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Overprinted strike-slip deformation in the southern Valley and Ridge in Pennsylvania

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ABSTRACT

Two major faults, over 32 km long and 6.4 km apart, truncate or overprint most previous folds and faults as they trend more northerly than the previous N25°E to N40°E fold trends. The faults were imposed as the last event in a region undergoing sequential counter-clockwise generation of tectonic structures. The western Big Cove anticline has an early NW verging thrust fault that emplaces resistant rocks on its NW limb. A 16 km overprint by the Cove Fault is manifested as 30 small northeast striking right-lateral strike-slip faults. This suggests major left-lateral strike-slip separation on the Cove Fault, but steep, dip-slip separation also occurs. From south to north the Cove Fault passes from SE dipping beds within the Big Cove anticline, to the vertical beds of the NW limb. Then it crosses four extended, separated, Tuscarora blocks along the ridge, brings Cambro-Ordovician carbonates against Devonian beds, and initiates the zone of overprinted right-lateral faults. Finally, it deflects the Lat 40°N fault zone as it crosses to the next major anticline to the northwest. To the east, the major Path Valley Fault rotates and overprints the earlier Carrick Valley thrust. The Path Valley Fault and Cove Fault may be Mesozoic in age, based upon fault fabrics and overprinting on the east–west Lat 40°N faults.

1. Introduction

The early structural history of the Valley and Ridge province in south-central Pennsylvania includes several episodes of sequential deformation within the Alleghanian Orogeny, prior to the formation of the two out-of-sequence faults that are the subject of this paper (Fig. 1). Earliest history includes NW directed, pre-folding, layer-parallel-shortening defined by conjugate strike-slip faults in quartz arenites and cleavage attitudes or slip along the Antes–Coburn detachment in black shale of the Reedsville Formation (Stose, 1909; Pierce, 1966; Root, 1968; Clark, 1970; Gwinn, 1970; Okuma, 1970; Main, 1978; Berg and Dodge, 1981; Nickelsen, 1996). Later fold axes, associated with a major thrust in the northern Big Cove anticline, formed counter-clockwise from the attitude they would occupy if formed during the earlier shortening event. This counter-clockwise sequence is typical at this and other localities on the SW limb of the Pennsylvania Salient. The overprinted steep, late faults that I will describe have different fault fabrics and environmental parameters from those of earlier faults.

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2. Two different fault populations in the region

Four lines of evidence suggest more than one fault population: (1) differences in the fault fabrics of faults ascribed to the two fault systems, (2) different structural relations and trends in the two systems, (3) differences in the ambient temperature and composition of fluids in the two systems, as indicated by fluid inclusions in syntectonic quartz crystals of one system, and (4) presence or absence of iron oxides in the fault fabrics or the matrix of breccias in outcrops or in float at historic, 19th century iron mines. In the following discussion the two fault populations will be referred to as Early Faults or Late Faults.

2.1. Early Faults

These faults have excellent fault fabrics in which slickensided surfaces of cataclasite with slickenlines demonstrate their slip direction and sense (Figs. 2 and 3). Outcrop surfaces are usually small, measuring several square meters but at large limestone quarries there are strike-slip surfaces measuring 100 m^2. The faults have associated gash veins or steps on the fault surface that contain syntectonic quartz crystal fillings. Fluid in quartz crystals has revealed saline solutions and the presence of CO_2 and CH_4. Melting temperature of salt crystals ranging from −8.8 °C to −12.4 °C

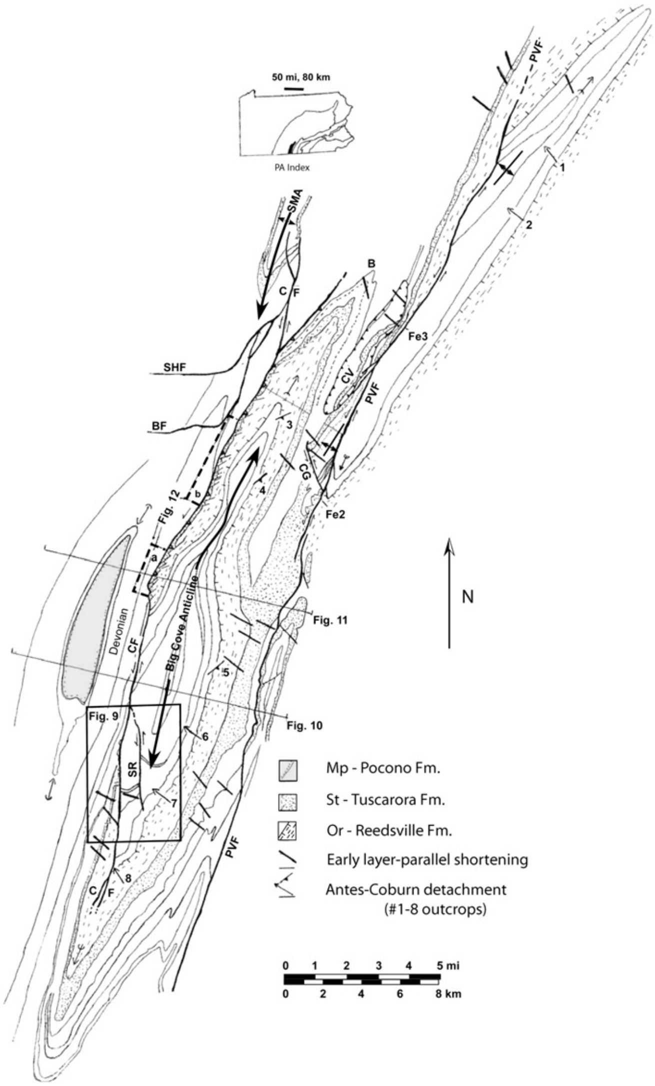

Fig. 1. Regional geologic map, with index map. Identification of map symbols: Mp-Pocono Fm., St-Tuscarora Fm., Or-Reedsville Fm., Early shortening directions, Antes–Coburn detachment, localities 1–8., B = location of Figs. 4 and 5, SMA-Shade Mountain Anticline; Faults: BF-Breezewood Fault, CG-Cowans Gap Fault, CF-Cove Fault, CV-Carrick Valley thrust fault, PVF-Path Valley Fault, SH-Sideling Hill Fault. SR-Spring Run Fault. Fe2 and Fe3 are historic iron mines along the Path Valley Fault. Locations of Figs. 9–12 shown.

indicate about 15% NaCl. Methane Th ranges from 172.5 °C to 197.2 °C, showing that Early Faults were active during migration of hydrocarbons through the system. Fig. 1 shows the orientation of pre-folding shortening directions at localities throughout the study area, where bedding has been rotated to horizontal about bedding strike. Data for these pre-folding shortening directions are (1) the acute bisector of conjugate strike-slip faults, (2) the mean strike of an array of strike-slip faults, or (3) the direction of slickenlines on small intrabed thrusts and backthrusts, which are derived from Early Faults (Figs. 4 and 5). Slickenlines on early, pre-folding strike-slip faults commonly parallel the bedding/fault plane intersection, but during folding the overprinting, younger slickenlines diverge from parallelism with bedding, as is consistent with a later syn-folding origin (Nickelsen, 1979). Data from the N30° east plunge-out of the Big Cove anticline (labeled B on Fig. 1) are more complete than most localities and a schematic drawing (Fig. 4) shows the structural relationships between strike-slip faults, slickenlines and

Fig. 2. Slickensided and slickenlined Early Fault surface, Tuscarora Formation on northwest limb of Big Cove anticline. Right-lateral sense, Slickenlines parallel bedding trace in adjacent rock. Scale: photo width, 6 in (15 cm).

later folding. Fig. 5 is a stereonet plot of the rotated trace of strike-slip faults to demonstrate the derived shortening direction of azimuth 349°. At this locality, the normal to the fold crestal trace at 300° is oriented 50° counter-clockwise from the derived shortening direction.

At 8 localities (Fig. 1), the Antes–Coburn detachment (Nickelsen, 1988) shows bedding-parallel transport toward the northwest in an array of directions from Az. 300° to 349°, similar to the array of shortening directions described above. The detachment occurs near the base of the Reedsville Formation in the Antes shale member, where it is expressed as a one-meter thick cleavage duplex in a black, graptolitic shale just above the top of the Cambro-Ordovician carbonate section (Fig. 6). Pierce (1966) referred to this structure as the Tuscarora Fault and recognized that it formed before folding, because it verges NW on both the SE and NW dipping limbs of first-order folds. It is a widespread regional structure that was identified 50 miles (80 km) to the NNE, was noted in a deep well 75 miles (121 km) to the NE on Shade Mountain, and included in sections by Perry (1978), 100 miles (161 km) to the SW in West Virginia. The Antes–Coburn detachment may serve as a boundary between the underlying

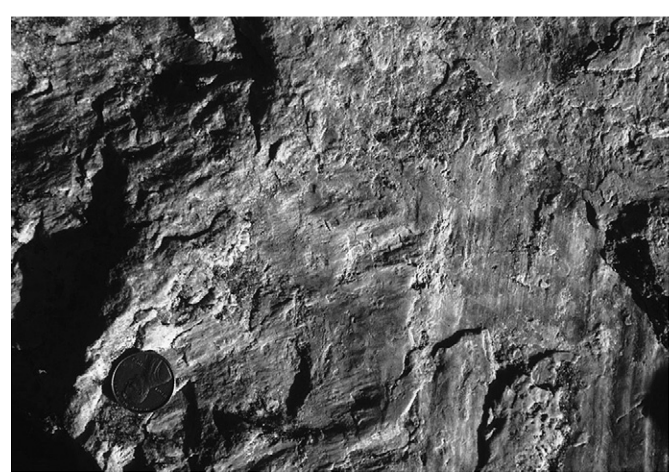

Fig. 3. Two sets of slickenlines on Early Fault surface, Tuscarora Formation, northwest limb of Big Cove anticline. Vertical slickenlines parallel trace of bedding on fault surface. Overprinting horizontal slickenlines are interpreted to be synfolding. Width of photo is 4.5 in (11 cm), penny for scale.

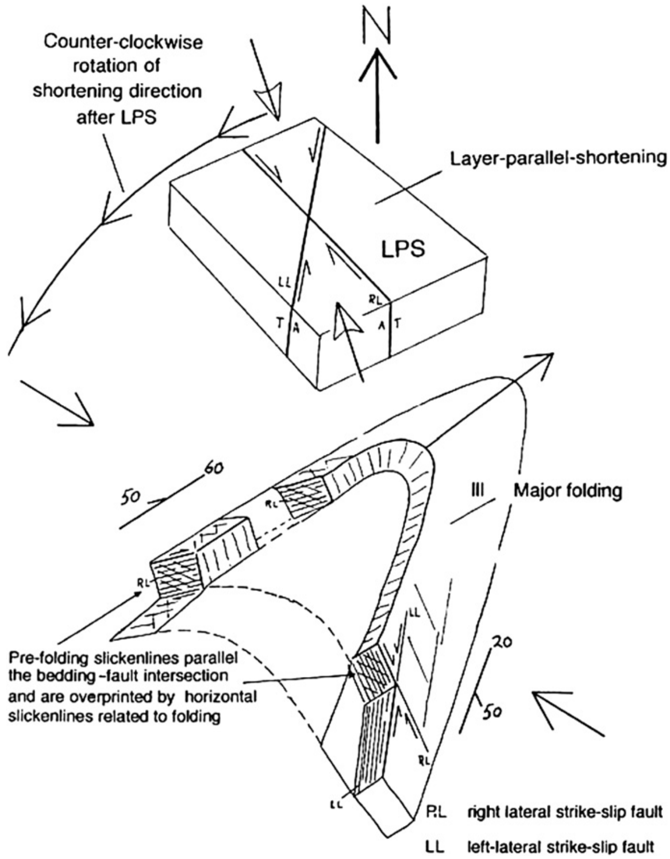

Fig. 4. Drawing of fold/strike-slip fault relations at NE plunge-out of Tuscarora Formation on Big Cove anticline (locality B, Fig. 1). Acute bisector of right-lateral and left-lateral faults strike-slip faults is layer-parallel-shortening direction. pre-folding slickenlines parallel bedding trace on fault. Right-lateral faults are in appropriate orientation for overprint of slickenlines during folding. Fold axis has rotated counter-clockwise from LPS direction.

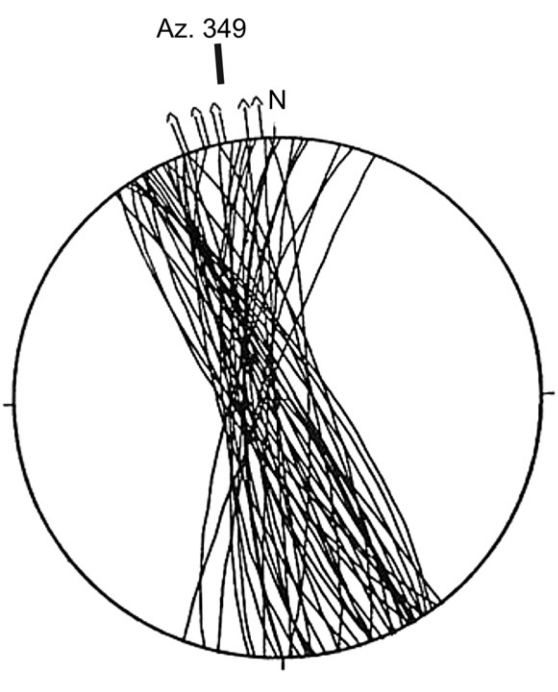

Fig. 5. Stereographic projection of traces of rotated strike-slip faults (locality B on Fig. 1) showing inferred LPS direction that is parallel to acute bisector of conjugate pairs, or of the mean orientation of the whole array.

Cambro-Ordovician carbonate rock duplex and different structural styles of the overlying Upper Ordovician, Silurian, and Devonian stratigraphic sequence.

2.2. Late Faults

These faults are recognized at exposures of the two major faults in the study area, the Cove Fault, cropping out for 24 miles (39 km) along the northwestern side of the Big Cove anticline, and, farther east, the Path Valley Fault, cropping out for 33 miles (53 km) along the western side of the Path Valley and the Mercersburg area (Fig. 1). Smaller faults that strike N50°E–N60°E and occur along 10 miles (16 km) of the north half of the Cove Fault are also Late Faults (Fig. 1). These faults are difficult to interpret because fault surfaces are never slickensided or slickenlined, but are identified by their truncation of bedding and the rare presence of angular fault breccia showing no progression toward fine cataclasite (Fig. 7). No syntectonic quartz crystal fillings in breccia openings or grooves in the fault plane are available to investigate fluid inclusions.

An important feature of Late Faults is the presence of iron oxides on fault plane coatings or in the matrix of quartzite fault breccias (Fig. 8). Several localities along both the major Late Faults were important iron mines (limonite var. goethite) in the period 1822–1847 and all mining apparently ended before 1886 (d'invilliers, 1887). Three mines of interest are Fe1, located along the Cove Fault at Lowery Knob (Fig. 9), and Fe2 and Fe3, located along the Path Valley Fault (Fig. 1). Traces of iron sulfides have been found (Smith, personal communication, 1995, 1996) in float at these mines. The combination of the abundance of iron oxides in Late Fault rocks and the presence of iron mines suggests that the two major Late Faults served as conduits for ore bearing fluids.

3. Description of relationships between Early Faults, folds and Late Faults

Both major Late Faults will be described and illustrated in map view from south to north, emphasizing features for their interpretation.

3.1. Cove Fault

The Cove Fault ends near the south plunge-out of the Big Cove anticline (Fig. 1) in two splays within the Reedsville Formation. After juxtaposing Middle Ordovician carbonates on the crest or SE limb of the anticline with Upper Ordovician Reedsville shale, the fault crosses toward the vertical Tuscarora Formation on the NW limb. Here, the Tuscarora and underlying formations are rotated at two places to a NW strike and are bounded by small, right-lateral, strike-slip Late Faults striking NE across the ridge (Figs. 1 and 9). Northward, all bedding strikes swing to NW, and the NE strike-slip faults increase in abundance, bounding most outcrops at Lowery Knob (Fig. 9). To the north, the fault is within the vertical to overturned NW limb of the Big Cove anticline. For 1.5 miles (2.4 km) to the north, most bedding is obliterated by deformation of the Tuscarora and this stiff unit is effectively a megabreccia of four 200 × 3–500 ft (61–152 m) blocks (1–4, Fig. 9) surrounded by more ductile shales of the underlying Juniata Formation or the overlying Rose Hill Formation and various Devonian shales. Estimates of stratigraphic thickness at a vertical section south of Lowery Knob show that this deformation has reduced the thickness of this section by 40% (Line A, Fig. 9). The zone of fault thinning is at least 900 ft (274 m) wide but it is not clear whether the thinning is due to strike-slip, dip-slip or oblique movements in the fault zone.

North of the Tuscarora blocks in the Cove Fault zone, middle Devonian shales west of the fault are in contact with the oldest

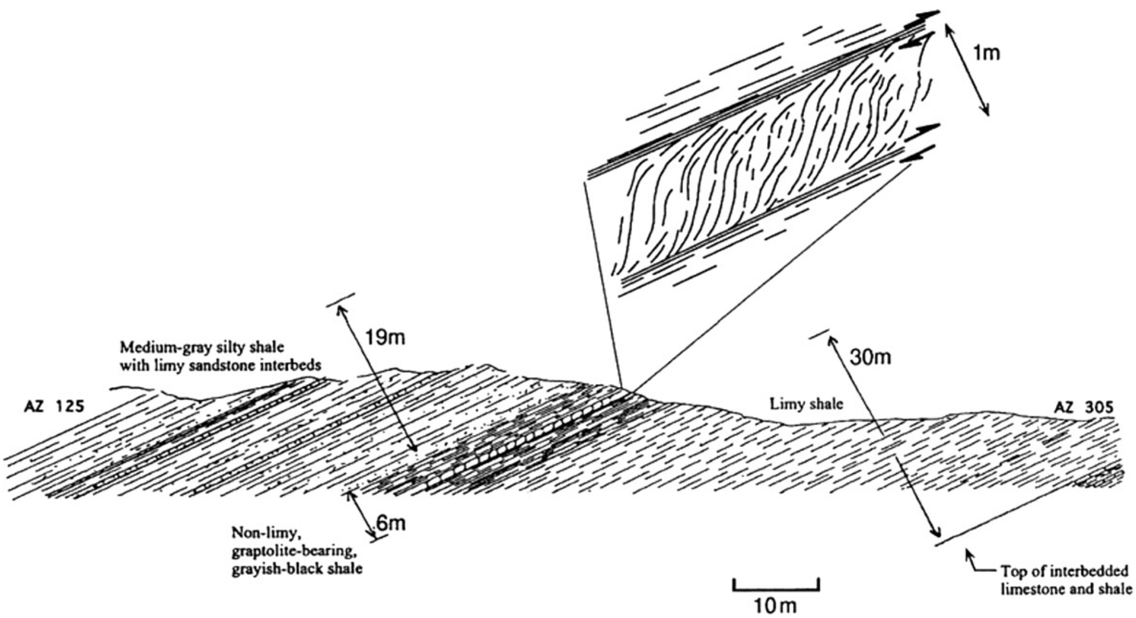

Fig. 6. Drawing of the Antes–Coburn detachment, a 1 m thick cleavage duplex near the base of the Reedsville Fm at location 7 on Fig. 1.

rocks in the region, the Cambrian Warrior limestone and Gatesburg sandy dolomite. This block of oldest rock is bordered on the east by the left-lateral strike-slip Spring Run Fault that, because of either dip or oblique slip at its north end, brings these oldest rocks to the surface. The Spring Run Fault compartmentalizes the structure of the south plunge of the Big Cove anticline and substantial changes of fold geometry occur across it (Fig. 9). Left-lateral strike-slip on this fault is suggested by displacement of contacts of Ordovician carbonate units.

Left-lateral separation (or slip?) on the Cove Fault is inferred to be the cause of the increased strain and obliteration of bedding, intense conjugate right-lateral strike-slip faulting, extension and separation of stiff blocks of Tuscarora in a more ductile, shaly matrix, and 40% tectonic thinning of a vertical stratigraphic section. The only deep well in the region is the I.T. Nesbit well, drilled just west of the crest of the Big Cove anticline to a depth of 8650 ft (2637 m). Ordovician and Cambrian carbonate rocks occur to 5480 ft (1670 m) before the well goes through 3170 ft (967 m) of the Reedsville Formation. This well is shown on the structure section of Fig. 10 that also passes through the Cove Fault and the 5th separated Tuscarora block 2 miles (3.2 km) north of the previously described blocks. My interpretation shows the contact between the Upper Devonian Brallier and Harrell Formations and the Lower Ordovician Axeman Formation to be the surface of the left-lateral strike-slip Cove Fault that has distributed Tuscarora blocks for 3 miles (4.8 km) northward from Lowery Knob. The thrust fault displayed in the Nesbit well does not reach the surface in the section.

Three miles (4.8 km) to the north, the structure section of Fig. 11 shows the Tuscarora Formation above the thrust at the NW limb of the Big Cove anticline, but also lying above the steeply dipping Cove Fault. This relationship suggests that the earlier thrust fault was overprinted by a thick zone of left-lateral strike-slip movement along the Cove Fault, producing the belt of 30 conjugate

Fig. 7. Late Fault plane with angular breccia, but not slickensided or slickenlined. Iron oxide coating on top surface to left of cm scale.

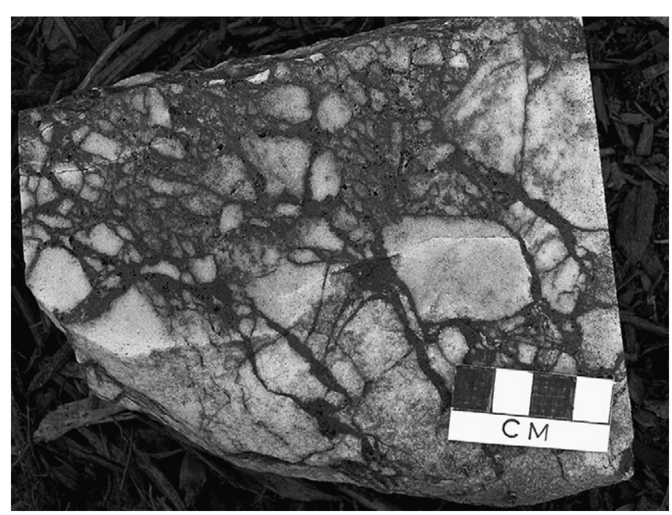

Fig. 8. Sawed surface of Late Fault, Tuscarora Formation breccia with limonite matrix and marginal dissolution of breccia fragments.

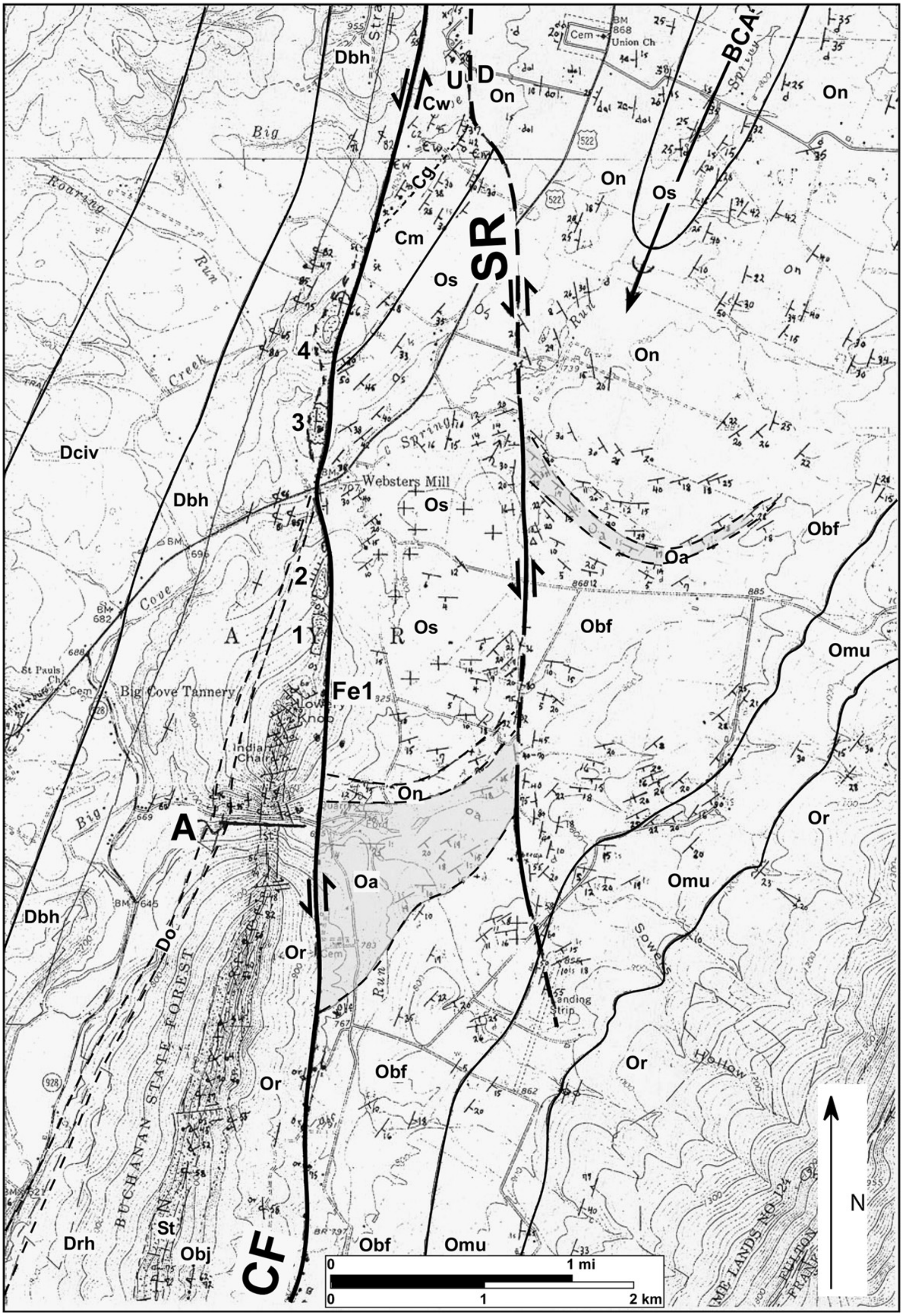

Fig. 9. Geologic map near south end of Cove Fault, showing Spring Run Fault, Fe1 historic iron mine along Cove Fault at Lowery Knob. A-tectonically thinned section, BCA-Big Cove Anticline. Separated Tuscarora Fm. blocks # 1,2,3,4. Map units, from youngest to oldest, Devonian: Dciv-Catskill-Irish Valley Fms., Dbh-Brallier-Harrell Fms., Do-Onandaga limestone, Drh-Rose Hill shale, Silurian: St-Tuscarora Fm, Ordovician: Obc-Bald Eagle-Juniata Fms., Or-Reedsville Fm., Omu-middle-upper Ordovician undifferentiated, Obf-Bellefonte Fm., Oa-Axeman Fm., On-Nittany Fm., Os-Stonehenge Fm., Cambrian: Cm-Mines Fm., Cg-Gatesburg Fm., CW-Warrior Fm.

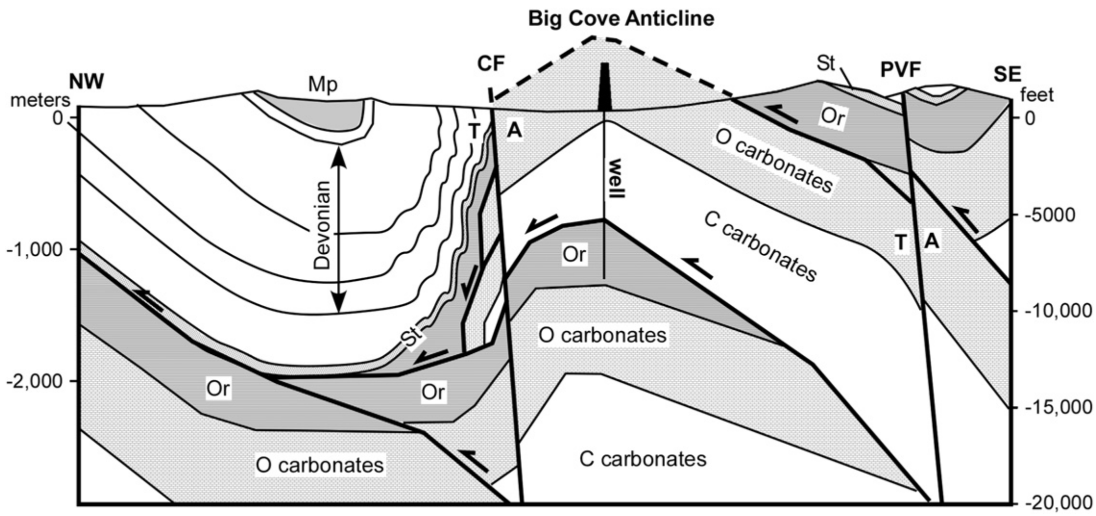

Fig. 10. Structure section through Nesbit deep well, drilled to 8650 ft (2637 m). No vertical exaggeration. CF-Cove Fault, PVF-Path Valley Fault. Mp-Mississippian Pocono Fm., St-Silurian Tuscarora Fm., Or-Ordovician Reedsville shale.

right-lateral strike-slip faults that occur for 10 miles (16.1 km) along the NW limb (Fig. 12). A one and a half mile (2.4 km) segment of the most closely spaced right-lateral strike-slip faulting along Little Scrub Ridge (Fig. 12a) has produced an extension of 153%, but another 3 miles (4.8 km) of Scrub Ridge in the Meadow Grounds, farther north, shows an extension of only 32% (Fig. 12b). Analogous rotated blocks have been documented elsewhere as a deformation style associated with active strike-slip faulting (Terres and Sylvester, 1981).

Farther north, the Cove Fault leaves the NW limb of the Big Cove anticline and crosses to the east limb of the south-plunging Shade Mountain anticline where it is exposed as several blocks that have slipped south, compatible with left-lateral strike-slip on the Cove Fault (Fig. 1). Between Big Cove anticline and the Shade Mountain anticline there are two major east–west faults, the Sideling Hill and Breezewood Faults (SH and BF, respectively, Fig. 1) that form part of the Lat 40° fault zone described by Root and Hoskins (1977). These two faults deflect to the north, consistent with the curvature expected from the left-lateral displacement in the Cove Fault zone.

The best evidence for left-lateral slip or separation on the major 22 miles (35 km) Cove Fault is: 1) the conjugate small, right-lateral strike-slip faults in two different zones along the fault (Fig. 12), 2) extension in the Tuscarora Formation outcrops along a ridge over or adjacent to the Cove Fault zone (Fig. 9), 3) separation of five large blocks of Tuscarora Formation over a distance of 3 miles (4.8 km) northward from where the Cove Fault crosses the Tuscarora outcrop (Fig. 9), and 4) the northward bend of two east–west trending Lat 40° fault zone faults as they are crossed by the Cove Fault zone (Fig. 1).

3.2. Path Valley Fault

The Path Valley Fault, a Late Fault with orientation and fault fabrics identical to the Cove Fault crops out for 30 miles (48 km) along the east side of the map (Fig. 1). The data available for this study are personal observations for the northern half and the work of for the southern half. Mapping of the Path Valley Fault, which is the contact between Reedsville Formation on the west and fractured carbonate rocks on the east, was very accurate because sink holes in fractured carbonate rock define the contact. At the south end of my mapping there are 3 structures that aid in interpreting the fault zone: 1) the Cowans Gap left-lateral

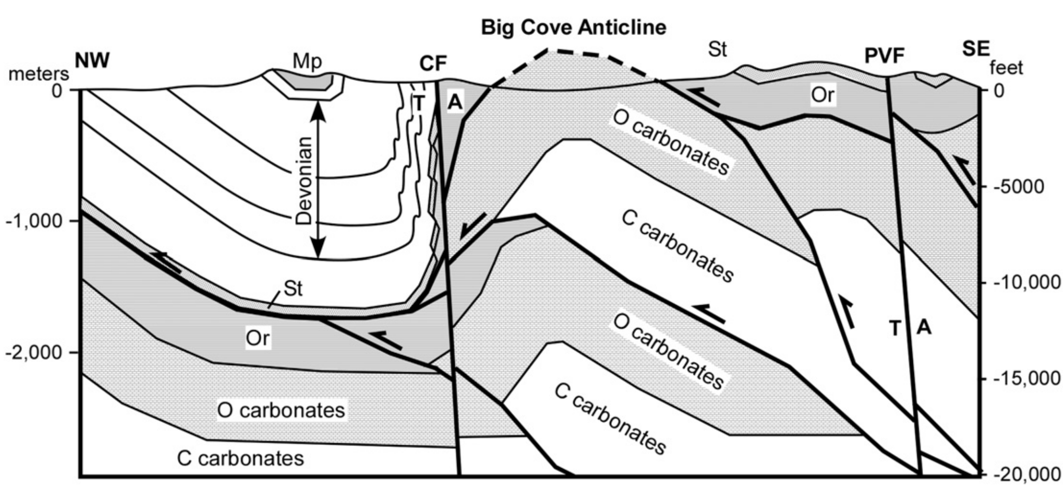

Fig. 11. Structure section displays early thrust fault and Big Cove anticline overprinted by the left-lateral strike-slip zone of the Cove Fault. No vertical exaggeration. CF-Cove Fault, PVF-Path Valley Fault. Mp-Mississippian Pocono Fm., St-Silurian Tuscarora Fm., Or-Ordovician Reedsville shale.

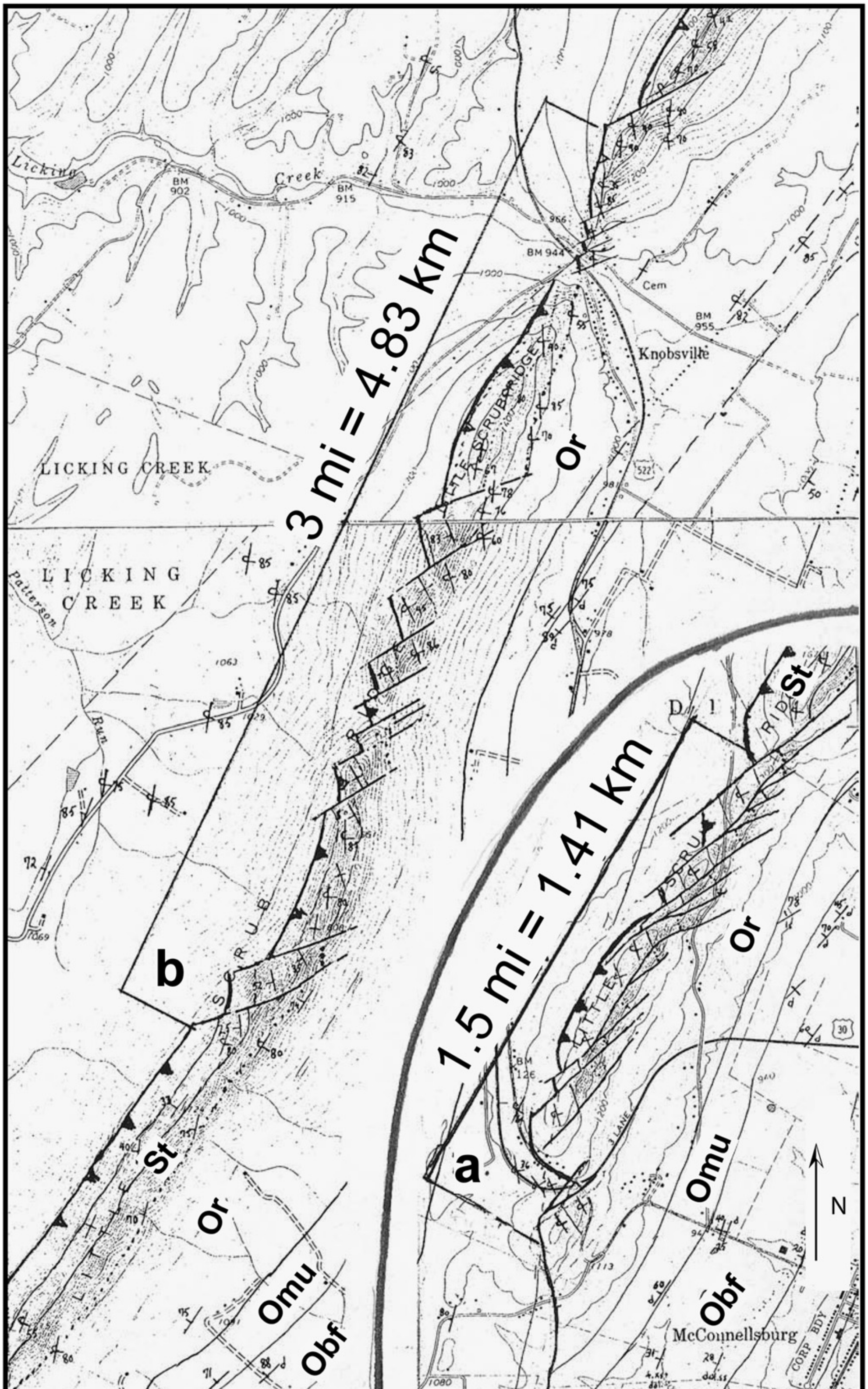

Fig. 12. Two segments of the right-lateral strike-slip faults to show different extensions in the 1.5 miles (1.4 km) segment (a) and the 3 miles (4.8 km) segment (b). Units defined in Fig. 9. All right-lateral fault blocks contain section of St and Obc with basal Bald Eagle conglomerate, where observed, marked by large dots.

strike-slip fault (Fig. 1), 2) an anticline trending N35°E that is visible for 1.5 miles (2.4 km) just north of the Cowans Gap Fault, and 3) the Late Path Valley Fault that truncates both the Cowans Gap Fault and the N35°E anticline (Fig. 1). The Cowens Gap Fault, the N35°E anticline, and the Carrick Valley thrust are all consistent in orientation with the early layer-parallel-shortening-directions and pre-folding Antes–Coburn detachment transport directions (Figs. 1, 5 and 6), and so are interpreted as also having formed early in the deformation sequence. It is certain that the truncation of the N35°E anticline by the long Path Valley Fault was a late event on the regional fault. The N35°E trending anticline is truncated on the W side of the Path Valley Fault and is repeated 8 miles (13 km) to the north on the E side of the fault as an anticline plunging toward N40°E (Fig. 1). There is no compelling evidence that the separation of the anticline segments (8 miles, 13 km left-lateral) represents the slip on the Path Valley Fault, but clearly the fault is a major disruption of the tectonic grain of the region.

The Carrick Valley thrust also illustrates the effect of the Path Valley Fault upon the regional structure. It is a folded thrust fault deflected on the east by an up-dip component of the Path Valley Fault and dipping northwest into the syncline between the Big Cove anticline and the Path Valley carbonate valley. Beneath the Carrick Valley thrust are overturned folds, verging northwest, that formed during the thrusting. They are overprinted by two splays of the Path Valley Fault that displace the thrust fault and complicate the duplicated section of the Tuscarora Formation formed by the thrust. There is no evidence that the Path Valley Fault relates to the earlier formation of the overturned folds or the Carrick Valley thrust fault that it abuts. Farther north the Path Valley Fault was the main influence on the Tuscarora Formation trend of N20°–25°E as it rotated beds to steep dips and truncated the carbonate anticline to the east. Finally, except for the suggestion of left-lateral, strike-slip transport on the Path Valley Fault provided by the intersected and displaced N35°E–N40°E anticline, other evidence of movement sense on this fault is of a steep or oblique upthrust, up on the east and down to the west.

4. Discussion and conclusions

There is considerable evidence that the region has two different classes of faults, identified as Early Faults and Late Faults. Early Faults are pre-folding or synfolding in relative age, slickensided and slickenlined, containing quartz with fluid inclusions. Late Faults lack fault fabrics for recognizing slip sense or orientation, are associated with historic iron mining, have limonite coatings on fault planes or in the matrix of breccias and overprint previous structures along major fault traces, 24–33 miles (39–53 km) in length, trending N10°–20°E. The Cove Fault (Fig. 1) along the west side of the Big Cove anticline is found, in the south, on the SE limb of the anticline, passes through the Tuscarora Formation of the NW limb and crosses a faulted syncline before encountering the next anticline to the northwest. Observations of separated Tuscarora blocks, extension of a faulted ridge with many right-lateral fault separations, and northward deflection of previous E–W faults all suggest left-lateral motion along the Cove Fault. The Path Valley Fault, 4 miles (6.4 km) to the east, overprints and rotates previous structures, such as the Carrick Valley thrust, and clearly defines the change in early N35°E trends to later N20°E structural trends. However, the fault has less evidence for left-lateral separation.

The maximum compressive stress (σ_1) direction indicated by the Early Faults is 300–320° over most of the Big Cove anticline but ranges up to 349° at the plunging north end of the fold (Fig. 1, at B). If the σ_1 direction for the Big Cove anticline is normal to the crestal trace, it should trend 285°, implying a 35° or greater counterclockwise rotation of σ_1 from Early Faulting to later folding. The same relationship has been noted in a larger region extending 30 miles (48 km) WSW to Maryland (Markley and Wojtal, 1996) and 40 miles (64 km) north to the Kishacoquillas Valley (Nickelsen, 1988). The optimum σ_1 direction for producing left-lateral slip on the Late Cove and Path Valley Faults (30° to the fault strike) is approximately 355°, more northerly trending than the stress direction for either the Early Faults or the folds.

Two scenarios appear to be consistent with these data. (1) Early Faulting with a σ_1 direction of 300–320°, followed by a counterclockwise rotation of σ_1 to 285° which produced the folds. The folds were truncated by later (unrelated?) strike-slip faulting along the Late Faults. (2) Alternatively, the folds formed oblique to the 300–320° σ_1 direction that produced the Early Faults. Oblique folding is consistent with deformation above lateral ramps controlled by preexisting structures. Continuing deformation caused σ_1 to rotate clockwise to 355°, and produced the Late Faults. The Late Faults in part followed older structures, for example the steep limb of the Big Cove anticline and, in part truncated the older structures. This allows all the structures to be part of a single progressive deformation with a NW to NNW shortening direction.

The different fault fabrics of the Late Faults, when compared to the Early Faults, indicate more brittle behavior, hence shallower burial for the Late Faults. Shallower burial might be the result of tectonic uplift and erosion, consistent with the Late Faults being a late part of the Appalachian folding. Alternatively, if left-lateral slip on the Cove Fault caused the bend to the north of the two Lat 40°N faults, then the evidence from Root and Hoskins (1977) about the probable age of those fault zones suggests that the Late Faults might even be Mesozoic.

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