W sedimentary dispersion.

that are progressively tighter with more gentle axial surfaces to the southeast, but lacking significant, emergent thrust faults that would have otherwise stack and repeat stratigraphic sections. In other words, it's one of the simplest geometric solutions that agrees with what we see at the surface, and that provides a minimal finite strain estimate based on having an eroded, folded cover sequence. As portrayed, the GPS syncline was shortened by over 50% from ensuing Alleghanian compression (Figure 20). One measurement of the penetrative, finite-shortening strain in the Devonian Bellvale Formation in the Green Pond Mountain region just from regional cleavage development is 44% (Herman, 1987).

The location of the current GPS is placed into a restored position as a Taconic synclinorium (Figure 20). The restored GPS contains broad, open, asymmetric, northwest-verging folds with localized, post-Taconic erosion of a basement-cored anticline. The anticline is a subsidiary fold in the greater synformal structure that was breeched by early erosion to expose the Proterozoic core during Taconic uplift and before Silurian deposition. Basal Silurian molasse now overlies crystalline rocks in the central area of the GPS near Green Pond, NJ, but Lower Paleozoic rocks elsewhere in all directions along strike and toward the foreland. Both Silurian and Middle Devonian molasse now occupies valleys in the GPS between crystalline blocks of the Reading Prong (Figures 3 and 4). This implies that the GPS was a structural depression then, and remains depressed today. This geometry also suggests that regional culmination during the Taconic was near the Green Pond Mountain region, where the maximum amount of erosion occurred within a great structural depression. This led Finks (1968) to conclude that there were “Taconic Islands” in this area stemming from Ordovician orogenesis.

Thomson (1957) conducted a comprehensive, petrologic and petrographic comparative study of the Shawangunk and Green Pond Formations in the NJ region. He found many sedimentary and stratigraphic relationships that bear on the depositional setting, continuity, and contemporaneity of the Silurian molasse in this region. He concluded that the two formations were probably continuous at one time from analyses of lithologies, cross-beds, and heavy-mineral fractions. Both formations contain an abundance of white quartz pebbles of probable igneous, metamorphic, and vein origin. Both formations show west to northwest cross bedding and contain white and pink zircons indicating two distinct sedimentary-source areas east of the current Great Valley and GPS. One nearby source includes the Lower Paleozoic cover and Precambrian gneiss of the Reading Prong as the source of pink zircons. The second, easternmost terrain includes argillaceous rocks of the allocthons and a “Taconia” root where other sedimentary, metasedimentary, and acidic granitic and/or metaigneous rocks provided euhedral, white zircons that reportedly are rare in the Reading Prong. He also noted that the basal Shawangunk contains considerable feldspar and the clear, euhedral zircon not found in basal sections of the Green Pond, even though is lies furthest northwest from the easternmost source. The basal Green Pond contains more jasper, chert, and flint, although Kummel and Weller (1902) noted significant plagioclase clasts in conglomerate on the east side of the GPS, and Jafee and Jafee (1973) reported coarse orthoclase pebbles at Lazy Hill, NY. The common occurrence of varicolored chert in Green Pond conglomerate led Emery (1952) to include Ordovician flysch as source rocks. Thomson (1957) also found that zircons are more rounded in the Green Pond in comparison to more elongate ones in the Shawangunk. He noted that the euhedral, white zircons first occur about 500 ft (152 m) above the base of the Green Pond Formation. He therefore proposed that the lower 500 ft (152 m) of basal Shawangunk is older than basal Green Pond because erosion began earlier, progressed more rapidly, and continued

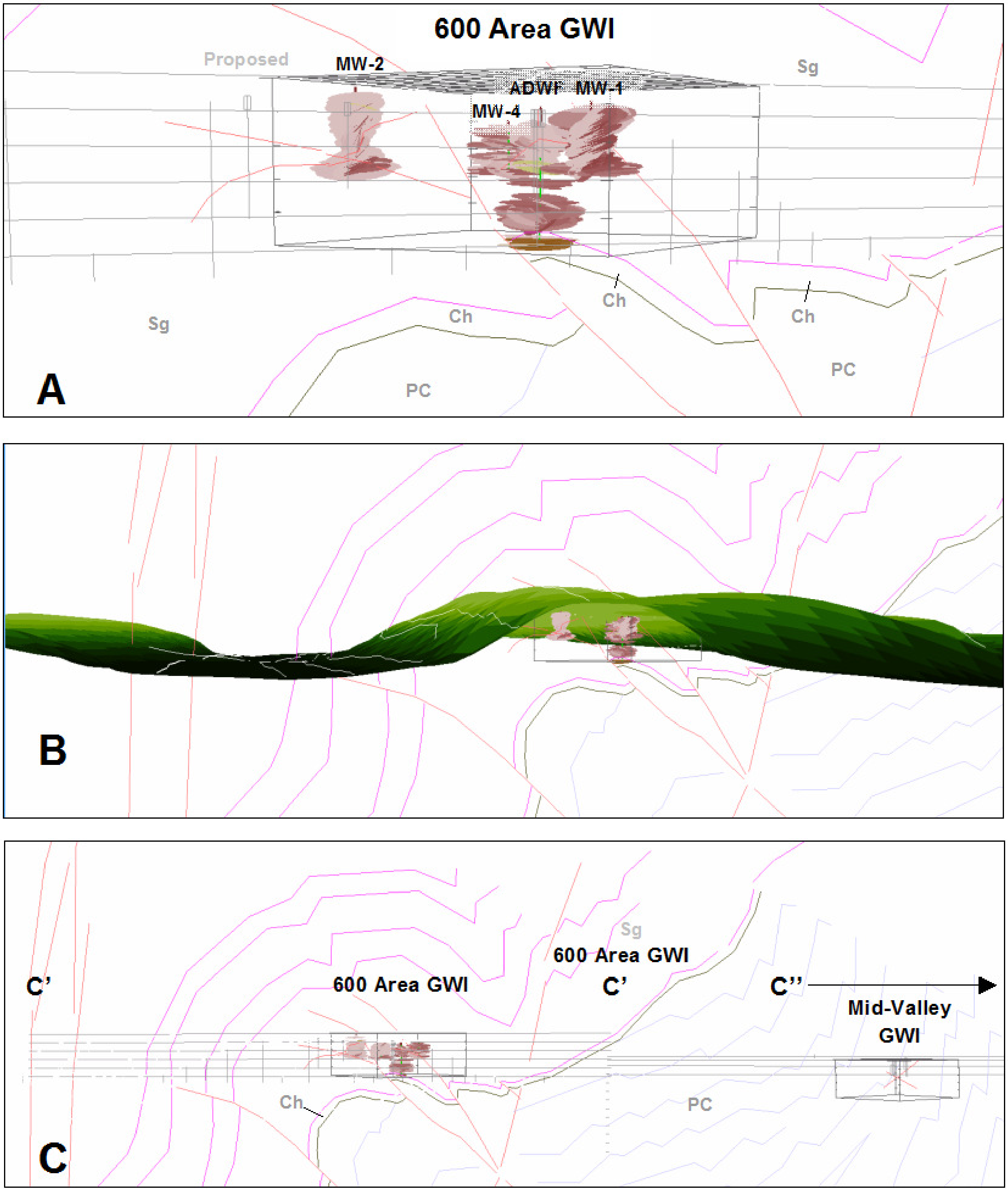
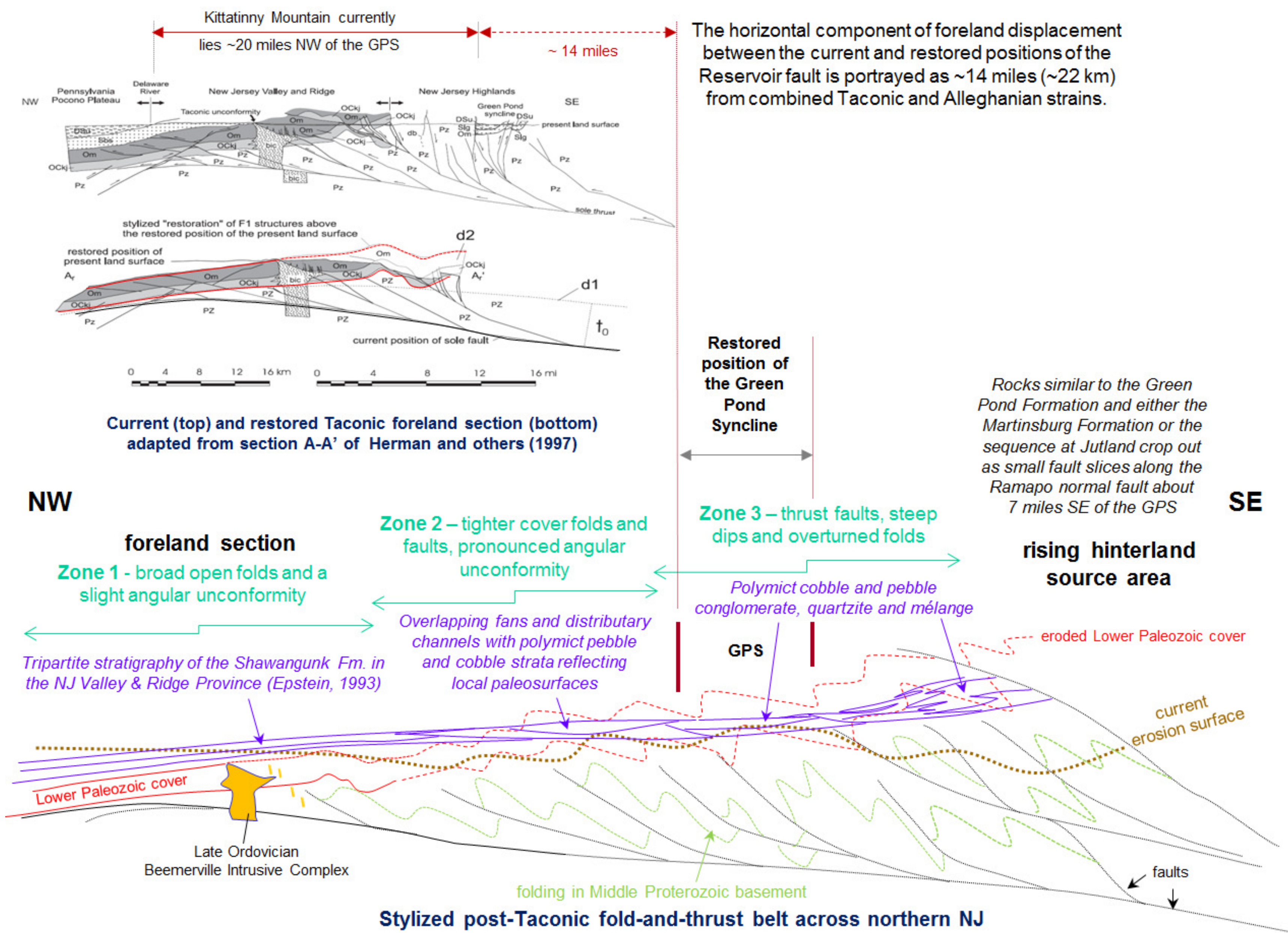


Figure 19. 3D graphic displays looking northeast of geologic and topographic details near 600 Area well field. Image A is shows the well field relative to cross section C-C', a grid with 50-ft (15-m) cells, and oriented bedding ellipses (pink polygons) that were generated at BTV record depths using 300 ft (91 m) major axes and 150 ft (46 m) minor axes. The deepest planes in well AWDF correspond to the Hardyston Quartzite (Ch in the section). Image B is shows the well field relative to ground surface represented by a digital elevation model (N.J. Geological Survey, 1999). Image C is shows the 600 and Mid-Valley groundwater investigation areas relative to cross-section C-C'-C". Profile locations mapped on Figure 13.

later in the Green Pond region than further northwest, where Early Silurian deposition began under "an eastward transgressing sea". But an alternate explanation for the apparent delay of the white zircons in the Green Pond hinges on the accumulation of early, thick, locally sourced materials without the need to invoke west-to-east stratigraphic deposition of the regional Silurian molasse. That is, initial alluvial facies of the Silurian molasse were probably deposited in localized structural depressions first, and then were overlapped by a thick, mature, alluvial cover that grew into the foreland as the hinterland source area culminated over time. In this manner, the basal Green Pond is older, and the Shawangunk becomes coeval with higher sections of the Green Pond.

A more recent description of a Taconic source area includes rift facies, pre-margin material and slope-and-rise rocks of Laurentia (Herman and Mitchell, 1991). The lower, conglomeratic part of Green Pond Formation is probably consolidated piedmont alluvium derived from nearby, deeply-weathered source area rising to the east, but its age is unknown owing to the lack of fossil or radiometric-age data. According to Thomson (1957), the Green Pond conglomerate is composed principally of white quartz and chert pebbles in a matrix of quartz sand and silt containing considerable amounts of hematitic clay, resulting in the deep purplish-red coloration. Sandstones in the lower sections of the formation grade laterally and vertically into conglomerates. The red shale intercalated with red, coarse alluvium strongly suggests a terrestrial origin; initially red sand grains washed by waves on beaches, and by streams on alluvial plains tend to lose their red color (Raymond, 1942). Having brown to light-brown orthoquartzite-conglomerate with only white vein-quartz pebbles on the west side of the syncline, and a red polymictic quartzite-conglomerate on the east limb points to the probability that the east-side, basal conglomerates were deposited within thick alluvial channels near an upland source area with subaerial exposure, deep weathering and soil development. At the same time, marginal-marine sedimentation may have occurred simultaneously along the west margin of the restored GPS where the red-purple rocks first give way to the typical brown, buff, and white colors of the Shawangunk Formation. And so it seems that alluvial and shallow marine deposits of Early to Middle Silurian age in the GPS resulted from the differential erosion of Middle and Upper Proterozoic and Lower Paleozoic rocks that supplied the sedimentary load for distributary channels draining localized uplands. Eventually, a thick blanketing molasse accumulated on the northwest regional slope in a complex transitional marine-continental environment (Epstein and Epstein, 1972) with oscillating marine shorelines in equatorial climates. Finks (1968) argued that the middle-to-upper parts of the Green Pond Formation and the lower parts of the Longwood Shale represent piedmont alluvium and marine sand deposited from a westward-transgressing shoreline.

It seems more plausible that the Green Pond was deposited first closer to a hinterland source, then was later blanketed by more regional, alluvial, and marginal-marine deposits. The Shawangunk Formation is reported as Early to Late Silurian (Epstein, 1993), and possibly Late Ordovician (Epstein and Epstein, 1972), whereas the current published age of the Green Pond Formation is Early to Middle Silurian (Drake et al., 1996, but they query the "Early" designation). The well rounded nature of the zircons toward the source area higher in the section is explained by repeated abrasion in a transitional marine, beach environment near the GPS, and reflects the tendency for Green Pond quartzite to be comparatively more mature than Shawangunk quartzite. It's more likely that erosion and deposition began in the east near the GPS where basal, immature, and thick Silurian alluvium filled local, elongate, structural troughs



Kittatinny Mountain currently
lies ~20 miles NW of the GPS
~ 14 miles
The horizontal component of foreland displacement between the current and restored positions of the Reservoir fault is portrayed as ~14 miles (~22 km) from combined Taconic and Alleghanian strains.
NW
Pennsylvania Pocono Plateau
Delaware River
New Jersey Valley and Ridge
Taconic unconformity
New Jersey Highlands
Green Pond syncline
SE
present land surface
sole thrust
stylized "restoration" of F1 structures above the restored position of the present land surface
restored position of present land surface
d2
d1
current position of sole fault
0 4 8 12 16 km
0 4 8 12 16 mi
Current (top) and restored Taconic foreland section (bottom) adapted from section A-A' of Herman and others (1997)
Restored position of the Green Pond Syncline
Rocks similar to the Green Pond Formation and either the Martinsburg Formation or the sequence at Jutland crop out as small fault slices along the Ramapo normal fault about 7 miles SE of the GPS
NW
SE
foreland section
rising hinterland source area
Zone 1 - broad open folds and a slight angular unconformity
Zone 2 – tighter cover folds and faults, pronounced angular unconformity
Zone 3 – thrust faults, steep dips and overturned folds
Polymict cobble and pebble conglomerate, quartzite and mélange
Overlapping fans and distributary channels with polymict pebble and cobble strata reflecting local paleosurfaces
Tripartite stratigraphy of the Shawangunk Fm. in the NJ Valley & Ridge Province (Epstein, 1993)
GPS
eroded Lower Paleozoic cover
current erosion surface
Lower Paleozoic cover
Late Ordovician Beemerville Intrusive Complex
faults
folding in Middle Proterozoic basement
Stylized post-Taconic fold-and-thrust belt across northern NJ

Fig
ure

before being covered and buried by more mature quartzite and sandstone in a subsiding basin that extended well past the Great Valley to the west.

The stylized nature of the Green Pond Formation in Figure 20 uses a tripartite stratigraphy for the Shawangunk Formation based on the work of Drake and Epstein (1967), Epstein and Epstein (1972), and Epstein and Lyttle (1982). Moving eastward over the Reading Prong, the molasse is shown as having overlapping and interfingered sedimentary lenses of restricted down-slope range meant to portray the infilling of restricted structural troughs and depressions that are aligned with regional strike, and lie about normal to the line of section. Moving farther southeast, the molasse is characterized as overlapping alluvial fans and mélange near the footwall of major Taconic over thrust raising a hinterland source area. However this thrust is probably not Thomson's (1957) "Taconia" root lying further southeast and hinterland of the Huntingdon Valley-Cream Valley fault in eastern PA and Cameron's line in NY (Figure 20).

Figure 20 also depicts a normal fault having Lower Paleozoic strata dropped down along the ancestral Reservoir fault. This interpretation is consistent with having repeat episodes of slip along older, deeply rooted faults within the Proterozoic blocks, some of which may have been active during Late Proterozoic and Early Mesozoic rifting (Ratcliffe, 1980; Hull et al., 1986). For example, the Reservoir fault has a long, complicated history of slip activity (Hull et al., 1986; Herman and Mitchell, 1991; Malizzi and Gates, 1989; Gates and Costa, 1998). Early normal slip on this fault may help explain the spotty occurrence of Martinsburg Formation on the western limb of the syncline in the Green Pond Mountain region, that must have at one time tied into the Martinsburg Formation in the southern part of the Hudson Valley (Figures 7 and 8). Therefore, in the center of the GPS, it appears that that Martinsburg flysch may have been deposited atop Middle Proterozoic basement because of the lack of other, nearby Lower Paleozoic rock (Herman and Mitchell, 1991; Figure5), although A. A. Drake, Jr., upon review of Herman and Mitchell's (1991) map, pointed out that this would be a unique occurrence in the Appalachians. It is more probable that the current cross sections underrepresent the presence and thickness of the Paleozoic cover beneath Martinsburg shale in the western, faulted limb of the syncline in NJ, but there is simply no way to know solely based on surface mapping. Where the Martinsburg is first mapped bordering the northeast end of GPS on its northwest side, there are Lower Paleozoic carbonates mapped between the Martinsburg Formation and Middle Proterozoic basement (Offield, 1967; Jafee and Jafee, 1973). But pre-Taconic, arching and open folding of the Lower Paleozoic sequence is well established in the region (Offield, 1967; Epstein and Lyttle, 1987; Herman and Monteverde, 1989; Herman et al., 1997), where early folds in the carbonate platform resulted in restricted, local stratigraphic variations of Middle Ordovician limestone and Upper Ordovician flysch (Monteverde and Herman, 1989).

More work is needed to resolve some issues arising from this work. A more comprehensive assessment of regional subsurface records, like the BTV record shown here (Figure 14), would be very useful for helping in characterizing the lateral stratigraphic heterogeneity and thickness of the Silurian molasse, and the angular discordance about the Taconic unconformity. The AWDF BTV record shows that basal parts of the Green Pond Formation can be locally fine grained near areas where it is also the thickest and coarsest. This area may have been subject to a brief period of post-Taconic relaxation with basement block faulting and local horst and graben structures involving Lower Paleozoic cover rocks, similar to Silurian Connecticut Valley–Gaspé Trough to the northeast (Rankin et al., 1997). In this case, the coarse grained clastics may have originated near fault scarps while more distal, finer alluvium filled more distal parts of local basins.

The Green Pond Formation may be the thickest near Green Pond Mountain NJ (~1,399 ft [426 m]), where the level of Taconic erosion within the GPS was the greatest (Figure 20). The unit thins to the northeast, down to as little as 25 ft (8 m) near Pea Hill, NY,= (Darton, 1894; Ries, 1895), before apparently pinching out. The thickness in the southwest part of the GPS is difficult to tell because of the friable nature of the unit and thick cover, but it may mimic the outcrop expression of the Shawangunk Formation, which generally increases in thickness from the northeast to the southwest across the NY recess (Figure 21). Darton (1894b) reports about 3 ft (0.9 m) of Shawangunk grit at the northeast end of the outcrop belt near the fourth Lake at Binnewater, NY (Figure 21). Darton (1894 a, b) also notes about 290 ft (88 m) at Ellenville, NY, and up to 2,000 ft (610 m) in NJ. Epstein and Epstein (1972) report about 1,800 ft (549 m) near Delaware Water Gap, and it may reach a maximum thickness near Pine Ridge, PA (Figure 21), where the map unit changes from the Shawangunk Formation to the Clinton Formation continuing into the Pennsylvania Salient along strike (Swartz and Swartz, 1930; Epstein and Epstein, 1967). However there are structural complications in the sections from Delaware Water Gap and further southwest that makes an accurate accounting of the unit thickness difficult and imprecise.

The angular unconformity within GPS has only been directly observed in one place, in the subsurface where Green Pond overlies the unit interpreted as Hardyston Quartzite (Figure 14). Both units strike subparallel (northeast-southwest) but at slightly different dip angles (~10^o below the unconformity compared to ~30^o above). In areas of NJ where the Green Pond overlies Lower Paleozoic rocks, the contact has not been directly observed with certainty, but nearby dip angles vary, from negligible to as much as 18^o (see Gould's quarry note above). Where Green Pond Formation overlies Precambrian basement, gneissic layering immediately southeast of the GPS dips steeply southeast in northwest-verging, overturned folds only near the central and northeastern parts of the NJ Green Pond Mountain; further along strike in both directions, basement fold limbs become upright, with layering dipping northwest beneath the northwest-dipping limb of the Paleozoic syncline (Figure 17; and Jafee and Jafee, 1973). It's probably that a main phase of basement folding occurred in the Reading Prong from Taconic orogenesis, and the GPS reflects area-wide, semi-ductile infolding of this age. More work is needed in comparing the geometry of basement folding with that found in the Lower Paleozoic sequence in order to test this hypothesis.

Another aspect arising from this work is the need for more detailed geological maps of Orange County, NY. Only the 1:250,000 scale geological maps for New York are available in digital form, and there are some errors in this coverage in the form of mislabeled (miscoded) polygons for at least the Lower Hudson bedrock coverage. These errors were only detected and corrected in the personal themes needed for generating this report, but they persist in the source themes. Notice of these errors is being sent to the source agency, but users of these data should beware. Also, there are mismatched map units and misaligned unit contacts along the NY-NJ state border that need better definition, as well as those occurring along the quadrangle boundaries at the 1:24,000 scale (for example, see Figure 7). More detailed mapping is also needed in both NJ and NY in and around the GPS for assessing the nature of the late-stage cross faults that cut and offset the Lower Paleozoic rocks. The age and movement on these faults is intriguing and could include Late Paleozoic through Cenozoic movements. The strike of these faults in NY is similar to some cross-faults mapped in the NJ Highlands that may also cut and offset the GPS there, but they are currently mapped as not doing so (see the Mount Hope fault in Figure 4).

In conclusion, the bulk evidence points to the probability that a prominent, Taconic-age structural culmination occurred immediately hinterland of what is now the New York recess, with Taconic root structures now buried beneath Mesozoic cover of the Newark basin and Cenozoic coastal plain sediment laid down on the ensuing passive margin (Figure 1 and 20). It is also likely that these Taconic roots include both 'external' and "internal" basement massifs (Drake et al., 1989), the former including rocks of the Reading Prong and miogeoclinal cover,

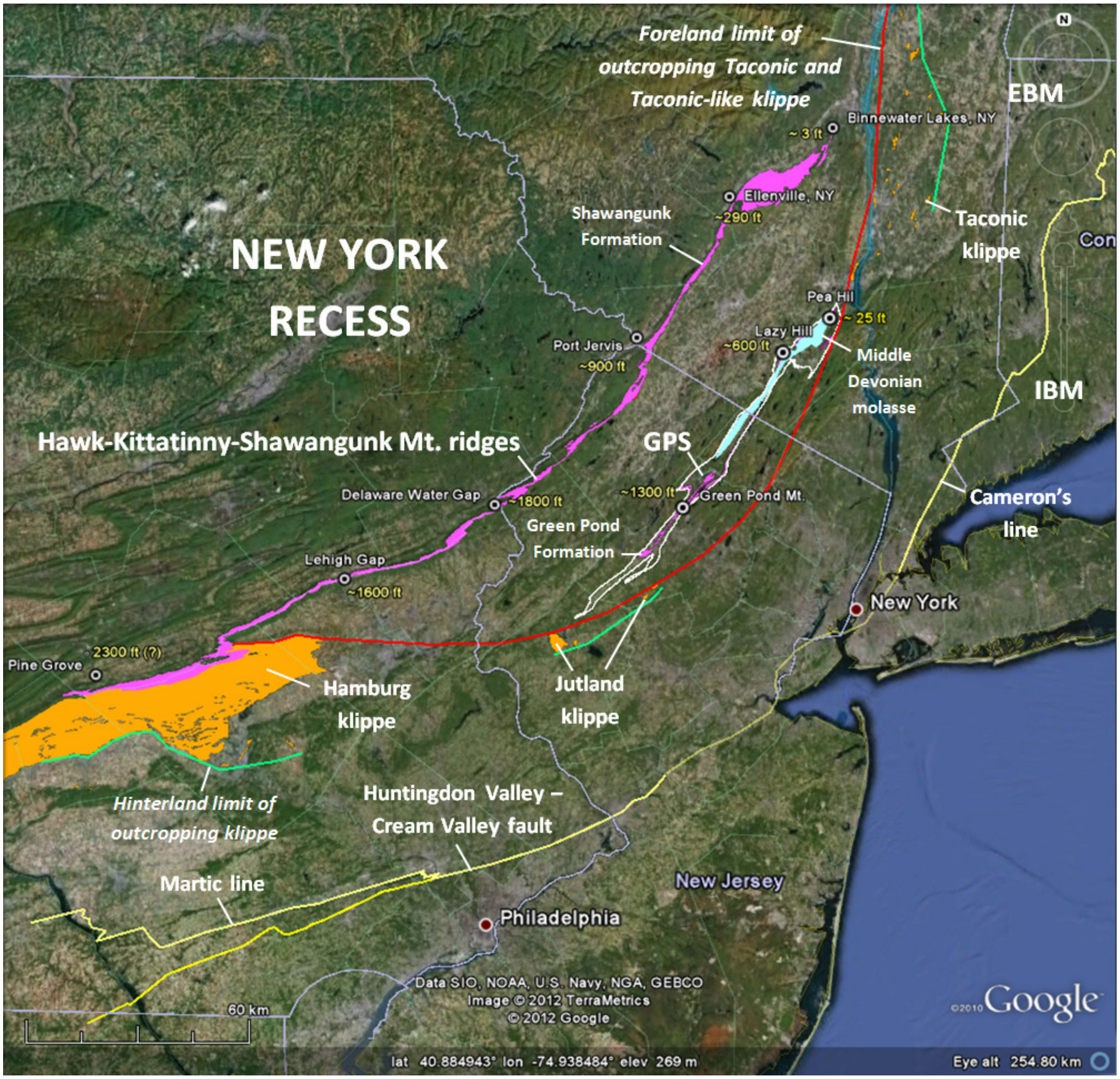


Figure 21. Aspects of the Taconic orogeny around the New York recess summarized using Google Earth. Geological shapes adapted from the US Geological Survey Online Spatial Data; Geological maps of US States (http://mrdata.usgs.gov/geology/state/). Klippe and other terminology after Drake et al. (1989). EBM – Terrain including "external basement massifs" and the foreland basin on the Laurentian margin. IBM – Terrain including "internal basement massifs" and their migeoclinal cover poking through thrust sheets containing eugeosynclinal rocks. The best estimate for the thickness of the Silurian molasse is compiled at a number of places for the Green Pond Formation in the GPS, and for the Shawangunk Formation in the Hawk-Kittatinny-Shawangunk Mountain ridges. See the discussion section for further explanation.

and the latter including abundant mafic rocks, granite, and highly strained eugeosynclinal rocks with "gneiss domes" containing Proterozoic basement like those mapped in New England and the PA Piedmont. These "internides" (Hatcher, 1987) may be the source of Thomson's (1957) euhedral, white zircons in the heavy mineral fraction of the Silurian molasse. It's probably more than just coincidence that the Watchung syncline (Figure 1), which contains the thickest accumulation of Early Mesozoic strata in the Newark basin, lies directly southeast of the area of maximum erosion of Paleozoic cover in the GPS. This spatial relationship suggests that the location of maximum structural relief on the New York recess stemming from Paleozoic orogenesis is coaxial with the location of maximum relaxation and normal slip on ensuing Mesozoic faults, including, but not limited to, the Ramapo fault.

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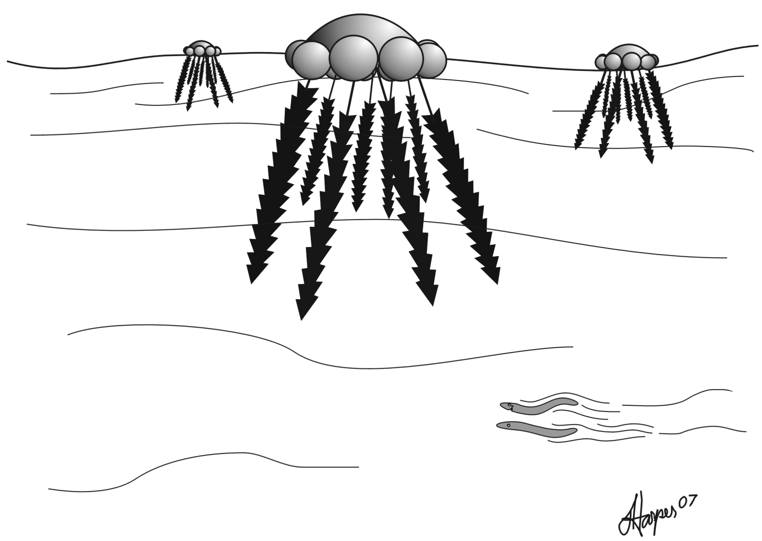
GREAT MOMENTS IN GEOLOGIC HISTORY
Part 4 - The Lower Silurian



I've ALWAYS wanted to move into one of those new low-rise apartments!