Geology of the Greater Trenton area and its impact on the Capitol City

Twenty Seventh Annual Meeting
Geological Association of New Jersey
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Field Guide and Proceedings
Edited by

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U.S. Geological Survey

New Jersey State Museum, Trenton, N.J.

Front Cover: Photograph of New Jersey State Capitol and Falls of the Delaware at high tide. Photo taken from the flood levee in Morrisville, PA.

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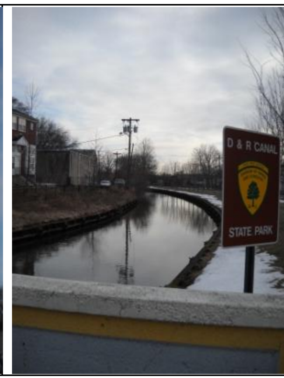

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Chapter 9

Geology of the Pennington Trap Rock (Diabase) Quarry, Mercer County

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Introduction

The purpose of this field stop is to visit the Pennington Trap Rock quarry where crushed stone products of Jurassic diabase are quarried, processed, and sold. Stratigraphic and structural features exposed in the 3rd level of the quarry will be examined and agate (banded cryptocrystalline silica), jasper (colored and massive cryptocrystalline silica), and opal (hydrous amorphous silica) from some late-stage hydrothermal veins will be collected. The term 'trap rock' refers to Early Jurassic igneous rocks in the region, including the intrusive diabase sheets and dikes, and the extrusive basalt flows. The focus of this stop and discussion is diabase.

Geological Setting

The Pennington Trap Rock quarry is located in Pennington Mountain in the center of the Newark basin (fig. 1). The Newark basin is one of a series of tectonic rift basins of Early Mesozoic age formed on the eastern North American plate margin during the breakup of the supercontinent Pangaea preceding formation of the Atlantic Ocean. The basin covers about 7500 km^2 and extends from southern New York across New Jersey and into southeastern Pennsylvania (fig. 1). Its filled with Upper Triassic to Lower Jurassic sedimentary and igneous bedrock that is fractured, faulted, tilted, and locally folded (see summaries in Schlische, 1992, 2003; Olsen et al., 1996a). Rifting in the Newark basin region probably began during the Middle Triassic and intensified during the latest Triassic and into the earliest Jurassic as evidenced by widespread igneous activity and a marked increase in sediment-accumulation rates (de Boer and Clifford, 1988; Schlische, 1992). Tectonic deformation and synchronous sedimentation in the region continued into the Middle Jurassic, at which time extensional faulting and associated folding became less-widespread, or may have ceased. Some time afterwards, the basin began a period of post-rift contraction, uplift and erosion (basin inversion) similar to that of other Mesozoic rift basins on the eastern North American continental margin (de Boer and Clifford, 1988; Withjack and others, 1998; Olsen and others, 1996a).

Extension fractures in the basin, including unmineralized joints and mineralized veins formed in three, overlapping groups (S1-S3) that record a counterclockwise strike progression including an early, border-fault orientation (S1; N045^{o}-060^{o}E), an intermediate intrabasin-fault orientation (S2; N015^{o}-030^{o}E) and a late stage (S3; N10^{o}W-N10^{o}E) set (fig. 1 and Herman, 2009a). All sets are paired with orthogonal cross joints, and the latest cross-fracture set (S3C; N80^{o}E-N110^{o}E) shows localized mineralization in fracture interstices and maybe dilation in response to ~ E-W compression at some late stage during the basins history. The directions of current crustal compression (CCC) and current plate-motion (CPM) are shown in figure 1.

The Pennington quarry is located within a kilometer of the trace of the Hopewell fault in the northern part of Mercer County (figs. 2 and 3). The Hopewell fault is a major, intrabasin, normal fault cutting the central part of the basin. In the vicinity of Pennington Mountain, the strike of the Hopewell fault departs from the regional strike of about N50^{o}E and includes segments that strike about N30^{o}E to N80^{o}E (fig. 2). The fault is interpreted to dip at moderate

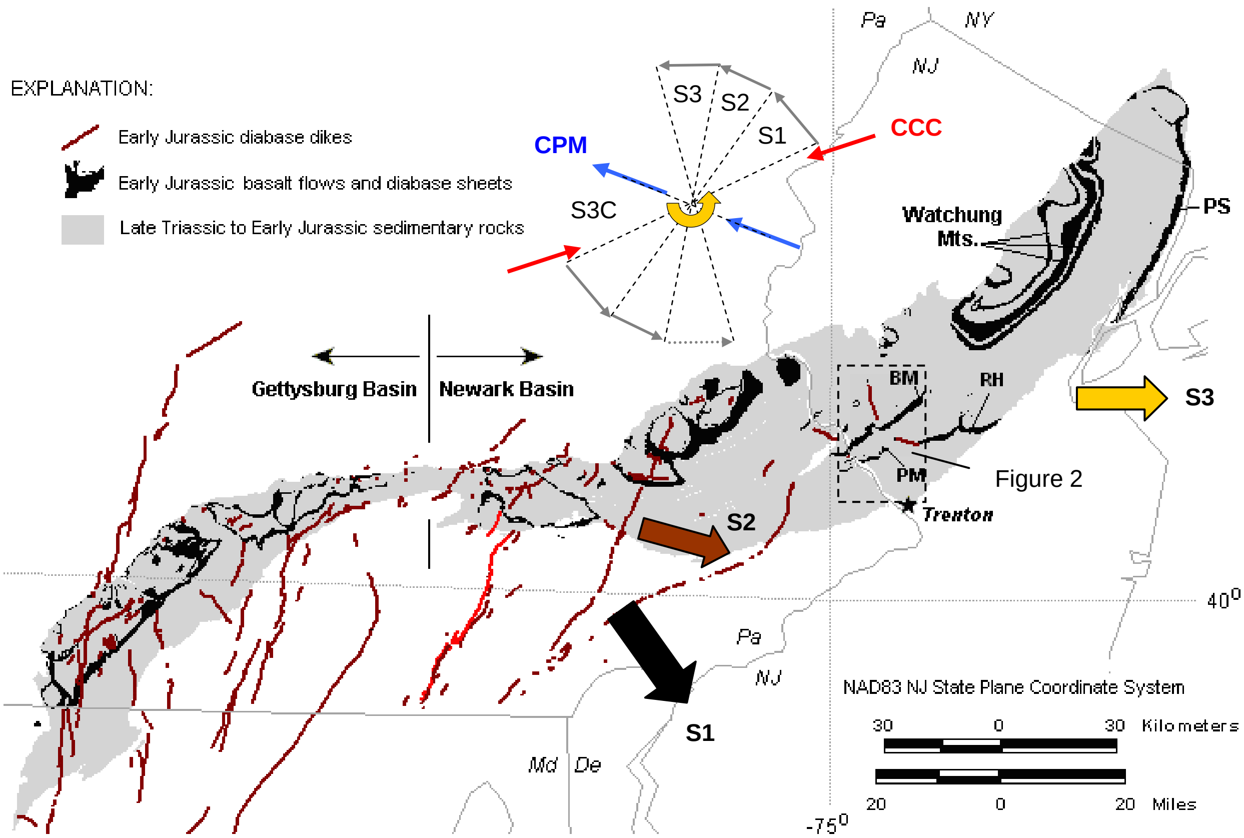

Figure 1. Generalized geologic map of the Newark and Gettysburg basins showing the distribution of Early Jurassic diabase and basalt (trap rock) in Maryland (Md), Pennsylvania (Pa), New Jersey (NJ) and New York (NY). Diabase sheets and dikes occur throughout the region, whereas basalt flows are mostly restricted to the area of the Watchung Mountains. The rotation of the progressive, extensional strain field from the Late Triassic through the Early Jurassic was counterclockwise from S1 to S3. PM – Pennington Mountain, PS – Palisades Sill. Belle Meade quarry, RH – Rocky Hill quarry. CPM – current plate-motion vector, CCV– current crustal compression

(45^o-59^o) angles to the south, with the hanging wall having dropped downward with over 5 kilometers of dip-slip movement (Drake and others, 1996). The amount of strike-slip movement on the fault is uncertain.

Schlische and Olsen (1988) described the Flemington and Hopewell faults as having developed late in the extensional history of the basin because strata cut by the fault lack thickness changes across the fault. Rocks close to the fault, especially in the hanging wall, are highly strained with many fractures, mineral veins, folds, and faults. The faults are composed of systematic networks of branching and splaying shear zones that include mineralized breccias and shear planes that cut late-stage leucocratic dike, hydrothermal veins, and joints. Compositional layering and fractures are commonly crumpled, folded and sheared.

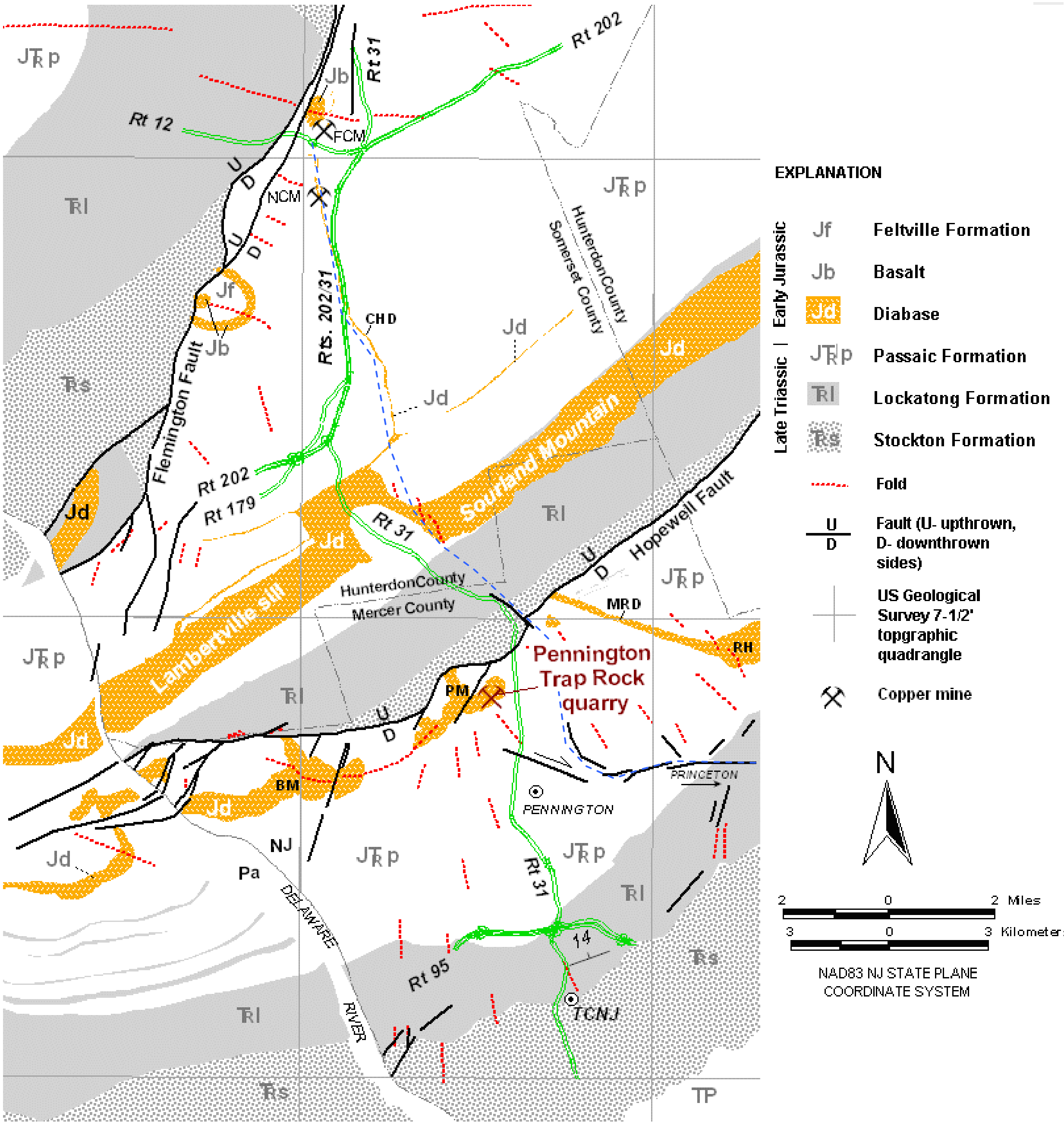

Figure 2. Geologic map in the central part of the Newark basin along Rt. 31 from Trenton to Flemington showing the location of the Pennington trap rock quarry. The blue dashed line that parallels the Copper Hill dike traces a suspected, late-stage pull-apart structure that cuts across strata and early faults. BM – Baldpate Mountain, CHD – Copper Hill dike, FCM – Flemington copper mine, MRD – Mount Rose dike, NCM – Neshanic copper mine, PM - Pennington Mountain, RH – Rocky Hill sill, TCNJ – The College of New Jersey.

Trap Rock Background

During the period of continental breakup and associated igneous activity, many diabase dikes intruded large extensional cracks in the Earth's crust and ultimately resulted in the extrusion of

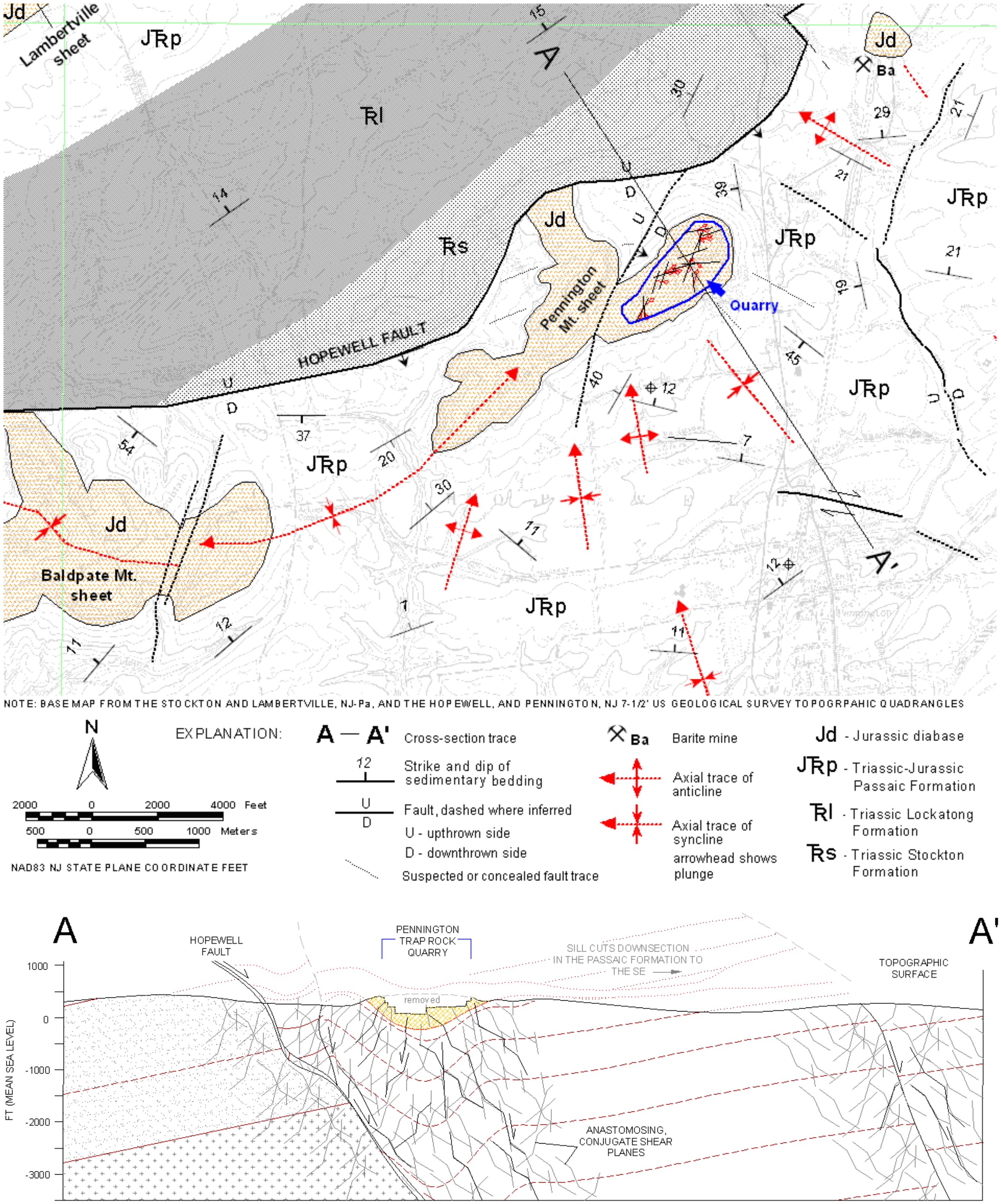

Figure 3. Geologic map (above) and cross section (below) in the area of the Pennington Trap Rock quarry, Pennington, NJ. Measured features in the quarry including fault-slip directions are detailed in figures 5, and 6, and table 1. The Pennington Mountain diabase sheet and the Pennington trap rock quarry sit in the hanging wall of the Hopewell fault, a large normal fault with late, strike-slip movements. Braided, splaying, and branching shear planes form close to the fault to accommodate crustal extension, subsidence, and warping in a collapsing basin.

flood basalts on land surface during an estimated 580 ky time span (Olsen and others, 1996b). The combined basalt and diabase and rocks preserved in the basin are commonly called “trap rock” because of the distinct, systematic columnar joints formed in these rocks from slow cooling following emplacement at or near the land surface. These fractures sometimes resemble blocky stair steps (fig. 4) and the “trap” adjective is thought to have originated from a Scandinavian noun "trappa” (stair) or trappasteg" (stairstep), according to Wikipedia.

In the Newark basin, the basalts are extrusive flows that are interbedded with Early Jurassic sedimentary rocks, mostly in the area of the Watchung Mountains, whereas diabase occurs as thin dikes and thin-to-thick sheets, or sills, that cut up through and intrude into Late Triassic sedimentary rocks. Diabase dikes commonly extend outside of the basin in Pennsylvania and Maryland where they also cut into the surrounding Precambrian and Paleozoic basement rocks (fig. 1).

Much previous work has been done on characterizing the trap rocks with respect to their locations, mineralogy, and commercial usages. Johnson (1957) covered the geological setting of the New Jersey trap rocks during a Geological Society of America field trip originating

Figure 4. West view of diabase layering and columnar jointing in the western rock face, 3rd quarry level at station 77916 (fig. 5). Layering is about 2 to 15 m thick and dips steeply from the upper right to the lower left (~N094E/80S) with polygonal cooling joints (below) formed in each set of layers and generally oriented at high-angles to layered contacts. The density of fracturing varies among and within layers. Most fracture surfaces are slickensided shear planes that locally form sigmoid structures (S - white dotted line), suggesting that cooling and slip may have been contemporaneous. No compositional differences were seen between the more massive and finely fractured intervals within the same layer, but different layers locally vary in both composition and texture.

out of Atlantic City, NJ. He noted then, that these rocks had been quarried for over 100 years for road metal, railroad ballast, aggregate, rip-rap and jetty stone based on properties such as their weight, reactivity, resistance to abrasion, and bonding characteristics. He also noted that because of their resistance to erosion, they typically form topographic highs that favor quarrying with faces and benches. He commented on the ever-increasing demand for trap-rock stone products to meet the needs of extensive industrialization, an expanding highway system, and to help in the continuing battle of beach erosion, despite unfavorable zoning restrictions on quarrying and the encroachment of residential districts.

With respect to the composition, texture, and structure of diabase, the first geologic studies on diabase in the New Jersey area were focused on the Palisades sill (fig. 1) because of its prominent exposure along the banks of the Hudson River. These outcrops led Lewis (1908) to characterize the diabase as dark gray to medium gray rock with locally developed greenish tints developed in the altered chloritic parts. He also reported the occurrence of an olivine-rich layer near the base of the sheet due to gravity-induced magmatic differentiation, horizontal sheeting in the sill near the upper and lower contacts, and sets of steeply-dipping joints and faults striking primarily N-S and orthogonal cross joints that are prominent from Jersey City northward. Hotz (1952) found that a typical diabase sheet has the gross shape of a saucer with upturned margins; geometry later illustrated by Husch (1990) for the Palisades sill and related diabase sheets in the Newark basin.

Johnson (1957) characterized the mineralogy of the "typical diabase" as consisting of augite, plagioclase feldspar, quartz, orthoclase and magnetite "in that order of abundance", except for an olivine lens, that consists of nearly pure, granular olivine. Froelich and Gottfried (1985) pointed out that up until about 40 years ago, lower Mesozoic diabase intrusive rocks in the Eastern United States were considered essentially uniform in chemical and mineralogical composition. However, detailed geochemical studies of diabase in North Carolina (Weigand and Ragland, 1970) and Pennsylvania (Smith and Rose, 1970; Smith and others, 1975) found unique chemical signatures among the different dikes and sheets, including olivine-normative and quartz-normative tholeite compositions, the latter type including high and low TiO_2 varieties.

Husch and others (1988) conducted detailed geochemical and petrologic studies of a number of diabase sheets in the central part of the Newark basin, including samples of the Pennington Mountain diabase from the Pennington trap rock quarry. They concluded that these diabase sheets evolved from quartz-normative, high-titanium tholeitic magmas that were selectively contaminated by surrounding country rock. They found evidence of multiple magma injections in individual sheets, and proposed that residual magmas enriched in quartz and alkali feldspar were displaced horizontally and vertically in the crust by ensuing magmatic pulses. They also found consistent and homogenous chill-margin compositions and a spatial relationship where pyroxene-laden cumulate layers occur in sheets occupying the lowest stratigraphic positions in the Triassic section, whereas highly-fractionated, coarse-grained granophyres occur at higher stratigraphic levels (such as with the Pennington Mountain sheet). They proposed that the classic petrogenetic model of olivine-dominated, vertical fractionation was not supported by the available geochemical, petrographic, and structural data. Rather, the occurrence of the olivine cumulate layer of the Palisades sill may have formed as a separate intrusion of a distinct magma type, perhaps stemming from deep crustal fractionation of a high-titanium, quartz normative magma, leaving behind a residual melt enriched in olivine and parent magma to that part of the Palisades sill.

Mason (1960) conducted a detailed mineralogical study of the trap rock minerals in New Jersey as a curator of physical geology and mineralogy with the American Museum of Natural History in New York City. This work included a list of active quarries then, detailed petrographic (microscopic) and X-ray analyses of mineral associations in the rock and in rock voids. He found the mineral association in the intrusive trap rocks to be the same as reported by Schaller (1932) which include:

1) Solidification of magma and initial cooling,
2) Residual melts become saturated with silica, which locally replaces and alters the primary rock,
3) Water is added from the outside and residual melts become saturated in lithophile elements, including calcium and aluminum, forming minerals such as prehnite, that marks the prehnite-pumpellyite metamorphic facies characterized by 250^{o} - 300^{o} C and pressures on the order of 2-7 kb (~7-20 km depth),
4) More water is added with more lime (Ca) and soda (Na) and zeolite minerals form, and
5) Late-stage calcium carbonate (calcite) period.

Puffer and Horter (1993) describe the occurrence of pegmatite segregation veins in the Watchung basalt and relate their formation to downward propagation of columnar joints through rigid barriers capping accumulating, water-enriched, segregated melts during the magmatic solidification process. These veins are aligned in the plane of compositional layering and are different from the hydrothermal veins crosscutting layering (S0) in the diabase. Different types of leucocratic, magmatic dikes and hydrothermal veins are found cutting diabase layers. Laney and others (1992) detail leucocratic dikes that were injected into and cut the diabase sheets that were probably derived from residual granophyric magmas produced by crustal fractionation. Mineral veins are reported in the diabase sheets within the many Newark-type basins along the eastern coast of North America (Walker, 1940; Robinson, 1988; Puffer and Peters, 1974; Laney, 1992; Laney and others 1995; among others). Many different mineral associations are reported including albite, calcite, chlorite, clinopyroxene, epidote, magnetite, oligoclase, prehnite, pyrite, quartz, sericite, and sphene, among others. Steckler and others (1993) reported that relatively high temperature hydrothermal systems operated in the Newark basin through the Early Jurassic, with most of the exposed strata cooled below ~220^{o}C at 180 Ma (Late Jurassic) and ~100^{o}C at 140Ma (Early Cretaceous).

Stratigraphic and Structural Notes on the Pennington Trap Rock Quarry

We visited the trap rock quarry on three days in 2004 and 2010 to collect geologic notes as part of a geological mapping effort in the Pennington 7-1/2’ topographic quadrangle, and to prepare this field stop for GANJ. Structural measurements of compositional layering, fractures, dikes, veins, and faults were taken at a number of spots in the quarry (figs. 5, 6 and table 1).

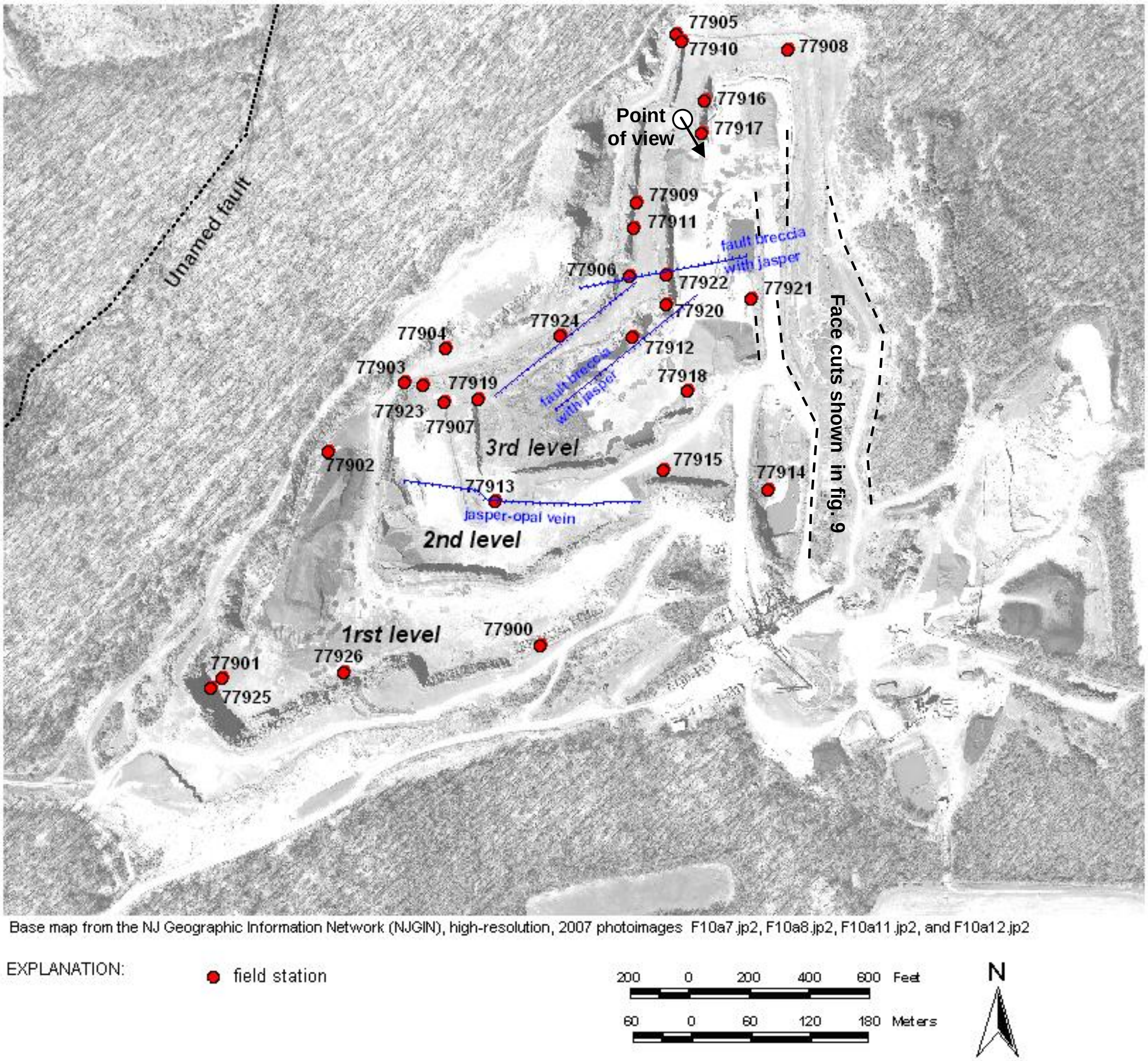

Figure 5. Aerial photograph of the Pennington trap rock quarry showing the location of geologic field stations and a panoramic perspective (fig. 6). This field stop focuses on features exposed in the western walls of the 3rd level.

X-Ray diffraction and microscopic analyses of the minerals associated with the diabase, dikes, and veins were conducted in 2010 in laboratories of the NJ Geological Survey.

The diabase here is medium-grained common diabase to coarse-grained granophyric diabase that is highly strained with complex structures resulting from repeated episodes of dip-slip and strike-slip movement along the Hopewell fault. More detailed mapping is needed to more fully characterize the exposed stratigraphic and structural features. Layering is complex and highly strained. We found sheeted magma layers about 1 to 15 m thick with varying compositional textures that were intruded along complex and locally conjugate flow paths, with some layers pinching out along other layers (fig. 7b). Layers dip gently to steeply in many directions (fig. 8), and are locally sheared and folded by faults striking NE-SW, N-S, and

Table 1. Structures mapped in the Pennington Trap rock quarry; March 3, 2004, June 11, and August 27, 2010

Structures by Station	Plane strike/dip	with Lineation plunge/trend and movement sense, if any if determined
STATION 77900		
Leucocratic vein	019/87S	
Leucocratic vein	012/87S	
Early normal fault	048/87S	
Leucocratic vein	130/87NE	
Leucocratic vein	124/85N	
STATION 77901		
Mineralized shear plane	026/70S	with slickenlines 52/164 normal, right lateral and 10/160
Mineralized shear plane	176/52W	with slickenline 25/165 normal
Leucocratic extension vein	101/60S	
Leucocratic extension vein	072/60N	
Fault with breccia and Mineralized shear plane	055/72S	with slickenline 50/197
STATION 77902		
Mineralized, polished shear plane	012/58S	
Mineralized, polished shear plane	020/58S	with slickenline 58/095 normal
STATION 77903		
Mineralized shear plane	049/77S	with slickenline 4/058 left lateral
cut by fault	015/30S	with slickenline 25/080 normal, right lateral
STATION 77904		
Mineralized (epidote) shear zone	063/82N	
Calcite vein	090/82N	
STATION 77905		
Layering	045/50S	
Joint	074/65S	
Joint	050/85N	
Joint	060/60S	
Mineralized (epidote) shear plane	035/28S	with slickenline 28/125 normal
Mineralized (epidote) shear plane	075/62S	with slickenline 42/088
Mineralized (epidote) shear plane	080/45S	with slickenline 2/090 (left lateral?)
Mineralized (epidote) shear plane	058/82S	with slickenlines 10/58 normal and 80/147 strike slip
STATION 77906		
Mineralized (epidote) fault zone	106/90	
Mineralized shear zone with malachite (copper carbonate)	104/80N	
Mineralized shear plane	018/76S	with slickenline 11/192
STATION 77907		
Mineralized shear zone	065/52N	
Mineralized shear zone	075/60S	with slickenline 5/069 right lateral
STATION 77908		
Joint	058/59S	
Vein (calcite?)	100/86S	
STATION 77911		
Mineralized shear plane	070/57N	with slickenline 3/055 right lateral
STATION 77913		
Mineralized (light-blue opal) vein	090/65-76N	

Table 1 (Continued). Structures mapped in the Pennington Trap rock quarry, March 3, 2004, June 11, and August 22, 2010

Structures by Station	Plane strike/dip	with lineation plunge/trend and movement sense, if any
STATION 77914		
Joint	010/80N	
Joint	010/65S	
STATION 77915		
Leucocratic-feldspathic dike	004/78E	
Mineralized shear plane	175/82/E	with slickenline 38/010 normal, oblique slip
STATION 77916		
Layering	094/80S	
Mineralized shear plane	005/35E	with slickenlines 25/075 and 26/090 normal, oblique slip
Mineralized shear plane	025/80E	
Mineralized shear plane	010/55E	
STATION 77917		
Leucocratic vein	100/88S	
Leucocratic vein with calcite	051/80S	
STATION 77918		
Layering	038/80N - 055/80S	
Fault with breccias and veining	055/85S	
STATION 77919		
Layering	020/46E	
STATION 77920		
Mineralized (epidote) shear plane	090/88N	
Vein with Jasper	090/80N	
STATION 77921		
Leucocratic-feldspathic dike	076/76N	
STATION 77922		
Fault breccias with Malachite and jasper	080/82N	
STATION 77923		
Fault breccias	050/90	
Mineralized (chlorite) shear plane	075/76S	with slickenline 11/090 right lateral
STATION 77924		
Fault with breccias (epidote)	035/69S	
Fault with breccias (epidote, calcite Brown jasper and light-blue opal)	050/40S	
Mineralized (epidote and calcite) Shear plane	050/40S	with slickenline 3/050 strike slip
Mineralized (epidote) shear plane	076/70S	
Mineralized (epidote) shear plane	030/64S	
STATION 77925		
Leucocratic (calcite) vein	128/86S	
Layering (compositional)	000/65W	
Layering (compositional)	032/60N	
Fault (anastomosing shear zone)	042/85S	
Fault (anastomosing shear zone)	055/85S	
STATION 77926		
Leucocratic (feldspathic) dike	105/62S	

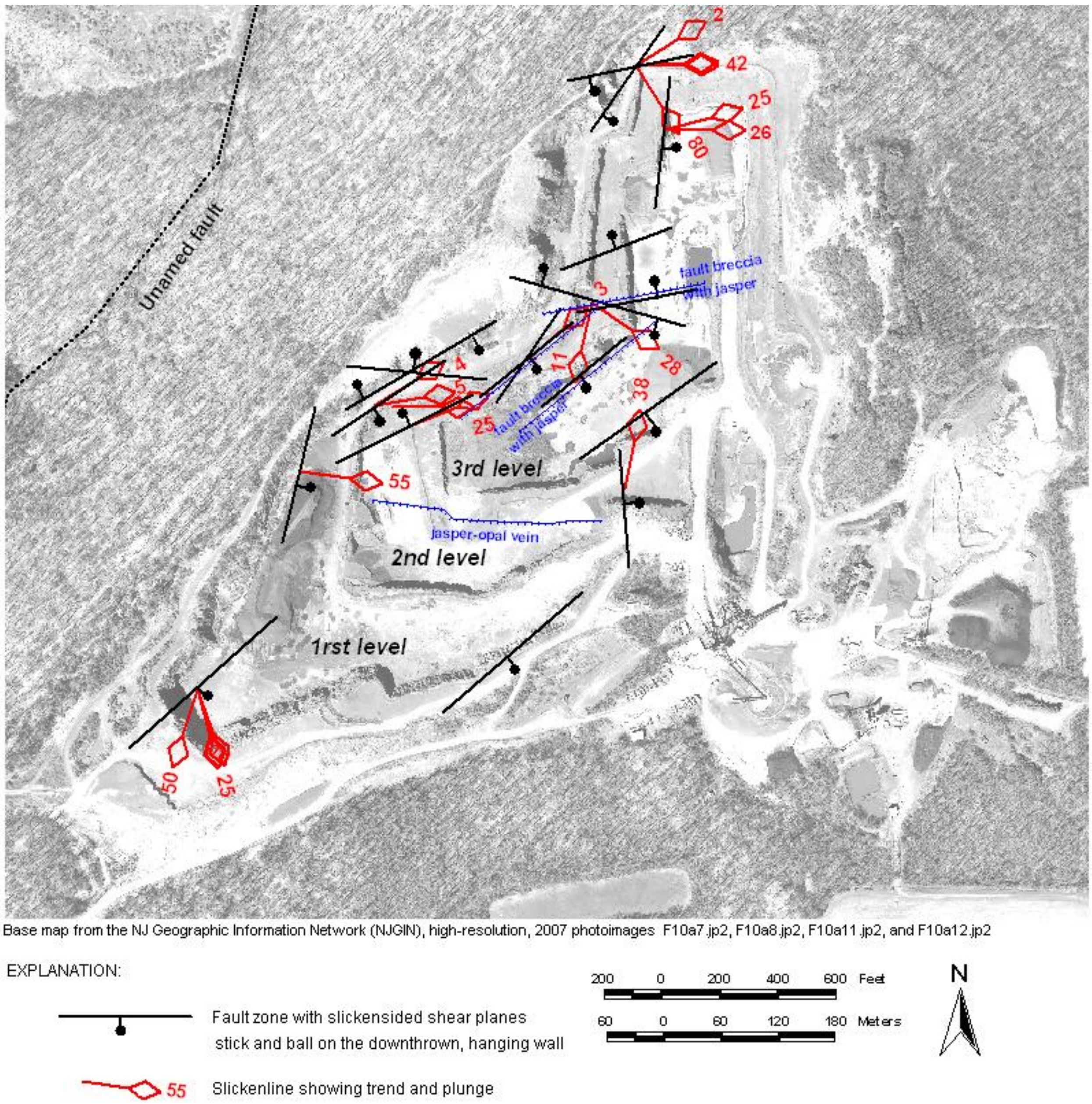

Figure 6. Some geologic faults and slip directions measured in the Pennington Trap Rock quarry at the stations noted in figure 5.

E-W that cut the quarry in many places (fig. 6 and table 1). Therefore, layers typically show much brittle deformation and locally form warped, steep, tall colonnades in open faces (fig. 7a).

Partially and unmineralized extension fractures (joints) show plumose structures on excavated surfaces (Herman, 2005) and are locally cut by shear planes showing normal dip-slip and strike-slip movements (fig. 9). In many places, polygonal joints are coated by iron-oxide minerals, and locally form in sigmoid alignment (fig. 4), suggesting that they formed when the diabase was both cooling and shearing. Joints that occur near shear zones commonly show

Figure 7. Examples of diabase layering. A. Warped and fractured diabase layers dip steeply west in a face cut on the East side of the first level of the quarry. Each layer has a thick base and polygonal jointed upper sequence that truncates against the base of the next layer. Note the curved extension fractures cutting the layers on the right. Dave Hall is looking north. B. Larry Mueller (left) and John Dooley (right) inspect unconformable layers along the north side of the quarry, 2nd level near station 77910. Layers are dipping steeply East (right). Dashed line traces the break in layering.

Figure 8. Panoramic view looking SE from the point of view noted in figure 5. Layers of magma caused by magma pulses are highlighted using white line in open faces on the 2nd and 3rd levels. The layering dips both NW and SE but is locally folded and cross cut by faults and shear zones.

Figure 9. Steeply-dipping, slickensided shear planes showing oblique-normal slip.
A. Dark, chloritic shear planes striking/dipping ~N20°E/80°E (S2) are highly-polished with sub horizontal, tool & groove slickenlines indicating right-lateral strike slip.
B. Epidote and calcite mineralized shear planes are highly grooved with striae, or ‘slickenlines’ showing normal-oblique slip . Many smaller shear planes branch and splay off of the larger planes within the shear zones. Light-blue, botryoidal opal coats depressions on the exposed shear-plane faces and is the latest mineral phase filling voids within the shear zones (box below and fig. 16A). An early, hydrothermal (quartz-feldspar-calcite) vein seen in the lower right hand corner (arrow) is cut by the shear plane.

evidence of minor slippage, having striated surfaces with thin mineral selvages of chlorite, epidote and then calcite. Joints are sometimes folded, or kinked with sharp fold hinges and straight, planar limbs.

Leucocratic, late-stage, magmatic dikes cut the diabase in a few places (fig. 10). These dikes range in thickness form a few centimeters to less than a meter thick, and occur in extension fractures cutting sharply across magmatic layering. In some places, they form in en echelon, brittle fracture arrays. They are medium- to light-pinkish gray containing plagioclase feldspar, pyroxene, and epidote. X-ray analysis of one sample showed that plagioclase is both albite and anorthite. These dikes have alteration rinds up to an inch or two thick (fig. 10B) and are locally sheared along their contacts with the diabase. These dikes are cut by the brittle faults. Laney and others (1995) and Walker (1940; 1969) reported sodic leucocratic dikes that intrude diabase elsewhere in the basin.

A few different types of hydrothermal veins also cut the diabase. These veins include: 1) quartz-feldspar-calcite veins, 2) calcite veins, and 3) chalcedony and opal veins. The first type show complex mineral banding of quartz, feldspar and calcite and pronounced wall-rock alteration rinds (fig. 11A). These veins have quartz cores that are flanked by plagioclase feldspar, then calcite concentrated along the vein walls. They also have sulfide minerals associated with the silica minerals (fig. 11B). The calcite veins occur in systematic, en echelon fracture swarms (fig. 12) that probably post-date the veins containing quartz and feldspar. The early, banded veins of quartz and feldspar with overgrowths of calcite may represent reactivated vein growth concurrent with the period of calcite veining. However, no interactions were seen between the different vein sets.

The chalcedony and opal veins also include different types. An extension vein at station 77913 (fig. 4 and table 1) is filled with about 2 to 10 cm of chalcedony in the form of a orange-brown jasper (fig. 13) and white to light gray agate (fig. 14). This vein strikes ~E-W and curves from dipping steeply north to south, and shows little fault slip. The core of the vein varies in thickness up to about 8 cm where it's filled with massive orange-brown jasper containing translucent, streaks of clear chalcedony or opal (fig. 13B) and veinlets of similar looking material. We have yet to inspect them petrographically. Other parts of this vein core are banded or streaked, brown-black jasper, or agate, depending upon if the banding accreted gradually or was rapidly chilled upon injection with preserved flow structure. This also needs further inspection. Open voids and within this vein show overgrowths of medium gray agate and late pyrite (fig. 14C). Malachite ($Cu_2CO_3(OH)_2$) also occurs along fracture walls in altered diabase. Dark gray and brown chalcedony (jasper) also occurs as smeared accretions in the cores of epidote-and-calcite mineralized shear planes within larger shear zones (fig. 1). These zones show similar hydrothermal alteration and associated iron, sulfide, and copper mineralization.

Light blue opal occurs on large shear planes, cored by the chalcedony and oriented along S1 and S3C orientations (table 1 and fig. 5). The blue opal coats extended pockets within fault horses and diabase blocks that are splayed and separated by faulting (fig. 9B and 16A). The epidote-green, slickensided shear planes (figs. 9B and 16B) that locally form open faces shows spotty coatings of the light-blue, botryoidal opal laying in vugs and depressions on the shear planes (fig. 16B). The light-blue opal coating postdates normal dip-slip movements (fig. 16B).

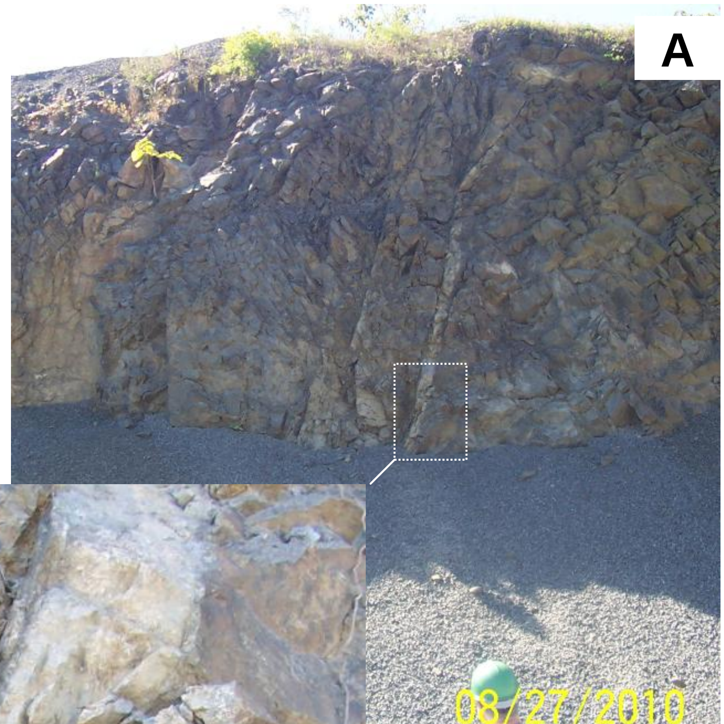

Figure 10. Leucocratic, feldspathic dike cutting the diabase. This dike, at station 77915 (fig. 4), is about 1 ft thick and strikes/dips ~N4^{o}E/78^{o}E. It is sheared along its eastern contact with the diabase (table 1). The dike has a one- to two-inch alteration rind along the diabase contact. This is visible in the upper part of 10B.

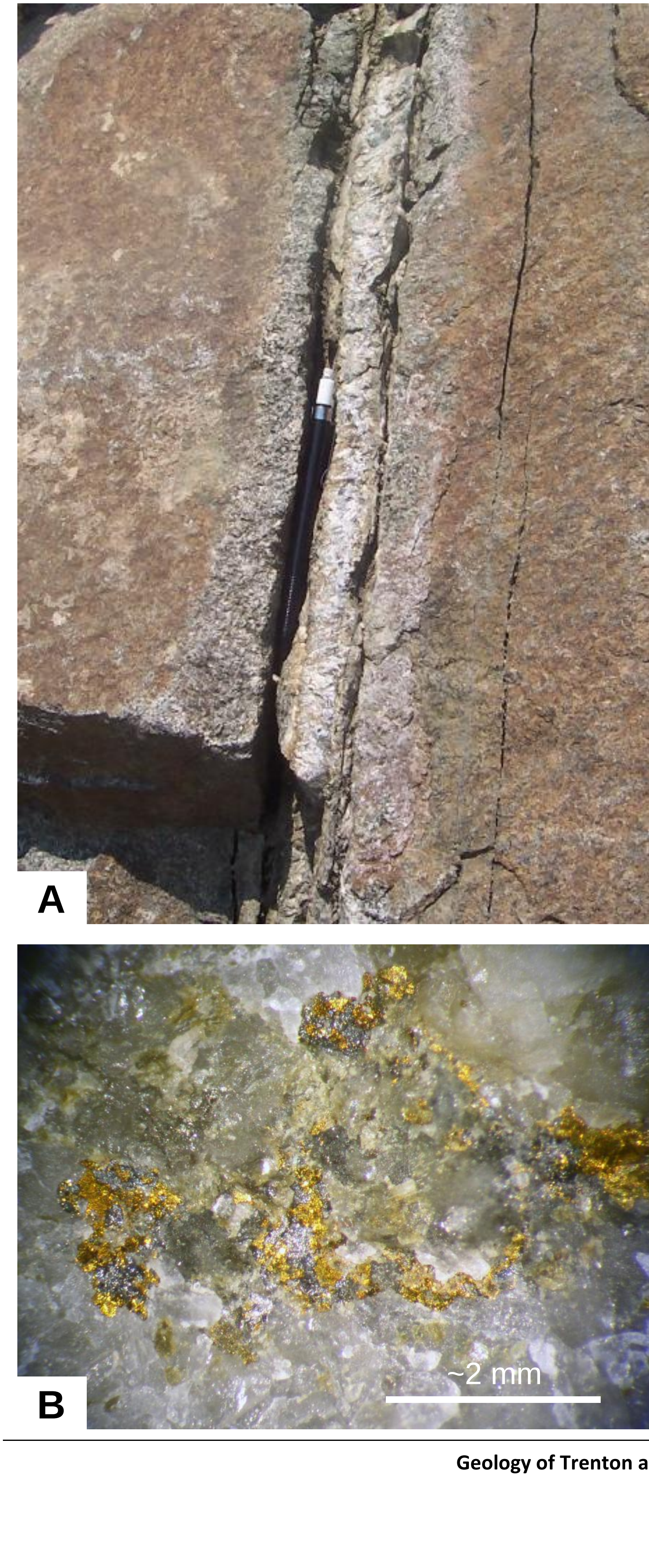

Figure 11. A. Hydrothermal, complexly banded quartz, plagioclase feldspar, and calcite vein showing wall rock alteration rinds. Note the pencil for scale, and the parallel, en echelon fractures immediately to the right of the vein that are partially mineralized. A vein core of quartz is flanked by feldspar and then calcite.
B. Sulfide minerals associated with the quartz-feldspar-calcite veins. Chalcopyrite ($CuFeS_2$ - bright yellow) surrounding chalcocite (CuS_2 - gray and silver).

Figure 12. Hydrothermal calcite veins at station 77925 striking/dipping ~N128°E/78°SW. They show alteration (bleaching) of the wall rock. These veins commonly occur as systematic swarms of cross fractures with fracture densities of about of 2-5 per meter measured normal to the vein plane. They locally form large, continuous and expansive surfaces in the quarry face cuts as seen at high elevations in the first level of the quarry. Field book for scale.

The mineralized shear planes in some places have both dip-slip and strike-slip striae on the same plane (table 1), with those having oblique and strike slip overprinting and postdating those with dip slip. These polished, chlorite and epidote-calcite mineralized shear zones (fig. 9) include strike-slip duplexes with many splaying, interconnecting and anastomosing shear planes similar to those reported cutting the Lambertville sill about 10 km north, and in another diabase quarry near the Hopewell fault at Belle Meade, NJ (Laney and Gates, 1996). Some of the striated fault blocks show the green (epidote) mineralized shear planes cutting hydrothermal veins that are also striated (fig. 16B). In general, the complex shear planes show early dip-slip movement along S1 (N045°E-N066°E) strikes that are cut by and reactivated by later S2 and the last S3-SC3 faults (fig. 17).

Discussion

The stratigraphic, structural and mineralogical aspects of the Pennington Mountain diabase are very complex and warrant further inspection. The absolute timing of diabase emplacement and faulting in the basin is unclear, but Schlische and Olsen (1988) suggest that the intrabasin faulting post-dates the Early Jurassic Feltville Formation. The Feltville Formation is the Early Jurassic shale, siltstone and sandstone sequence sandwiched in between the first (lower) and second (middle) Watchung flows. If intrusion of diabase spanned the entire time interval (~570 ky) during which the Watchung Mountain basalts were extruded (Olsen and

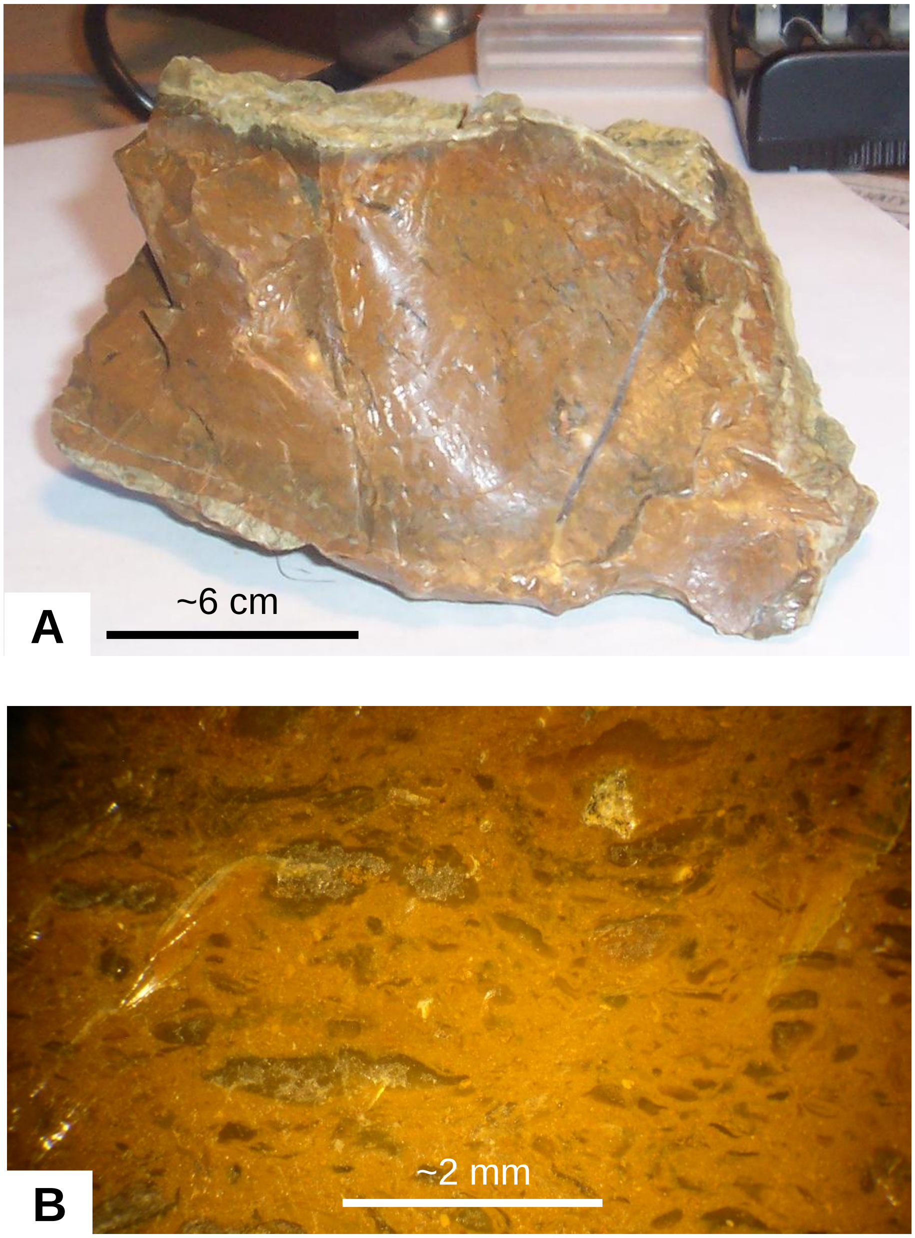

Figure 13. Photographs of the orange-brown jasper from station 77913. A. Hand sample of the vein-fill material showing the entire width of the vein and clear silica streaks and cross cutting veinlets (right side). The jasper is glassy and conchoidally fractured.
B. Photomicrograph of the jasper's internal texture . Transparent, light- to medium gray silica granules are entrained within the more iron-rich matrix of the jasper. Elsewhere, the veins fill includes dark gray to dark brown jasper with streaky flow banding.

others, 1996b) then intrabasin faulting postdating the Feltville Formation would allow ample time for diabase emplacement and faulting to overlap. Stratigraphic and structural evidence from the Pennington Trap rock quarry appears to support at least synchronous cooling and shearing of the diabase (fig. 4).

All three sets of extensional fractures (Herman 2009) and faults mapped in the basin are found in the quarry (fig. 6 and table 1). The strike of the different fracture sets, together with the recorded slip lineation (fig. 6) show that the hanging wall of the Hopewell fault was first subjected to southwest stretching and normal dip slip (S1), then was wrenched and down dropped eastward (S2, S3 and S3C), deforming and reactivating early structures (fig. 17). The S3C structures in the quarry striking E-W have steep dip angles and are part of a larger, regional oblique-slip transform-fault system involving strike-slip faults near Princeton to the east (figs. 2)

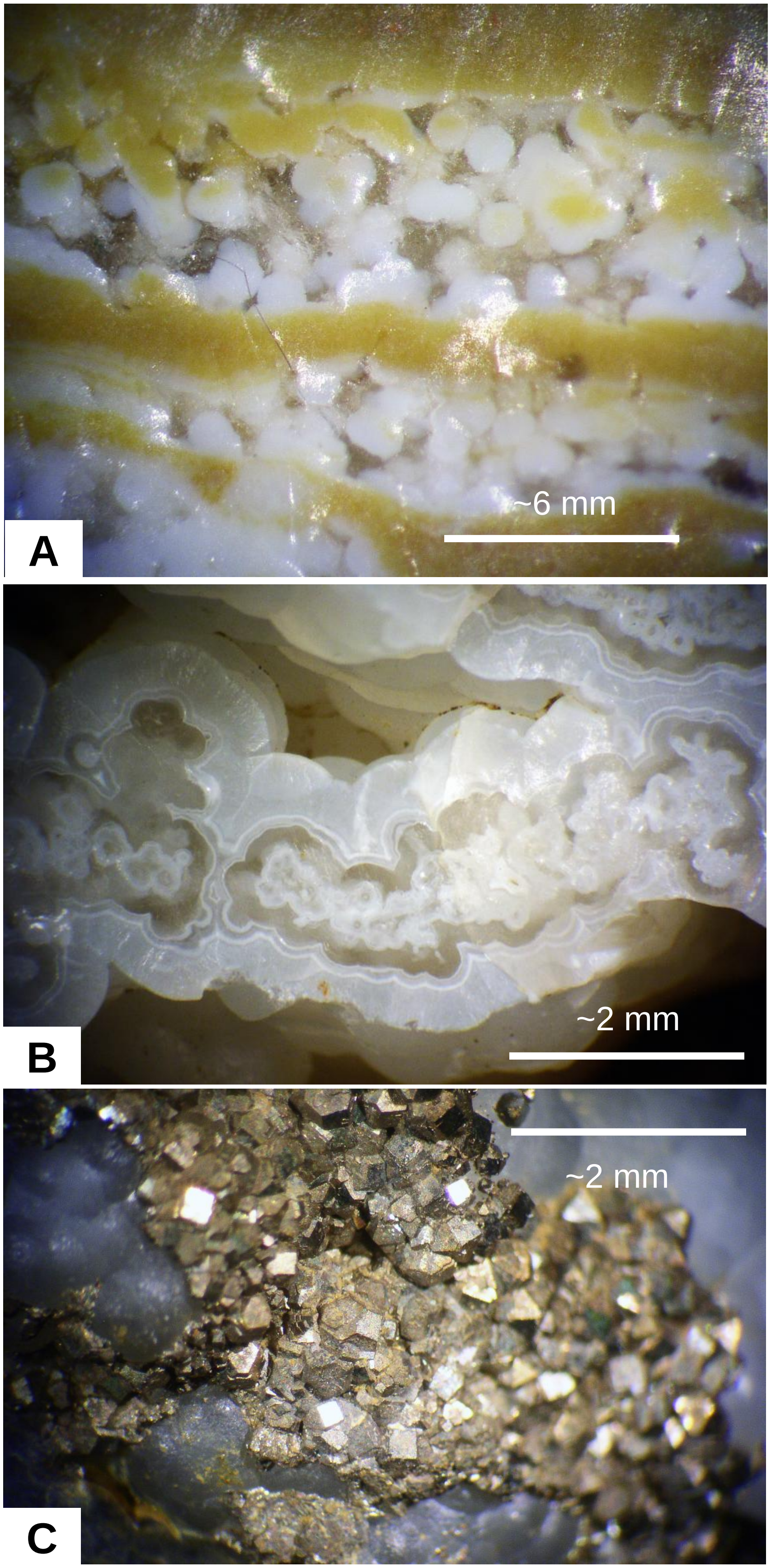

Figure 14. Photomicrographs of translucent, clear to milky-white agate lining pockets in the orange-brown jasper. A. The agate is spherically banded nodules that infill voids in the jasper matrix. B Detail banding and coalescence of agate nodules showing the banded, accretion textures. C. Details of the pyrite coating the opal.

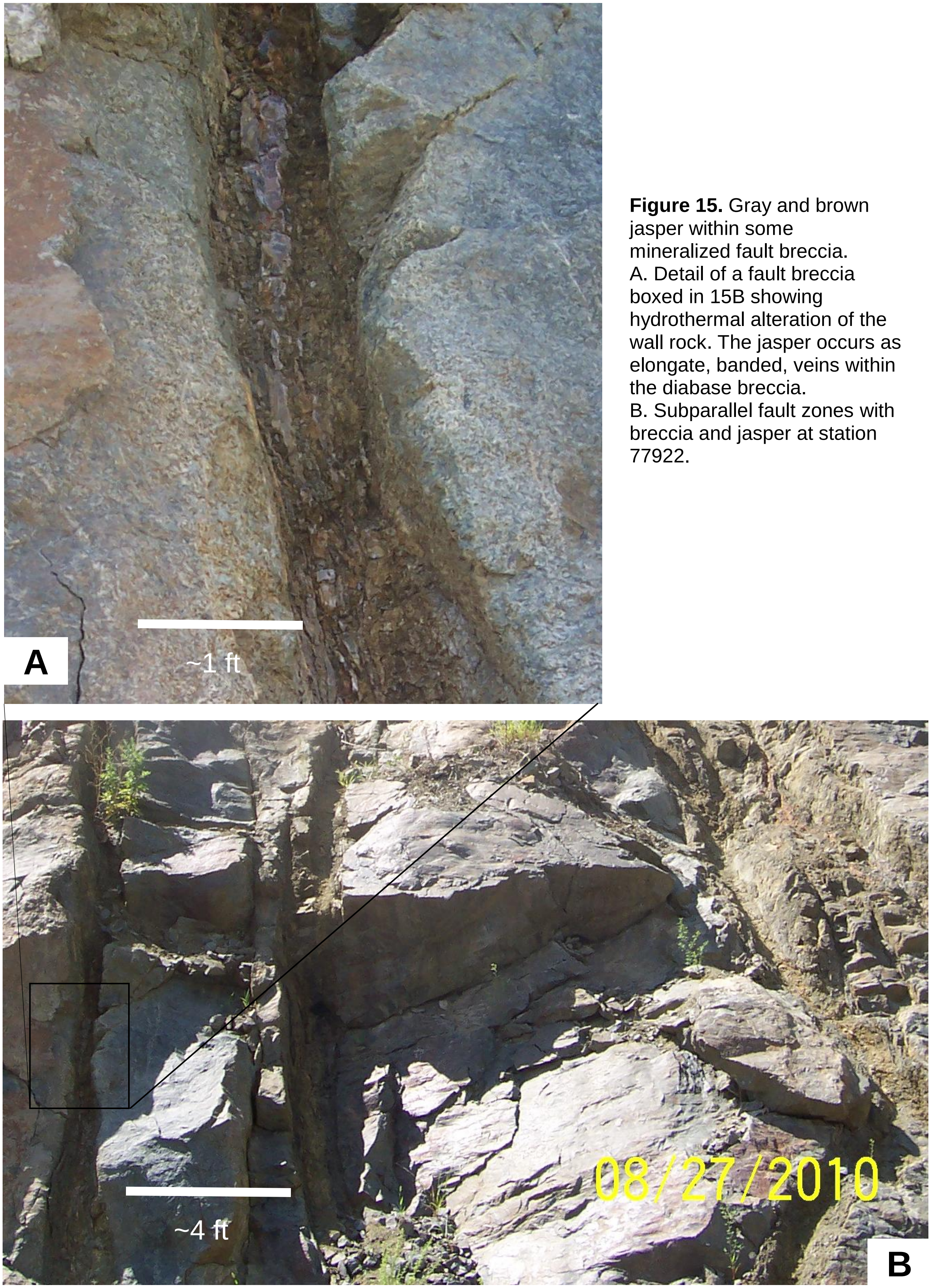

Figure 15. Gray and brown jasper within some mineralized fault breccia.
A. Detail of a fault breccia boxed in 15B showing hydrothermal alteration of the wall rock. The jasper occurs as elongate, banded, veins within the diabase breccia.
B. Subparallel fault zones with breccia and jasper at station 77922.

Figure 16. Late stage light-blue opal is also found within vugs developed in brecciated shear zones having other secondary minerals including chlorite, epidote, calcite, and iron oxyhydroxides. The slickensided shear planes are striated with slickenlines, A. Opal coating the walls of voids developed within a brecciated shear zone at station 77912 (fig. 9B shows a larger view of this fault). A Brunton compass is included for scale at lower center. B. Light-blue opal coating a steeply dipping S1 shear plane with normal dip-slip slickenlines at station 77924.

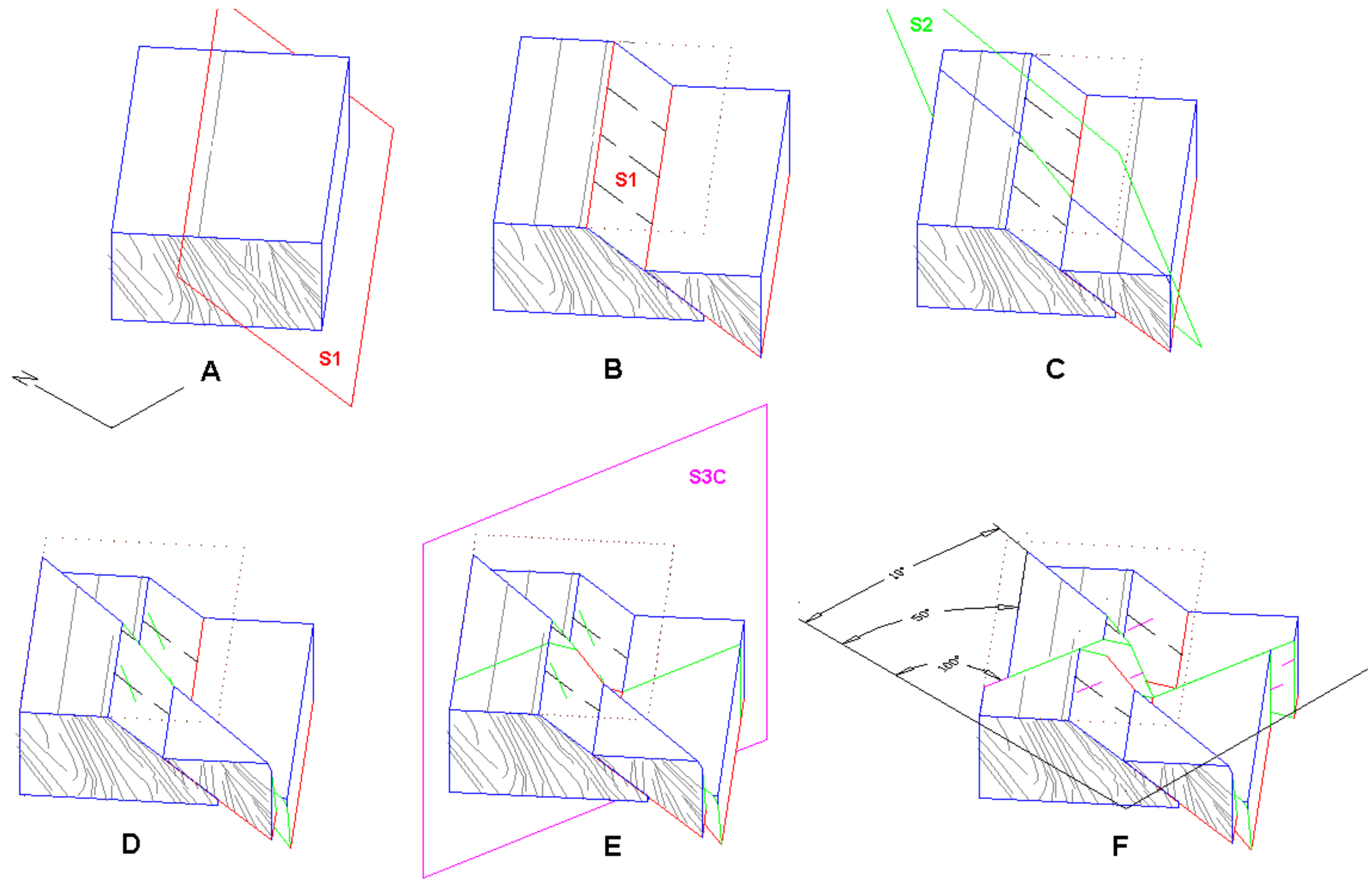

Figure 17. Block diagrams showing the structural sequence of faulting in the Pennington trap rock quarry. A. Layering and early faults strike about N50°E, with S1 fault dipping at moderate-to-steeply SE. B. Predominant normal dip slip on S1 fault and shear planes. C. Layering and S1 faults cut by S2 stage steeply-dipping faults striking N10°-20°E (S2) and N-S (S3). One fault plane is used to represent the later S2 and S3 shear planes for simplicity. D. Dip slip on S2-S3 shear planes with possible right-lateral slip. E. All earlier features are cut by the latest cross-cutting shear planes oriented about E-W (S3C). F. Normal-oblique dip-slip and right-lateral strike slip shear zone and shear planes.

and western segments of the Hopewell fault that link with the Chalfont fault in Pennsylvania (Ratcliffe and Burton, 1988). The latest stretching event produced renewed, oblique slip on older (S1 and S2) fault surfaces that were being pulled obliquely apart in an easterly direction. The light blue opal now fills open voids in shear zones that are otherwise grooved and striated at points of contact and grinding. The jasper and opal filled hydrothermal vein striking E-W (station 77913) appear to have only small amounts of fault slip associated with it, and may have been dilated during a late-phase E-W compression of the region.

The fault geometries and their interactions in the quarry support a hypothesis that the different orientations of intrabasin fault segments were active in different stratigraphic levels at different times (Herman, 2009b). For example, those segments orientated parallel to the border fault (~N40^{o}E to N60^{o}E or S1 faults) were probably active early in the depositional history of the basin, locally cutting early sedimentary deposits, and then were succeeded and overprinted by the later, S2 and S3 structures that cut through all strata, but primarily occur at the highest stratigraphic levels. The leucocratic dikes and veins within the quarry follow S1 through S3 orientations and suggest that repeated episodes of extension, cooling, and cracking allowed fractionated melts originating at depth to repeatedly migrate upward through the diabase during punctuated phases of extension.

The map geometry of the diabase bodies forming Pennington and Baldpate Mountains include discordant stems locate on their northwest side that are apparently truncated by the fault, whereas the bulk of both bodies are sill-like sheets that are concordant to surrounding beds (figs. 2 and 3). The main parts of both of these igneous bodies now sit within the keel of a syncline that is located close and parallel to the trace of the Hopewell fault (fig. 3). The truncated stems could indicate that the S1 fault segments provided localized flow conduits for diabase emplacement and migration upward through the sedimentary pile.

X-ray analysis of a vein-fill material of the opal-jasper vein at station 77913 showed the presence of witherite ($BaCO_3$), a low-temperature mineral often found associated with fluorite (CaF_2) and barite (BaSO4), both of which are found with diabase and faulting elsewhere in the hanging wall of the Hopewell-Chalfont fault system (Dombroski, 1980; Cummings, 1991; Laney, 1992). It is likely that the Barite deposit near Hopewell (figs. 2 and 3) and other barite deposits in the Hopewell-Chalfont fault block are positioned in the Triassic shale hornfels immediately beneath the eroded parts of the diabase sheets.

The main diabase sheet was being emplaced and sheared during the S1 phase of extension. Polygonal cooling joints commonly occur in the basal parts of layers, suggesting that the sheet was being partly formed by injection of magma pulses on the underhand side of the body, or incrementally thickening from the top down in some places. Perhaps, late, punctuated phases of strain extended blanketing layers to allow segregated melts accumulating at the bottom of the sill to break through to the top, feeding granophyres and dike complexes upsection within the Upper Triassic and Lower Jurassic sedimentary section. Leucocratic dikes and cooling joints following S2 trends are pronounced. However, these are also cut and sheared by later S3 and S3C faults. It's also possible that the granophyres and leucocratic dikes stem from magma differentiates at lower crustal levels.

Other nearby geological evidence shows that diabase within the basin was being emplaced along large, discordant crustal fractures during the S3 phase of regional extension. For example, the Copper Hill and Mount Rose diabase dikes (fig. 2) align with folds along a down warped hinge in the Lambertville diabase sheet (Herman, in press) located immediately east of the saddle and midway along its strike length (fig. 2). The eastern half of the sill is mapped as intruding a lower stratigraphic position than the western half (fig. 2), but this apparent offset may be a result of structural down warping above a blind, late stage, normal shear zone cutting across the sill. This great fracture continues northward where the Copper Hill dike shoots off the uppermost part of the sill, striking towards Flemington, cutting across all of the Late Triassic section, and driving hydrothermal fluids that emplaced copper minerals at the Neshanic and Flemington copper mines. It is likely that the Copper Hill and Mount Rose dikes are late-stage, discordant parts of the intrusive complex that follow partly buried, crustal planes of weakness associated with the S3 fracture system and crosscutting earlier S1 and S2 structures, allowing the central part of the basin to collapse eastward in one of the latest phases of basin extension.

The sequence of mineralization found in the quarry is probably the same as reported by Shaller (1932) and Mason (1960) for trap rock elsewhere in the basin. But some uncertainty remains with respect to the timing of the late-stage, epithermal veins of hydrous silica minerals and associated sulfide and copper carbonates. Copper sulfides are found in the early veins cored with silica and feldspar. Copper carbonates are found in the altered diabase in contact with both the epidote-calcite shear zones, and the lower temperature and pressure chalcedony and opal veins. Additional sampling and petrographic work is needed in order to assign relative ages to the late opal and calcite mineralization phases. Also, more work is needed to better establish the association of the metal sulfides with respect to he different types of veins. We also don't know if the opal and jasper veins extend outside of the diabase into the Upper Triassic red and gray shale.

The Trenton region may hold many keys that will help to resolve some long-standing questions regarding the emplacement of the diabase and stages of cooling, mineralization as tectonism. For example, which Early Jurassic diabase dikes, if any of those currently mapped, were feeder dikes to the basalt flows? Which parts of the trap-rock plumbing system were active during the span of time over which the different basalt formations were extruded? How does the geometry of this plumbing system relate to the different phases of tectonism? To what extent does the regional plumbing system reflect synrift faulting, and to what extent did this system utilize large, crustal faults in spreading diabase throughout the basin? How does the cooling history of the basin and the associated sets of hydrothermal veins relate to the extensional versus compress ional tectonic phases that the New Jersey region was subjected to? And finally, how does the architecture of this grand pull-apart structure relate to the modern tectonic setting?

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