GEOLOGICAL REPORT ON THE SKYTOP ROAD CUTS

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Introduction

Skytop is the name given to a wind-gap in the Bald Eagle Ridge, approximately 10 miles (15 km) west of State College, in central Pennsylvania (Figure 1). This wind gap has long been used as a transportation route between Nittany Valley to the east and Bald Eagle Valley to the west. State highway Route 322 and Interstate 99 (currently under construction) cross the ridge through this saddle. A number of unusual geologic conditions contribute to the location of the ridge as well as the position of the wind gap. These include an overturned sequence of competent (and erosionally resistant) sandstones units and less competent limestone and shale units beneath a major thrust fault, a set of mesoscopic to macroscopic scale low angle faults striking generally 110^{o} (see Figure 1), with a left lateral strike-slip component, and a late vein system trending generally 160^{o} through the competent rocks. The presence of chevron folds in the Silurian beds underlying the western slope of the ridge was another unexpected condition conducive to the development of landslides. Recent construction of highway I-99 through the Skytop windgap required deep excavation into the bedrock, revealing a major pyrite-bearing vein system. While the presence of pyrite has been problematic, the new bedrock exposures afford an exceptional view of the stratigraphy and structure in Bald Eagle Ridge. All of these conditions have provided a challenge to highway construction.

Because these conditions are site specific, it is convenient to consider the problems encountered by locality. Fortuitously, the engineering Section C-12 corresponds to a geologic terrane in which the bedrock structure is dominated by sharply hinged (chevron) folds, whereas the A-12 section is characterized by uniformly steeply dipping strata. The section C-12, west of the ridge crest (Figure 2), is slightly oblique to the strike of chevron folds, whereas section A-12 between Skytop and Buffalo Run curves through the bedrock lithology in a deep cut, well below oxidized

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near-surface rocks and above the ground water table. Pyrite-bearing veins, well developed in the Bald Eagle sandstone, were exposed in the "Large Cut Face" (LCF) road-cut over a distance of approximately 1000 feet. A visual estimate of 4 to 5% pyrite by volume is confirmed by chemical analyses of samples from along the road cut. Approximately 1 million cubic yards (2 millions tons) of pyritic rock was excavated. Pyrite veins are exposed for approximately 2/3 of the way up slope on the northern side of the road cut, before passing through a weathering related REDOX front into "oxidized cap rock" (OCR). There is a short term environmental hazard associated with the pyritic rock stored at various on-site localities, and a long term problem with the veins exposed in an approximately 30^{o} slope area of more than a 1000 feet long and 200-500 feet high (see Geological Maps).

Plate 11

Table 1
Table 2
Table 3
Table 4

Geological Setting

Central Pennsylvania is characterized by contrasting topography, with relatively flat Plateau land to the west, and sinuous ridges with broader intervening valleys to the east (see Figure 1). The former terrain is known as the Appalachian Plateau Physiographic Province; the latter the Ridge and Valley Physiographic Province. The dominant bedrock exposed in the Ridge and Valley Province are dolostones, limestone, shale and sandstone ranging in age from Cambrian (sandy dolostones and dolostones), through Ordovician (dolostones and limestones grading upward through shales and impure sandstones) into Silurian quartzose sandstones (orthoquartzites) and shales and limestones and finally into Devonian dolostones, limestones and shales. Mississippian and Pennsylvanian age strata (sandstones, shales and coal measures) are preserved locally in the troughs of synclines in the Ridge and Valley Province. In contrast, most of the strata exposed in the Appalachian Plateau are of Mississippian and Pennsylvanian age. A summary of the stratigraphic column and typical formation thickness in central Pennsylvania are given in Table 1.

Bald Eagle Ridge (Figure 1) is a prominent and continuous double ridge that extends for hundreds of miles through central Pennsylvania and south southwestward into West Virginia, and marks the start of the Ridge and Valley Physiographic Province. It is separated from the Appalachian Plateau Physiographic Province to the west by the Allegheny Structural Front. On the northwest side of the ridge Upper Silurian and Devonian age rocks underlie most of Bald Eagle Valley, and extend upwards into Mississippian and Pennsylvanian aged rocks on the Appalachian Plateau.

The thickness of these units is estimated to be 2000+ ft for the Silurian strata (Laughrey, 1999), 8000 ft for the Devonian strata (Harper, 1999), and 1280 ft for the Mississippian strata up to the Pocono Formation (Berg, 1999). Thus there is a stratigraphic discordance of 14,000 feet (4375 m) between the Tuscarora Formation in the crest of Bald Eagle Ridge and rocks at equivalent altitude on the Plateau (Pocono Formation). These accordant summits represent the Schooley peneplain, an early Tertiary erosion surface (Williams and Slingerland, 1985), with an estimated 15,000 feet (4573 m) of denudation at the Allegheny escarpment since the Permian (Paxton, 1983). These are important geological manifestations of the Allegheny Structural Front.

The Ridge and Valley Physiographic Province is appropriately named for the sinuous ridges and valleys that extend throughout a belt approximately 100 miles (160 km) wide (State College to Harrisburg). The accordance of ridge crest elevations at approximately 2000 feet is remarkable, as is the correlation of topography with bedrock structure and composition. Cultural and agricultural development likewise is influenced by topography and geology. The valleys between the more resistant sandstone ridges are eroded into carbonate rocks, over which are developed thick soils suitable for arable agriculture. Communication between the early settled valley bottoms was mainly through the wind and water gaps that occur at irregular intervals through the ridges. Modern transportation routes tend to follow the early road networks, but with an enhanced scale of excavation.

Stratigraphy

The dominant lithologies along 1-99 between Bald Eagle Valley and State College decrease in age from Devonian to Cambrian (See Table 1). The pertinent section at Skytop is:

Silurian

Rose Hill Formation 600-800 ft ? Dominantly shale and siltstone
Tuscarora Formation 400 ft Quartzose sandstone (orthoquartzite) and minor shale

Ordovician

Juniata Formation 600 ft Red shales, siltstones and sandstones

Bald Eagle Formation 700 ft Green impure sandstones, with minor siltstones and shales
Reedsville Formation 600-700 ft Dominantly shales, minor siltstones and coquinas
Antes Member 70-80 ft Black carbonaceous, calcareous shale
Coburn Formation Interbedded limestone and calcareous shale

These units represent a succession of transgressions and regressions, progressing upwards from marine shelf carbonates and shales to clastic "red beds" and the beach sand deposits of the Tuscarora Formation.

A reduction of thickness for all formations exposed along I-99 through Skytop is apparent when compared to the typical regional thicknesses for these units. The greatest reductions are in the shaly units. In particular, the upper member of the Juniata Formation appears to be missing.

Coburn Formation:

The upper part of the Coburn Formation is exposed in the eastern part of the southbound LCF, at station 902+00 and in the northbound road cut bank at station 901+00. Here the beds strike 060°, dip steeply southeast and are overturned, with tops to the northwest. The contact with the overlying Reedsville Formation coincides with the break in slope leading up to Bald Eagle Ridge. The topography from here to Buffalo Run is characterized by gentle swales, a paucity of surface drainage, and sinkholes (in the vicinity of the settling ponds). This underdrained drainage system reflects the carbonate bedrock.
The Coburn Formation typically consists of interbeds of dark gray to black calcareous shale and dark bluish gray limestone. The beds range in thickness from 20 to 50 cm, with a shale to limestone ratio of approximately 1:1. The limestone beds are very fine-grained to micritic with relatively rare fossils. These interbeds are considered to be rhythmites, deposited below storm wave base in a shelf/slope environment. A spaced cleavage (097°/40°) with a sigmoidal shape is developed in the shale beds and appears to be refracted into the limestone beds (see Plate 1-1,a). Although this cleavage is compatible with an overturned limb of an anticline, the shallow angle suggests it was formed before the limb was rotated to its current overturned attitude: probably before the development of the Birmingham thrust system.

Antes Member: The Antes Member of the Reedsville Formation is exposed as a 70-80 feet thick section of black carbonaceous calcareous shale. It is exposed in the road cuts as a fissile shale (Plate 1-1, c & d). Springs and seeps occur along the contact with the underlying Coburn limestone. A non-cohesive mud near the base is the source of some road-bed instability. The occurrence of syngenetic pyrite and the high organic content in these shales suggests euxenic (anoxic) depositional conditions.

Reedsville Formation:

The calcareous shales of the Antes Member grade upward into olive gray shales and buff/tan siltstones of the Reedsville Formation. Towards the eastern end of the southbound road cut (LCF), the shale is weathered to a buff/brown color to a depth of 50 feet (Plate 1-1, b). Shale is the dominant lithology in the lower part of the formation (Plate 1-2, a), with minor siltstone interbeds 10 to 50 cm thick towards the middle (Plate 1-2, b). Rare coquinas (fossil hash) (Plate 1-2, d) that locally are ferruginous and sideritic (Clinton-type iron ore) are more common near the top of the formation, where they are seen as rusty weathering zones, up to 1m thick, in the road cut.

The general attitude of the beds is $060^{o}/80^{o}$ (Plate 1-1, a) with tops to the northwest (i.e., overturned). Some 4th order folds occur locally. Their S configuration and shallow plunge suggest they are drag folds associated with the Nittany anticlinorium. Well developed joints (Plate 1-2, c) are preserved locally, and some of these host thin (< 1 mm) veinlets of pyrite. The general attitude for these fractures is $160^{o}/90^{o}$, and they are interpretated to be the Late Alleghanian J2 joint set.

A number of faults striking 090^{o} to 120^{o}, and dipping 30^{o}-50^{o} north, are apparent in the northbound lane road cut as the break-away surfaces of small landslides (Plate 6-1, c; Plate 6-2, a & b). Although these fault surfaces are smooth, they are not planar, but tend to be scalloped and irregular on a meter scale. With a transport direction of $30^{o}/285^{o}$, these faults are classified as left oblique slip normal. The development of land-slip scarplets (Plate 6-2, b) where the faults were "daylighted" on the northbound road cut slopes, prompted PennDOT to lay these slopes back to 2H:1V. Another fault (strike 120^{o}, dip steeply northeast) displaces the Reedsville/Bald Eagle contact in the north side road cut approximately 120 feet up from station 889+00 to 891+00 (Plate 6-1, a). Rotation of the adjacent beds into the fault plane and sense of displacement for stratigraphic juxtaposition suggest this fault has a high dextral strike-slip component.

The transition into the overlying Bald Eagle Formation is marked by an increasing number of sandstone interbeds over an interval of 20-30 feet. The contact is placed at the first persistent sandstone bed. It is a muddy sandstone, generally devoid of any internal structure and highly bioturbated.

Bald Eagle Formation:

The Bald Eagle Formation consists mainly of greenish-gray impure sandstone (low rank graywackes) in beds typically 1 m thick (Plate 2, a). Rip-up-clasts (Plate 2, c), up to 20 cm across, occur at the base of many of the beds, which grade upward through poorly sorted cross-bedded sandstone into planar bedded shale and siltstone 3-10 cm thick. The bedding cycle is repeated in a coarsening upward sequence. Despite the deep excavation in Bald Eagle strata at Skytop, the degree of alteration from the emplacement and weathering of sulfide veins renders these rocks poor candidates for developing a stratigraphic section. The imprint of sulfide mineralization is sufficient to alter the nature of the host, where the sandstones have been reduced in color and competence to a drab green/gray color friable "funky" sandstone, some of which have an oily green hue (Plate 2, a & d). Two distinct colored zones are apparent in the LCF above the southbound lane. The lower zone has a drab green/gray color that takes on whitish yellow overtones during dry periods, whereas the light rusty brown to buff colored upper section, near the skyline, is part of the "oxidized cap rock" gossan.

The Bald Eagle low rank graywackes are composed mainly of quartz and minor feldspar set in a matrix of chlorite and illite (Thompson, 1970a, 1970b). The rocks exhibit a granular "sugary" texture, with subangular to subrounded quartz grains that vary in size from coarse to fine. Accessory minerals include magnetite, xenotine, and zircon (Horowitz, 1970). The diagenetic history has been complex, and it is apparent that the green-gray color is not primary, but represents a later regional episode of aqueous reduction and dissolution (Thompson, 1970a). These reducing "fluids" were neither pervasive nor stratabound. A deep-maroon colored sandstone was exposed at station 888+00 approximately 40 feet above the base, and at the new Route 322 bridge over I-99, red sandstone beds (Plate 3, a) change along strike into green beds (Plate 8-1, a & b). At this latter site red beds (Plate 3, a) of the Bald Eagle Formation, with similar morphology and composition (rip-up-clasts, cross-bedded sandstone and overlying siltstone and shale) owe their color to ferruginous clays and hematite (Horowitz, 1970). It is apparent that reduction diagenesis converted the clay minerals to chlorite and the hematite to magnetite (Thompson, 1970a). Pyrite that occurs as the matrix, cementing quartz grains in small knots of 1-3 mm across, is believed to be part of this reduction process. A likely cause is the late Alleghanian gas drive, recognized by Engelder (2004) and Lacazette (1991) as the hydrofracturing medium for the regional J2 joints.

The contact with the overlying Juniata Formation is an enigma, because a commonly held criterion based on color is invalid. Unfortunately, the convenient stratigraphic marker of the Lost Run Conglomerate (present elsewhere in the state) is not developed locally. The Lost Run Conglomerate marks the transition from a coarsening upward to a fining upward depositional condition for the Juniata Formation; a sequence increasingly dominated by red shale. Thus the rocks assigned to the Bald Eagle Formation should be restricted to those deposited in the regressional cycle, and those of the Juniata Formation to the next transgressional cycle.

Juniata Formation:

The basal sandstones of the Juniata Formation resemble those of the Bald Eagle Formation with shale rip-up-clasts in coarse to fine grained, cross-bedded sandstones on a meter scale, with thin interbedded shales and siltstones (Plate 3, b). The shale beds become thicker and more dominant upwards (Plate 3, b & d). They are characterized by a deep red to maroon color and the pervasiveness of ferruginous clays (dominantly illite) and hematite in the matrix. At Skytop, the formation is projected to be approximately 600 feet thick, with part of the Middle (Plummer Hollow Member) and Upper Juniata (Run Gap Member) strata missing.

Pale green to cream-colored reduction zones are apparent in these vividly colored rocks. The REDOX fronts either are stratabound (usually sub-parallel to some sandy bed), or are transgressive to bedding (associated with fractures and/or sulfide-bearing veins).

The contact with the overlying Tuscarora Formation is marked by the presence of a very light gray to white, clean, well-sorted sandstone (orthoquartzite) interbedded with vari-colored cream, pink and buff-colored shale and siltstone over a stratigraphic interval of 10-15 feet.

Tuscarora Formation:

The Tuscarora Formation typically is made up of beds 20 cm to 2 m thick of a hard, clean, whitish cross-bedded (Plate 4, b), quartzose sandstone (orthoquartzite) with thin shale interbeds (Plate 4, a). The sandstones are composed dominantly of well-sorted quartz grains cemented with quartz to form a tough, hard, competent rock with minimum porosity. Most of the quartz grains are subrounded, and vary in size from coarse to fine in well defined cross-beds. The rock is referred to as quartzite because a siliceous cement bonds adjacent grains.

These rocks are exposed along the crest of the western (highest) ridge and underlie parts of the upper northwest slope. At Skytop they crop out behind the microwave antenna and in the road cut to the southwest along old Route 322 (Plate 4, d). In contrast to the steeply overturned attitude of the underlying Juniata Red beds, these quartzite beds dip 20°-40° to the southeast and appear to be overturned. Mesoscopic scale asymmetric chevron folds were exposed during construction of the C-12 section of I-99 between stations 813+00 to 861+00 (Plate 5, d). These were seen to have long (30-50 m) southeast limbs dipping 30°-50° NW and shorter northwest limbs (10-15 m) dipping 20°-40° SE (Plate 4, c).

Favorable conditions for slope failure (landslides) were developed when and where construction cut slopes exceeded the bedding dip (Plate 6-2, c & d). Because of close match in scale between natural (chevron folds) and anthrogenic (road cut) slopes many small landslides developed on both sides of the road cut (Plate 5-2, b). To stabilize these slopes those adjacent to the northbound lane were cut back from 1H: 2V slope to 2H: 1V slope gradient. In addition, as a preventative measure, the toe on the northbound road bed was raised up to 17 feet between stations 833+00 and 855+00 (the bifurcation zone).

Joints are well developed in the Tuscarora Formation. Three sets occur pervasively with fairly regular spacing from 30 cm to 1 m. The earliest is J1, a strike joint dipping approximately perpendicular to bedding. Later cross-strike joints J2 are nearly vertical joints, developed in the dip plane of the beds. The third set are bedding joints. In many places along Bald Eagle Ridge these joints are stained with iron oxyhydroxide (gossan) minerals. These are part of an oxidized cap rock, widely diffused beyond the limits of any underlying sulfide-bearing veins, along the J1 joints. Steeply dipping sulfide- and sulfate-bearing veins are exposed locally in the road cuts. They have a general strike of 160°, and locally form vein networks (stations 858+00 to 861+00) (Plate 8-1, c). Phosphate minerals of the wavellite group have been found in some of the J2 joints (Plate 9-1, d).

The tendency for the resistant quartzite beds to break out (also by frost heave) into rectangular shaped blocks, led to their use as foundation stones in many of the early settlement buildings, and as refractory brick (ganister) in iron ore and ceramic furnaces. Frost heaved Tuscarora float occurs locally in open scree (talus) patches along the upper northwest slopes of Bald Eagle Ridge, and these were exploited as a source of ganister during the late 19th Century and early years of the 20th Century.

Rose Hill Formation:

The overlying Rose Hill Formation is exposed locally in the road cut near the southwest end of the bifurcation zone (stations 813+00 to 817+00). The beds near station 813+00 dip southeast and appear to be overturned (045^{o}-$055^{o}/40^{o}$-45^{o}), but this may be anomalous due to the presence of kink band chevron folds on thrust faults. Vari-colored shales and siltstones occur at the base in a gradational contact with the interbedded shales and sandstones of the Tuscarora Formation. The Rose Hill Formation consists mainly of buff/brown to khaki-colored shales with minor silt interbeds. The high illite content in the shales enhances the slaking properties of these shales and their conversion into sticky mud.

Structure

Two distinct and separate structural domains are apparent on the mesoscopic scale. Fortunately these two domains coincide with the construction sections designated C-12 for the western slopes of Bald Eagle Ridge and A-12 for the eastern slopes (see Figure 2). Bedding attitudes range from 30^{o} NE to 30^{o} SW on the west facing slope (C-12 section), to steeply dipping overturned in the main A-12 road-cut. The general attitude for the Juniata and Bald Eagle strata is $070^{o}/80^{o}$ (overturned), and the relatively tight cluster (Figure 3) is consistent with steeply dipping beds in a relatively uniform monoclinal setting. In contrast, bedding attitudes for the C-12 domain define two maxima (Figure 4) with S-poles distributed along a steeply dipping great circle (a p girdle), whose pole, ß ($5^{o}/060^{o}$) defines a fold axis. This is the domain of the chevron folds with an interlimb (dihedral) angle of 84^{o}. These settings are depicted in conceptual structural models in Figure 5, where the structural discordance of the Tuscarora Formation beds is accommodated in a kink band splay thrust setting. These models reflect a pre- and a post I-99 excavation knowledge base. The "overturned fold model" presumed the Tuscarora beds exposed in the Rte 322 road cut was overturned and detached from the underlying Juniata strata. A series of lystric thrust slices is assumed for the "imbricate thrust model" to account for the mesoscopic scale chevron folds in the Tuscarora beds.

Structural anomalies noted during the excavation stage (April to August, 2002) need to be reconciled. These include a mesoscopic scale fold (plunging 0°-5°/237°), exposed (August, 2002) above the present road bed locality near 863+50, in Juniata "red beds" (Plate 5, a). The counter-clockwise sense of this fold, indicating an east verging, anticlinal fold to the northwest is incompatible with the overall structural setting. A similar relationship was noted during the excavation stage (April, 2002) above and to the east of Station 838+00, where bedding (223°/75°) and cleavage (225°/45°) indicate a synclinal axis beneath Bald Eagle Ridge in an east verging fold. Potential rotation in the landslide block that was mapped in this area is insufficient to account for the reversal in cleavage attitude: kink band rotation on a duplex is a more likely explanation.

Mesoscopic scale faults are ubiquitous and their attitudes appear somewhat random (Figure 6) until commonalities in type and setting are taken into account. Most of the bedding faults, so common in the Bald Eagle beds, have down dip slickenlines (dip-slip movement) that are consistent with a flexural slip mechanism during the folding of these beds in the Nittany Anticlinorium. However, some of these bedding faults have a dominant strike-slip component. These show up as the densest cluster of great circles, oriented ENE and dipping steeply SSE.

At least a dozen mesoscopic scale, low angle, oblique-slip faults were mapped in the Reedsville Shale, particularly in the north-facing road-cut in the A-12 section. They have a general ENE strike and dip less than 45° north (Plate 6-1, c). Although these faults have smooth surfaces on a mm scale, they are scalloped and grooved on a mesoscopic scale, with a left oblique-slip normal component plunging 30°/290°. However, the extent of mapping on these was limited to individual beds; although no magnitude of displacement could be determined, it was judged to be small. Extension cracks and scarplets developed locally where the cut slopes intersected less steep fault planes (Plate 6-2, a & b).

Another group of faults trending ESE and dipping steeply to the southwest. The trace of one can be seen in the LCF, approximately 100 feet up-slope from Station 888+00 (Plate 6-1, a) where it displaces marker beds approximately 100 feet (30 m) in a right lateral sense. The trace of another fault (140°/57°) is apparent in the northbound lane road cut near station 887+60 (Plate 6-1, b). This group most likely is associated with the fault mapped across Nittany Valley to the east (Figure 1).

A number of high angle reverse faults were mapped in the shale outcrops along Old Route 322. They have a general ENE strike and a 65° northerly dip.
The steeply dipping, northerly trending faults (Figure 6) appear to be later than the rest. One of these faults (207°/77° SE) was exposed 375 feet east of the Route 322 bridge abutment in the southbound road cut, near Station 885+70. Three sets of slickenlines are apparent on a highly polished surface (mirror finish), indicating it has a high strike-slip component (Plate 6-1, d). The significance of this fault is that it cuts and displaces a vein network of pyrite.

A macroscopic scale fault is inferred to extend through the gully near Pond M and across the divide west of Station 868+00. Five hundred feet to the west, near station 861+00, another fault trending 175° is inferred from the juxtaposition of Juniata "red-beds" are against Tuscarora "quartzites".

Three dominant joint sets in the Skytop rocks are identified as J1 (strike joints), J2 (cross-strike joints), and bedding joints. The J2 joints have a preferred SSE orientation (Figure 7; Plate 1-2, c) and steep dip. These have been attributed to a hydrofracing event during a late Alleghanian gas drive (Lacazette, 1991; Engelder, 1966, 2004) after the formation of the Nittany Anticlinorium. J1 joints are nearly horizontal, with shallow northerly to northwesterly dips (Figures 7 and 8). They are strike joints perpendicular to bedding, and probably developed before the strata were folded during Alleghanian deformation. In the A-12 section they appear as the flat dipping joints (Plate 2, a). In the C-12 section, the orientation pattern is more complex, with two distinct groupings; one dipping northwest at approximately 30° and the other southeast at 40° (Figure 8). These two populations reflect the attitudes of strike joints perpendicular to bedding in the limbs of the chevron folds (Figures 4).

Epigenetic Veins: mineralization and chemistry

Prior to the recent road construction, virtually no veins were exposed at Skytop. However, their existence was suspected from the presence of arsenic and a phosphatic mineral in the old ganister workings along the ridge to the southwest, as well as the gossan (Plate 11, a) overlying pyrite veins exposed along Old Route

322 in a road cut into the Bald Eagle sandstone near station 882+00 (site of the new Route 322 bridge). The new road cuts have exposed the vein system for detailed mapping. The relationship of the superimposed veins to the regional structure is portrayed in a modified block diagram (Figure 10), as viewed from the south.

Although veins that transgress bedding are exposed in all the road cuts, most are concentrated in the Bald Eagle sandstones (Plate 7-1, a, b, c, & d: Plate 7-2, a, & c), and to a lesser extent in the Tuscarora quartzites and Juniata sandstones (Plate 7-2, d: Plate 7-3, b, c:& d:) Plate 8-1, b, c, & d: Plate 8-2, a, b, c, & d). These "cross-strike" veins are far less common in the over- and underlying shaly formations. The preferential development of veins in the more competent strata is attributed to the well-developed J2 joint system in these units. Although the orientation of the veins is relatively constant, different types are distinguished by composition, thickness and alteration halos. Sulfide-bearing veins are by far the most abundant and occur as steeply dipping, cross-strike sets oriented generally SSE (Figure 9), essentially coincidental with the preferred orientation of the J2 joint set (compare with Figure 7). The slightly geometrical obliquity suggests there may have been two different hydrofracturing events; an early one to form the J2 joint set and a later vein forming event.

Quartz and calcite veins occur marginal to the high concentration of sulfide veins exposed in the road cut through the Bald Eagle Formation. A few thin veins of early quartz covered by later pyrite have been found near the contact of the Bald Eagle and Juniata formations. One vein with barite as a major constituent is exposed in the Juniata red beds in the western road cut near station 867+60. Wavellite was identified in a sample of Tuscarora quartzite float picked up during construction near station 840+00. The veins host mineral assemblages interpreted as hydrothermal in origin. The minerals tentatively identified and suspected are listed in Table 2.

The majority of veins are composed of sulfides. These are best developed in the Bald Eagle sandstone strata exposed in the A-12 section LCF road cuts between stations 881+00 and 888+00. Locally veins of pyrite, up to 2 cm thick, generally on the order of 1 cm or less, occur with a spaced interval of 50 cm to 1 m (Plate 7-1, a, c, & d; Plate 7-2, c). The strike of these steeply dipping veins ranges from 130^{o} to 190^{o}, (see Figure 10) and overlaps spatially with the regional J2 joints (Figure 7). Cross-linking veins locally form vein networks that vary from fine (centimeter scale) (Plate

7-1, b) to open (decimeter scale) (Plate 7-2, d). The distribution of vein and vein networks is not uniform and an average grade of 4-5% sulfides in the LCF road cut is based on integrated visual estimations made in traverses at 50 feet intervals across the slopes of the road cut (see detailed map of A-12 section road-cut). A more rigorous estimate of pyrite content was attempted by Ed Meiser and Arthur Rose (Meiser, 2004), who sampled the northern LCF road cut at 3 ft intervals. These samples were composited into 30 ft units (10 adjacent samples) and analyzed for major and minor chemical element contents (Table 3). Sulfur contents ranged from 0.66% to 4.69% to yield an average grade of 2.27% S, or 4.25% pyrite. Samples of aggregate from the 2RC aggregate piles had a range of sulfur content from 1.13 to 1.46% with an average of 1.25% S. Higher sulfur values, reflecting a pyrite content from 4.5 to 24 %, were obtained from selected samples from the southbound side (LCF) road cut and the northbound lane beneath the bridge. Samples from the fault zone near Station 880+00 consist mainly of pyrite, yielding a sulfur content of 32.10%.

Broad spectrum chemical analyses for major, minor and trace elements in five samples of Bald Eagle sandstone and one Tuscarora quartzite are given in Table 4. The main components are silica, iron, aluminum, potassium and sulfur. Except for sample S-370, located in a fault zone, all samples show SiO2 contents of greater than 60% by weight. Aluminum as Al2O3 ranges from 2.16 to 6.67%, in an inverse relationship to sulfur content. Iron as Fe2O3 ranges from 3.57% in low sulfur rock to 37.16% in the highly pyritic fault gouge. Potassium as K2O likewise shows an inverse relationship to sulfur content. Sulfur ranges from 0.39 to 25.38%, and appears to be insufficient to accommodate all the iron as pyrite: some monosulfide phases (pyrrhotite or greigite) must be present. No simple correlations were apparent for phosphorus, reported as P2O5 with values in the range of 0.02 to 0.06 wt %. Dilution of the amount of clay minerals (chlorite and illite) by the addition of pyrite should account for the inverse relationship between these elements and sulfur content.

Amongst the trace elements zirconium is uniformly high (63 to 315 ppm). Surprisingly the values for vanadium (0.5 to 44 ppm) and gold (0.2 to 11 ppb) are unexpectedly low. As expected the base metals, copper (8 to 50 ppm), lead (7 to 430 ppm) and zinc (7 to 753 ppm) correlate positively with sulfur content for samples from the Bald Eagle sandstone sites, but not for the pyritic rock in the Tuscarora quartzite (station 859+10 in section C-12). An elevated barium value of 138 ppm is consistent with the presence of barite in nearby veins.

The antithetic relationship between sulfur and the Rare Earth elements, Y (6 to 18 ppm), La (9 to 20 ppm) , and Ce (19 to 44), as well as for thorium (1.4 to 4.5 ppm) and zirconium (63 to 315 ppm) suggests a dilution effect from the addition of sulfides, and that these elements are hosted in accessory detrital minerals such as zircon, xenotime and apatite. Cadmium shows a weak positive correlation with sulfur, and arsenic (1 to 46.4 ppm) peaks in the pyritic fault gouge. No obvious patterns are present in the cobalt (6 to 18 ppm) and chromium (11 to 20 ppm) analyses. A Black Shale provenance suggested from the base metals content is not supported by the low values for vanadium.

Hammarstrom et al. (2005) report mineralized samples from the A-12 road cut (LCF) to contain as much as 34 wt % Fe, 28% S, 3.5% Zn, 1% Pb, 88 ppm As, and 32 ppm Cd. X-ray diffraction analysis on the 5 samples of Bald Eagle sandstone (listed in Table 4) show the presence of quartz, muscovite, pyrite (and marcasite) chlorite and kaolinite.

Veins in the Reedsville shales are rare and are unlikely to exceed 0.5% by volume of rock at any place. Calcite and quartz veins tend to occur in the lower Reedsville, with pyrite veins more common towards the top of the formation. Except for their transgressive orientation (160°), the pyrite veins differ markedly in thickness (< 1 mm) and habit (coating on J2 joint surfaces) from those in the Bald Eagle sandstone.

Veins in the "red beds" of the Bald Eagle and Juniata formations are much less common than in the green Bald Eagle beds, but are more easily discerned because of the green REDOX halo surrounding them. In addition to sulfides (mainly pyrite), sulfate (barite) is present in one vein near station 876+50. The reduced zones contain many fine veins that are seen to cluster around a fault with an irregular surface. Undoubtedly the fault and the veins were the conduits for reducing fluids; reduction zones vary from 10's to 100's feet thick, and locally follow stratigraphic horizons (usually more porous sandy beds).

Likewise veins in the Tuscarora quartzites are less common and thinner than in the Bald Eagle Formation. The veins exposed during excavation of the C-12 road bed were seen to contain pyrite beneath an oxidized cap rock with vari-colored stains from iron oxyhydroxide minerals, not only on the J2 joints but also the J1 and bedding joint planes. Although the J2 joints appear to be the favorable host for vein fill materials to deposit, subsequent oxidation and reduction allowed for the supergene minerals to disperse areally in the other well-developed joint sets (Plate 7-3, b, c, & d).

At station 856+00 in the eastern road cut of the C-12 section Tuscarora beds dip 30° SE and are overlain by Juniata beds higher up the slope. The attitude of these beds in an extensive pyrite vein network, exposed between stations 858+00 and 861+00, is not known in detail (Plate 8-1, c). This has developed into an acid leach zone since the completion of construction, and is discernable as a slope area on which seeded vegetation has not taken root.

A characteristic of epigenetic vein deposits is the surface development of gossan; a term applied to the alteration products of sulfide minerals from oxidization and hydration above the water table. A REDOX front is the interface between the reduced "pyritic" rock (usually drab green and gray) and the "oxidized cap-rock" (rusty browns and reds) from iron oxyhydroxide mineral encrustations (commonly referred to as gossan). The gossan represents the weathering and alteration products of sulfide minerals in the oxidized and hydrated cap-rock, and as such is essentially devoid of any sulfide minerals. The secondary mineral deposits in the gossan are referred to as supergene. The distribution of the oxidized cap-rock is shown by a special pattern in the accompanying geological maps (Plate 8-1, a & b). A second form of REDOX occurs when sediments deposited in an oxidizing environment (usually red in color due to the presence of hematite, the high oxidation state for iron) are altered by reduced fluids with the conversion of hematite to magnetite (a lower oxidation state for iron) and an attendant color change to drab greens and grays. Transgressive veins that carried reducing fluids through the "redbeds" are easy to spot by the abrupt color change (green/gray) at the REDOX front (Plate 8-1, c & d: Plate 8-2, a, b, c, & d). Rocks representing both these processes are exposed at Skytop. Their combined effects are apparent where sulfide-bearing veins (reducing environment) in the Juniata "red beds" pass into the "oxidized cap rock" (Plate 7-3, c & d: Plate 8-2, a). However this is not the full story of REDOX events at Skytop. There is evidence of a regional gas (dominantly methane) migration (drive) during the late Alleghanian Orogeny (Lacazette, 1991; Engelder, 1996, 2004) that reduced much of the Bald Eagle Formation. The legacy of this event are small knots (1-2 mm across) of pyrite-cemented quartz grains disseminated in some Bald Eagle sandstone beds.

In addition to the supergene minerals, such as hematite, limonite/goethite and jarosite (see Table 2) that formed in the gossan over time as the surface weathered down, there are a host of secondary efflorescent minerals currently growing in response to solution and evaporation of vadose ground water. A number of efflorescent minerals have been identified (see Table 2). Amongst these, the iron sulfate salts such as alunogen, copaipite, halotrichite, melanterite and rozenite grew in moist seeps as saturated ground water evaporated at the surface to form cauliflower head like blooms (Plate 10, a, b, c, & d). These salts are extremely soluble in water and do not survive the next rain. Their dissolution results in an immediate increase in sulfate ions in the runoff.

Regional fluid inclusion (Orkan and Voight, 1985; Lacazette, 1991) and fission track (Blackmer, 1994) studies suggest host rock temperatures ranging from 150° to 250°C. and a depth of 5-8 km at the time of sulfide fluid migration. Recently completed fluid inclusion temperatures on co-genetic vein quartz at Skytop increases this range to 140°-375°C, with most between 180°-350°C , and salinities from as little as 9.2% to as much as 25% (Detrie et al., 2005). Pyrite occurs in a wide range of morphologies, from cuboctahedral crystals to massive blocks, laths, matchsticks and fine needles (Sicree, 2005). Sicree (2005) concludes that (a) early striated pyrite followed by smooth-faced cubic crystals reflects a change from low-supersaturation, higher temperature (> 250°C) to moderate-supersaturation, lower temperature conditions, and (b) that the needle-like forms indicate a continued shift to lower temperature (<250°C), low-supersaturation as the main stage of mineralization ceased.

The number of stages and age(s) of mineralization has yet to be determined. A tentative Os/Re age of 18.9 Ma needs to be refined and verified. Clearly, the variety and distribution of "cross-strike" veins in all the road cuts attests to a complex geological history at Skytop.

Conclusions

• A reduction of thickness is apparent in the stratigraphic units exposed at Skytop, and the Lost Run Conglomerates unit in the Bald Eagle Formation, as well as part of the Middle and Upper Juniata Formation appear to be missing.

• The sulfide minerals exposed at Skytop represent an epigenetic vein system transgressive to bedding in a zone approximately 900 feet wide.

• Vein minerals include pyrite, pyrrhotite and marcasite, with minor sphalerite and galena and traces of chalcopyrite and greenockite.

• Different morphologies of pyrite are consistent with a wide temperature range (140°-375°C) and saturation of the hydrothermal fluids, and suggest multiple stages of deposition.

• A depth of vein (and sulfide) emplacement of 5-10 km, inferred from fluid inclusion studies on quartz in the veins, is consistent with fission track and coal vitrinite reflectance estimates of 5-8 km of unroofing at the Allegheny Front.

• The timing for emplacement is post Alleghanian: the setting is in a deep seated fracture zone that probably is related to other SSE trending lineaments in the Ridge and Valley Physio-graphic Province: these lineaments are manifest in the alignment of wind- and water-gaps.

• The sulfide veins at Skytop are coincident with the regional cross strike J2 joints that were formed by hydraulic fracturing during the late Alleghanian deformation.

• Although the veins are best developed in the more competent sandstone units, the Bald Eagle sandstones appear to be the preferred site for deposition.

• Three distinct REDOX events are apparent: the first is a late Alleghanian gas/fluid drive that reduced most of the "red bed" units in the Bald Eagle Formation, and locally segregated pyrite as small knots in the sandstone matrix. The second involved reducing sulfide-bearing solutions, that likewise caused transgressive bleached green zones to develop in the "red beds". Current weathering has developed an oxidized cap rock above the groundwater table and gossan over the sulfide veins.

• Excavations below the groundwater table in similar geological settings should anticipate the exposure of toxic sulfide minerals.

• Efforts are needed to suppress the development of efflorencent minerals in the large exposed cut faces.

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Bald Eagle ridge (Figure 1) is a prominent and continuous double ridge that extends for hundreds of miles through central Pennsylvania and south southwestward into West Virginia, and marks the start of the Ridge and Valley Physiographic Province. It is separated from the Appalachian Plateau Physiographic Province to the west by the Allegheny Front. On the west side of the ridge Upper Silurian and Devonian age rocks underlie most of Bald Eagle Valley, and extend upwards into Mississippian and Pennsylvanian aged rocks on the Appalachian Plateau. The thickness of these units is estimated to be 2000+ ft for the Silurian strata (Laughrey, 1999), 8000 ft for the Devonian strata (Harper, 1999), and 1280 ft for the Mississippian strata up to the Pocono Formation (Berg, 1999). Thus there is a stratigraphic discordance of 14,000 feet (4375 m) between the Tuscarora Formation in the crest of Bald Eagle Ridge and rocks at equivalent altitude on the Plateau (Pocono Formation). These accordant summits represent the Schooley peneplain, an early Tertiary erosion surface (Williams and Slingerland, 1985), with an estimated 15,000 feet (4573 m) of denudation at the Allegheny escarpment since the Permian (Paxton, 1983). These are important geological manifestation of the Allegheny Front.

Stratigraphy

The dominant lithologies along 1-99 between Bald Eagle Valley and State College decrease in age from

Devonian to Cambrian (See Table 1). The pertinent section at Skytop is:

Silurian

Rose Hill Formation 600-800 ft ? Dominantly shale and siltstone
Tuscarora Formation 400 ft Quartzose sandstone (orthoquartzite) and minor shale

Ordovician

Juniata Formation 600 ft Red shales, siltstones and sandstones
Bald Eagle Formation 700 ft Green impure sandstones, with minor siltstones and shales
Reedsville Formation 600-700 ft Dominantly shales, minor siltstones and coquinas
Antes Member 70-80 ft Black carbonaceous, calcareous shale
Coburn Formation Interbedded limestone and calcareous shale

These units represent a succession of transgressions and regressions, progressing upwards from marine shelf carbonates and shales to clastic "redbeds" and the beach sand deposits of the Tuscarora Formation.

Juniata Formation:

The basal sandstones of the Juniata Formation resemble those of the Bald Eagle Formation with shale rip-up-clasts in coarse to fine grained, cross-bedded sandstones on a meter scale, with thin interbedded shales. The shale beds become thicker and more dominant upwards. They are characterized by the deep red to maroon color and the pervasiveness of ferruginous clays (dominantly illite) and hematite in the matrix. At Skytop, the formation is projected to be 500 feet thick. Pale green to cream colored reduction zones are apparent in these vividly colored rocks. The REDOX fronts either are stratabound (usually subparallel to some sandy bed), or are transgressive to bedding (associated with fractures and/or sulfide bearing veins).

The contact with the overlying Tuscarora Formation in marked by the presence of a very light gray to white, clean, well-sorted sandstone interbedded with vari-colored cream, pink and buff colored shale and siltstone over a stratigraphic interval of 10-15 feet.

Tuscarora Formation:

The Tuscarora Formation typically is made up of beds 20 cm to 2 m thick of a hard, clean, whitish cross-bedded, quartzose sandstone (orthoquartzite) with thin shale interbeds. The sandstones are composed dominantly of well-sorted quartz grains cemented with quartz to form a tough, hard, competent rock with minimum porosity. Most of the quartz grains are subrounded, and vary in size from coarse to fine in well defined cross beds. The rock is referred to as quartzite because a siliceous cement bonds adjacent grains. Scree talus of frost heaved Tuscarora float also is developed locally along the upper northwest slopes and was exploited as a source of ganister during the early 1900's.
These rocks are exposed along the crest of the western (highest) ridge and underlie parts of the upper northwest slope. At Skytop they crop out behind the microwave antenna and in the road-cut to the southwest along old Route 322. In contrast to the steeply overturned attitude of the underlying Juniata Red beds, these quartzite beds dip 20°-40° to the southeast and appear to be upright (in some early cross-sections they are interpreted to be overturned (ref)). Mesoscopic scale asymmetric chevron folds were exposed during construction of the A-12 section of I-99 between stations 813+00 to 861+00. These were seen to have long (30-50 m) southeast limbs dipping 30°-50° NW and shorter northwest limbs (10-15 m) dipping 20°-40° SE. Favorable conditions for slope failure (landslides) were developed when and where the construction cut slopes exceeded the bedding dip. Small landslides developed on both banks of the road cut (see photographs, Plate)

Favorable conditions for slope failure occurred when and where the cut slopes angle exceeded the dip of the beds. Because of close match in scale between natural (chevron folds) and anthrogenic (road cut) slopes many small landslides developed on both sides of the road-cut. To stabilize these slopes those adjacent to the north-bound lane were cut back from 1 to 2 slopes to 2 to 1 slopes. In addition, as a preventative measure, the toe on the north-bound road bed was raised up to 17 feet between stations 833+00 and 855+00 (the bifurcation zone).

Joints are well-developed in the Tuscarora Formation. Three sets occur pervasively with fairly regular spacing from 30 cm to 1 m. The earliest, J1 is a strike joint dipping approximately perpendicular to bedding. Later cross-strike joints J2 are nearly vertical joints, developed in the dip plane of the beds. The third set are bedding joints. In many places along Bald Eagle Ridge these joints are stained with iron-oxyhydroxide (gossan) minerals. These are part of an oxidized cap rock , widely diffused beyond the limits of any underlying sulfide-bearing veins, along the J1 joints. Steeply dipping sulfide and sulfate bearing veins are exposed locally in the road-cuts. They have a general strike of 160°, and locally form vein networks (stations 858+00 to 861+00). Phosphate minerals of the wavellite group have been found in some of the J2 joints.

The tendency for the resistant quartzite beds to break out (also by frost heave) into rectangular shaped blocks, led to their use as foundation stones in many of the early settlement buildings, and as refractory brick (ganister) in iron ore and ceramic furnaces. Frost heaved Tuscarora float occurs locally in open scree (talus) patches along the upper northwest slopes of Bald Eagle Ridge, and these were exploited as a source of ganister during the late 19th Century and early years of the 20th Century.

Rose Hill Formation:

The overlying Rose Hill Formation is exposed locally in the road cut near the southwest end of the bifurcation zone (stations 813+00 to 817+00). The beds near station 813+00 dip southeast and appear to be overturned (045-055°/40-45°), but this may be anomalous due to the presence of kink band chevron folds on thrust faults. Vari-colored shales and siltstones occur at the base in a gradational contact with the interbedded shales and sandstones of the Tuscarora Formation. The Rose Hill Formation consists mainly of buff/brown to khaki colored shales with minor silt interbeds. The high illite content in the shales enhances the slaking properties of these shales and their conversion into sticky mud.

Two distinct and separate structural domains are apparent on the mesoscopic scale. Fortunately these two domains coincide with the construction sections designated C-12 for the western slopes of Bald Eagle Ridge and A-12 for the eastern slopes (see Figure 1). Bedding attitudes range from 30° NE to 30° SW on the west facing slope (C-12 section), to steeply dipping overturned in the main A-12 road-cut. The general attitude for the Juniata and Bald Eagle strata is 070°/80° (overturned), and the relatively tight cluster (Figure 3) is consistent with steeply dipping beds in a relatively uniform monoclinal setting. In contrast, bedding attitudes for the C-12 domain define two maxima (Figure 4) with S-poles distributed along a steeply dipping great circle (a p girdle), whose pole, ß (5°/060°) defines a fold axis. This is the domain of the chevron folds with an interlimb (dihedral) angle of 84°. These settings are depicted in conceptual structural models in Figure 5, where the structural discordance of the Tuscarora Formation beds is accommodated in a kink band splay thrust setting.

Epigene Veins
Sulfide-bearing veins are by far the most abundant and occur as steeply dipping, cross-strike sets oriented generally SSE. Quartz, and calcite veins occur marginal to the high concentration of sulfide veins exposed in the road-cut through the Bald Eagle Formation. A few thin veins of early quartz covered by later pyrite have been found near the contact of the Bald Eagle and Juniata formations. One vein with barite as a major constituent is exposed in the Juniata red-beds in the western road-cut near station 867+60. Wavellite was identified in a sample of Tuscarora quartzite float picked up during construction near station 840+00.

Amongst the trace elements zirconium is uniformly high (63 to 315 ppm). Surprisingly the values for vanadium (0.5 to 44 ppm) and gold (0.2 to 11 ppb) are unexpectedly low. As expected the base metals, copper (8 to 50 ppm), lead (7 to 430 ppm) and zinc (7 to 753 ppm) correlate positively with sulfur content for samples from the Bald Eagle sandstone sites, but not for the pyritic rock in the Tuscarora quartzite (station 859+10 in section C-12). An elevated barium value of 138 ppm is consistent with the presence of barite in nearby veins.

Veins in the "red-beds" of the Bald Eagle and Juniata formations are much less common than in the green Bald Eagle beds, but are more easily discerned because of the green REDOX halo surrounding them. In addition to sulfides (mainly pyrite), sulfate (barite) is present in one vein near station 876+50. The reduced zones contain many fine veins that are seen to cluster around a fault with an irregular surface. Undoubtedly the fault and the veins were the conduits for reducing fluids; reduction zones vary from 10's to 100's feet thick, and locally follow stratigraphic horizons (usually more porous sandy beds).

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