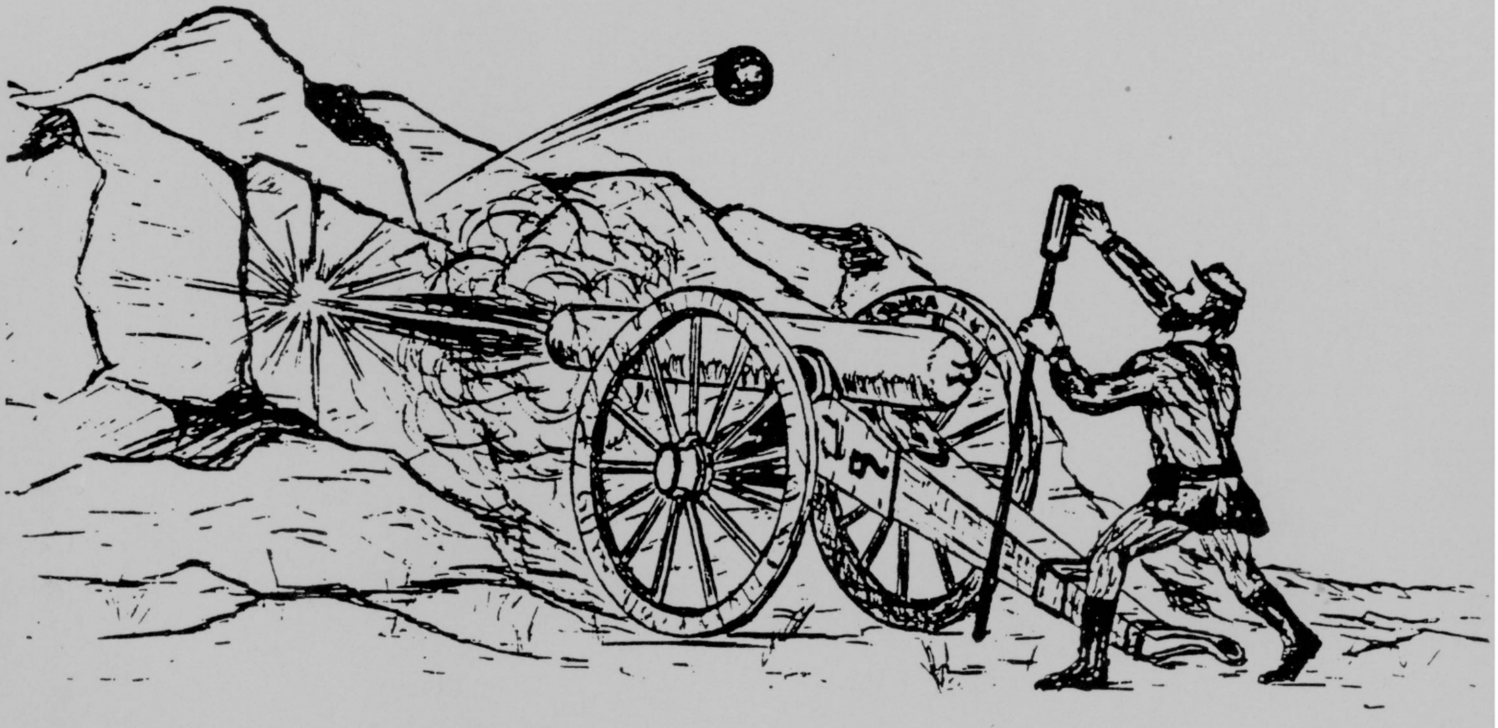
Guidebook for the 6th Annual Field Trip of the

HARRISBURG AREA GEOLOGICAL SOCIETY

April 25, 1987

LOWER JURASSIC DIABASE AND THE BATTLE OF GETTYSBURG



Guidebook for the 6th Annual Field Trip of the

HARRISBURG AREA GEOLOGICAL SOCIETY

April 25, 1987
Reprinted March, 1992
Reprinted July, 1994

Lower Jurassic Diabase

And The Battle of Gettysburg

by

D.T. Hoff, State Museum of Pennsylvania
J.R. Mowery, Harrisburg Area Community College
G.R. Ganis, TETHYS Consultants, Inc.

Copies may be obtained from:
Harrisburg Area Geological Society
c/o Pennsylvania Geological Survey
P.O. Box ~~2357~~ 8453
Harrisburg, PA   17105-~~2357~~ 8453

Table of Contents

List of Figures

List of Pertinent References Found After the Guidebook Narrative

1. Gettysburg: Includes excellent map of Battlefield
2. Geology and the Gettysburg Campaign
3. Geology and Geochemistry of Triassic Diabase in Pennsylvania. The York Haven-type and Rossville-type diabase are now considered to be Lower Jurassic in age.
4. Valley (Campbell's) quarry, Rocks and Minerals magazine article

COVER: Artwork by David Hoff, Roy Rogers fast food empire

LOWER JURASSIC DIABASE
AND THE BATTLE OF GETTYSBURG

Introduction

This field trip is the continuation of a program established by officers of the Harrisburg Area Geological Society in the Fall of 1981. One-day, annual field excursions concerned with the geology of our Harrisburg region serve several purposes. Members and friends of HAGS who work in specialized areas are given the opportunity to examine and discuss the diverse geology found within a one-day field trip range from Harrisburg. Subsequently, the field trip guidebooks can be used by schools for educational purposes. Last, but not least, the trips allow an opportunity for our members and friends to present their new and original work concerned with local geology.

The first annual HAGS field trip in 1982, and also the second trip, treated a broad spectrum of geological interests. The third and fourth annual trips were thematic in their approach, and the fifth trip returned to a diversity of geological subjects.

This field trip is thematic relative to the geomorphic "high ground" of diabase terrane and the Battle of Gettysburg. However, the trip subjects also include sedimentary and igneous geology, contact metamorphism, economic geology, and mineralogy.

From our starting point at HACC, we traverse southwesterly over the Great Valley Section of the Valley and Ridge physiographic province. Our route passes onto the Gettysburg Basin of the Triassic Lowland near Rosegarden along the Yellow Breeches Creek. This point is near the northeastern terminus of the Blue Ridge physiographic province. From Rose Garden, we traverse southwesterly over the Gettysburg Basin to the Gettysburg Battlefield. The field stops (Figure 1) are located in the Gettysburg Basin near Gettysburg.

The contributors to this guidebook and field leaders are as follows: Stops 2., 3., and 4., Ron Mowery; Stop 5., Don Hoff; Stop 6, Don Hoff and Bob Ganis. Stop 1. is the Gettysburg Battlefield Visitor Center and Electric Map participation. This guidebook was edited and assembled by Bob Ganis and TETHYS Consultants, Inc.

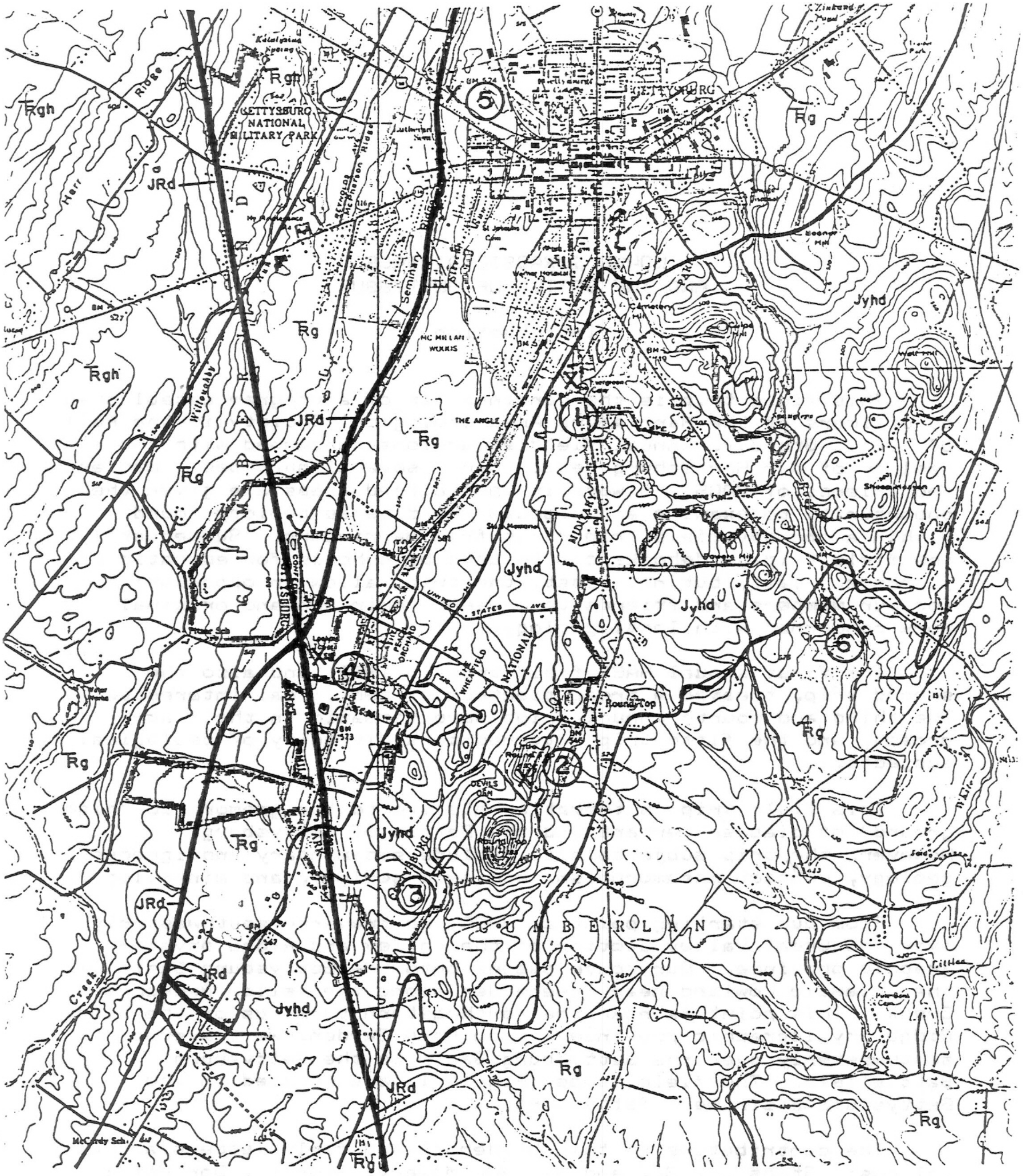


FIGURE 1.

Map showing location of stops and geology as schematized after Stose and Bascom (1929). Diabase types from Smith, Rose, Lanning (1975).

Jurassic: Early
Rossville-type diabase (JRd)
York Haven-type diabase (Jyhd)

Triassic: Late
Gettysburg Formation (TRg)
Heidlersburg Member (TRgh)

FIELD TRIP ROAD LOG AND STOP DESCRIPTIONS

Mileage		
Inc	Cum	
0.0	0.0	DEPART at 7:00 AM from Harrisburg Area Community College east parking lot, telephone booth area.
0.16	0.16	BEAR LEFT to Wildwood Park Road
0.24	0.40	STOP LIGHT. Turn left onto Wildwood Park Road to Cameron Street.
0.31	0.55	STOP LIGHT. Turn right onto Cameron Street and proceed to Maclay Street.
0.50	1.05	STOP LIGHT. Immediately before stop light; bear right on ramp to Maclay Street and proceed to Front Street.
1.05	2.10	STOP LIGHT. Turn left onto Front Street and proceed to Harvey Taylor Bridge.
1.05	3.15	STOP LIGHT. Turn right onto Harvey Taylor Bridge and proceed to U.S. Route 15 South.
1.95	5.10	STOP LIGHT. Intersection of Camp Hill bypass and 21st Street. Proceed straight ahead and follow U.S. Route 15 South to Gettysburg.
4.95	10.05	Pass under Pennsylvania Turnpike bridge.
3.70	13.75	Center of U.S. Route 15 bridge over Yellow Breeches Creek. At the south end of the bridge we pass from the Great Valley onto the Upper Triassic Gettysburg Basin. Rossville-type diabase forms the hill on the southerly side of Yellow Breeches Creek. A thin wedge of limestone fanglomerate of the Gettysburg Formation is located under the south end of the bridge (Root, 1978).
0.42	14.17	Good exposure of contact metamorphosed limestone fanglomerate of the Gettysburg Formation occurred near this point during road construction.
2.98	17.15	Range End Golf Course located adjacent to Dillsburg, and also the South Mountains of the Blue Ridge Province are to your right. Range End is an appropriate name for this golf course as the northeastern terminus of the Blue Ridge Province is located approximately two miles north-northwest of this point.
0.70	17.85	To your right, road cut in a Rossville-type diabase intrusion in the Gettysburg Formation.

5.95	23.80	To your left, Weiser fruit stand. The Weiser house and barn are located 0.20 mile east-northeast of this point and along old U.S. Route 15. The walk from the Weiser house to their driveway is capped with sandstone slabs which exhibit primary sedimentary structures such as ripple marks, and at least one dinosaur track. The sandstone, medium gray in color, is from the former Trostle quarry in the Gettysburg Formation, and further located along the Bermudian Creek 2.45 miles southeast of this point.
0.95	24.75	Near this point, pass from the Gettysburg Formation over a thin wedge of Ordovician carbonates (Beekmantown Group?), and then onto the Heidlersburg Member of the Gettysburg Formation. The abandoned quarry to your right is in the Beekmantown? (Stose, 1932).
.30	25.05	U.S. Route 15 exit to PA Route 94 and York Springs, continue straight ahead.
2.25	27.30	U.S. Route 15 bridge over Bermudian Creek.
3.50	30.80	U.S. Route 15 bridge over the Conewago Creek. Pass from the Heidlersburg Member of the Gettysburg Formation back onto the Gettysburg Formation.
3.00	33.80	U.S. Route 15 exit to PA Route 394 and Hunterstown.
3.05	36.85	Bear right onto U.S. Route 15 Gettysburg-York Street exit to U.S. Route 30.
0.25	37.10	Stop sign. Turn right onto U.S. Route 30 West.
2.05	39.15	Center square in Gettysburg. Go 3/4 of way around square and take Baltimore Street South.
0.45	39.60	Red light at intersection of Baltimore Street and Steinwehr Avenue, bear right.
0.58	40.18	Entrance to Cyclorama Center parking, turn left.
0.20	40.38	Stop 1. Park bus at Cyclorama Center.

THE ELECTRIC MAP

The Electric Map is located in the Visitor Center adjacent to the Cyclorama Center. The map is an audio-visual exhibit and consists of a 750 square foot relief map depicting the woodland and farmland as it was during the Battle of Gettysburg on July 1-3, 1863. The movements of Union and Confederate forces, and also areas of military conflict are shown by more than 600 colored lights which are coordinated with a taped narration.

Of special interest to this trip, is the "high ground" of military tacticians which is extremely well displayed by the Electric Map. The basic Confederate line of July 2-3 was on Seminary Ridge formed by a Rossville-type diabase dike. The Confederates were confronted by the Union line on Cemetery Ridge formed by York Haven-type diabase of the Gettysburg sheet.

The relative position of the Rossville-type diabase and the earlier York Haven-type diabase in the Gettysburg area, and also their respective geochemistry, igneous petrology, magma genesis, and trace elements, are given by Smith, Rose, and Lanning (1975). Please find a photocopy of this paper after the guidebook narrative. The Lower Jurassic age of the forenamed diabase types is reported by Berg, and others, 1983.

We will have some time to examine the Visitor Center's Rosensteel collection of Civil War artifacts in addition to participating in the Electric Map program.

Leave Stop 1.		Proceed back toward the Cyclorama Center's Steinwehr Avenue entrance.
0.15	40.53	Turn left onto Hancock Avenue before reaching Steinwehr Avenue. We are now on the Cemetery Ridge portion of the Battlefield. Please refer to Brown, Geology and the Gettysburg Campaign, PA Geological Survey, and also Gettysburg National Park Service, during our Battlefield tour. Both papers are in your packet.
0.30	40.83	To your right. Group of trees adjacent to High Water Mark.
0.35	41.18	To your left. Pennsylvania Monument.
0.40	41.58	Hancock Avenue becomes Sedgwick Avenue, continue straight ahead.
0.90	42.48	Sedgewick Avenue becomes Sykes Avenue, continue straight ahead.
0.20	42.68	Stop 2. Drive bus into Little Round Top parking along Sykes Avenue.

LITTLE ROUND TOP

York Haven-Type Diabase Saves The Day

From this point to the west, you can see Seminary Ridge formed by a Rossville-type diabase dike, about a mile across the valley. Between this ridge of York Haven-type diabase and Seminary Ridge is the Wheatfield and Peach Orchard, all strategic positions in the second day battle of July 2, 1863. The most crucial of these is Little Round Top. As you have seen from the electric map, this is the southern end of the "fish-hook" defense line of the Union Army, and from this elevated position, more than half of the Union line can be seen.

By the afternoon of July 2, neither army occupied this position, but Union signal flag men used this as a communication point. Brig. Gen. Gouverneur Warren, Chief Union engineer, recognized the tactical and strategic position of Little Round Top and attempted to commandeer troops to defend the site against advancing Southern troops. By late afternoon, this point became the focus of intense hand-to-hand combat, while to the west, bloody combat shifted control of the Wheatfield and Peach Orchard back and forth several times between Union and Southern forces over a 6-hour period. Two cannons were brought to the crest of Little Round Top and their aid tipped the fateful hand of the battle for this position in favor of the Union troops.

By 7:00 PM on the evening of July 2, the Union army had lost the battle ground west of Cemetery Ridge to the Confederates including Devil's Den.

On July 3, Confederate sniper troops in Devil's Den attempted to shake the Union troops from Little Round Top by picking off Union soldiers who could not dig trenches into the diabase sheet on Little Round Top.

Leave Stop 2. Continue south on Sykes Avenue

0.20	42.88	Turn right. onto Warren Avenue for circle tour of diabase terrane which includes Devil's Den.
0.28	43.16	Turn left onto Crawford Avenue. Follow Battlefield Tour signs.
0.12	43.28	Devil's Den.
0.40	43.68	The Wheatfield
0.43	44.11	Stop sign. Dead end of Sickles Avenue, turn right onto Wheatfield Road.
0.62	44.73	Turn right onto Sykes Avenue. End circle tour.
0.20	44.93	Little Round Top parking, continue straight ahead.

0.20	45.13	Intersection of Sykes Avenue and Wright-Warren Avenues. Continue straight ahead on South Confederate Avenue.
0.10	45.23	Big Round Top parking, continue straight ahead.
0.35	45.58	<u>Stop 3.</u> South Confederate Avenue bridge over Plum Run. Park bus near bridge.

Bridge Over Plum Run

This bridge is truly a stratigrapher's delight!! The capstones of the bridge have all been quarried in Adams County and represent the variety of rocks found in the County.

In addition to diabase rocks where impressions of facing tools may be seen, there are rocks from Trostle's quarry which show dessication patterns; both symmetrical and assymetrical ripple marks, some of which exhibit clastic dikes. There are also several capstones which have been interpreted as being casts of rain drops by some and as "dinosaur" skin by others -- what do <u>you</u> think? Two of the capstones show casts of reptile foot prints -- both forelimbs and hind limbs. This must have been a coelophysis-like dinosaur. Can you find the second stone with a footprint?

Please refer to mile 23.8 in your road log for location of Trostle's quarry.

Leave Stop 3. Continue westerly on South Confederate Avenue.

0.63	46.21	To your left. Alabama Monument. At this point, a dike of Rossville-type diabase cuts the York Haven-type diabase of the Gettysburg sheet. The cross-cutting dike is about 225 ft. thick as mapped by Stose and Bascom (1929). This point will be an extra stop if time permits. The possible field exercise will be to examine the diabase, and also rather scarce granophyre on the stone fences in the general area.
0.30	46.51	<u>Stop sign</u> at intersection of Confederate Avenue and Business Route 15. Continue straight ahead on West Confederate Avenue.

0.60	47.11	<u>Stop 4.</u> Observation tower. At this point, two dikes of Rossville-type diabase merge. One is the dike which cuts York Haven-type diabase to the south, and the second is the dike which forms Seminary Ridge. Pull bus into observation tower parking.

Observation Tower on Seminary Ridge

Looking east from this point, Cemetery Ridge may be seen with the Round Tops on the right, Cemetery and Culp's Hills on the left. On a clear day, Parr's Ridge composed of Piedmont schists and quartzites may be seen to the southeast.

This tower is situated on Seminary Ridge, and looking both northward and southward we see the battlefield position of the Confederate Army on July 2 and 3, 1863. Facing west, the white buildings surrounded by the white fence is the Eisenhower farm. The rounded ridge to the southwest is Ski-Liberty, a Jurassic diabase intrusion. The rolling hills in the near distance are other diabase sheets and they are separated by valleys underlain by the Triassic Gettysburg redbed formation and carbonate fanglomerates, such as seen in the Fairfield Quarry to the southwest of Gettysburg. On the western horizon is the South Mountain portion of the Blue Ridge physiographic province, a complex of precambrian metavolcanics and metasediments.

Transecting the South Mountain, just west of Gettysburg is the Carbaugh-Marsh Creek fault producing the Cashtown Gap, over which U.S. 30 now passes and through which Lee's Army crossed the South Mountain on July 1, 1983. Another minor fault cuts South Mountain near Fairfield creating Fairfield or Monterey Gap, which can be seen from here.

Leave Stop 4. Continue north on West Confederate Avenue

0.10	47.21	<u>Stop sign</u> at intersection of West Confederate Avenue and Wheatfield-Waterworks Roads, continue straight ahead along Seminary Ridge.
0.95	48.16	To your right, Virginia Monument
0.33	48.49	To your right, North Carolina Monument. This point will be an extra stop if time permits. Here, we can stand on Seminary Ridge formed by a dike of Rossville-type diabase and imagine Pickett's July 3, 1863 charge from this area to the Union positions on Cemetery Ridge situated about 0.75 mile east-southeast York Haven-type diabase of the Gettysburg sheet froms Cemetery Ridge. Continue north on West Confederate Avenue.
0.77	49.26	<u>Red light.</u> Intersection of West Confederate Avenue and PA Route 116, Hagerstown Road. The Confederate Army's main route of retreat was to the southwest on the Hagerstown Road. Continue straight ahead onto Seminary Avenue.

0.20	49.46	To your right, S.S. Schmucker Hall, Lutheran Theological Seminary.
0.15	49.61	<u>Stop sign.</u> Turn left onto U.S. Route 30.
0.08	49.69	<u>Stop 5.</u> Turn right into Larson's Quality Inn Parking.

Seminary Ridge Diabase Dike Exposure In Western Maryland Railroad Cut

The railroad cut is located on the northeastern side of the Larson Motel property. This cut exposes the Seminary Ridge diabase dike which cuts reddish silty shale and mudstone of the Upper Triassic Gettysburg Formation (Figure 2.) The red beds were contact metamorphosed to a hard, dense, dark gray to almost black hornfels adjacent to the diabase intrusion.

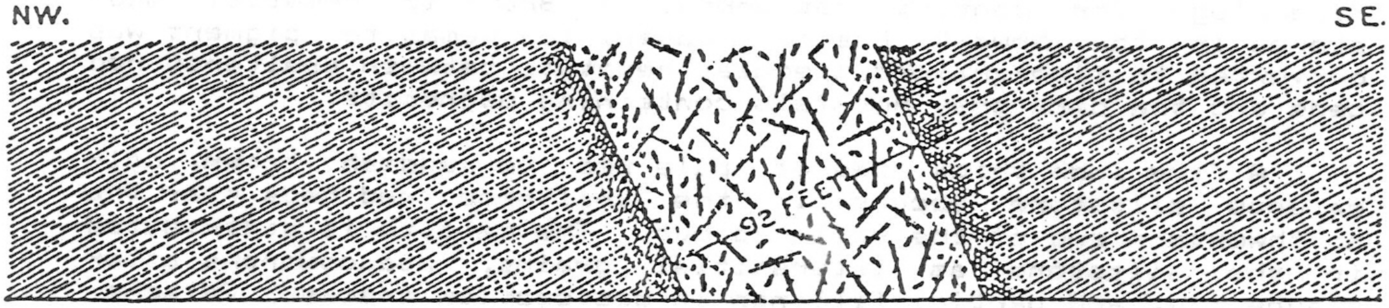


Figure 2. Geologic cross section of Seminary Ridge diabase dike, 92 feet thick, which cuts the Gettysburg Formation. This exposure is located in the CSXT (former Western Maryland) railroad cut near northwest corner of the Gettysburg Borough boundary (from Stose and Bascom, 1929, p.12).

Of special interest to this trip, is the opportunity of examining the texture of the diabase, its columnar jointing, and how the intrusion effected the red sediments. Stose and Bascom (1929) reported that the dike is 92 ft. thick, and dips 50° E. Smith, Rose, and Lanning (1975) reported that the Seminary Ridge dike is a Rossville-type intrusion.

Rossville-type diabase is characterized by sparse, centimeter-size, high-calcic plagioclase phenocrysts (anorthite to bytownite) in the chilled borders of sheets and dikes. Relative to the Rossville-type diabase, the York Haven-type chilled diabase does not possess high-calcic plagiclase phenocrysts, but contains greater amounts of Cu and Ti (Smith, Rose, and Lanning, 1975).

The highly chilled borders of the diabase dike at this stop cannot be readily studied because of excessive weathering. However, thorough examination of the diabase would probably locate sparse, anorthite to bytownite phenocrysts throughout the intrusion. This is relative to its cooling history. The diabase here is fine-grained which indicates rapid cooling, and is what one would expect for an intrusion only 92 ft. thick. In thicker Rossville-type intrusions, the phenocrysts resolved into the magma before total crystallization except in the chilled margins.

This locality allows one to observe a progressive color change from red in the shale and mudstone to dark gray in the hornfels (oxidized to reduced) as you approach the diabase. Van Houten (1969) reported a chlorite-sericite, epidote, hornblende, pyroxene, feldspar, tourmaline, magnetite, and cordierite mineralogy for contact metamorphosed Brunswick hematitic mudstones in the Newark Basin. Aphanitic hematite pigment was converted to fine-grained specular hematite between unaltered red beds and the dark gray hornfels containing magnetite.

A five inch thick bed of pale red to reddish brown, calcareous siltstone occurs in the unaltered red beds near the northwestern end of the railroad cut. The calcite is distributed in the siltstone as interstitial grains, pseudomorphs after glauberite, and partial fillings in desiccation cracks. Palache, Berman, and Frondel (1951) reported that isolated, glauberite crystals are found embedded in clastic sediments formed in arid environments.

The silty shale and mudstone of the Gettysburg Formation are suitable for brick production. The abandoned quarry of the former Gettysburg Brick Co. is located 0.20 mile northeast of this railroad cut. The former quarry now serves as a fish pond on Gettysburg College property.

Leave Stop 5. Take U.S. Route 30 East
(Buford Avenue) into Gettysburg

0.57	50.26	<u>Red light.</u> Bear left onto Chambersburg Street.
0.15	50.41	<u>Red light.</u> Turn right onto Washington Street and continue straight ahead to Steinwehr Avenue.
0.65	51.06	<u>Stop sign.</u> Turn right onto Steinwehr Avenue and continue straight ahead.

0.33	51.39	Entrance to Cyclorama Center parking, turn left.
0.20	51.59	Park bus at Cyclorama Center.

Lunch

You may consume your box lunch in the Cyclorama Center picnic area or visit one of the fast food restaurants along Steinwehr Avenue.

Leave Cyclorama Center and proceed back to Steinwehr Avenue.

0.20	51.79	Turn right onto Steinwehr Avenue and continue straight ahead to PA Route 97.
0.55	52.34	Red light. Turn sharp right onto PA Route 97 (Baltimore Pike). Continue straight ahead past entrance to National Cemetery.
1.65	53.99	Stop 6. Turn right into entrance of Valley Quarries, Inc., Gettysburg Plant and drive straight ahead to quarry area.

Valley Quarries, Inc. - Gettysburg Operation
Contact Metamorphism, Economic Geology, and Mineral Collecting

For this stop, please refer to the photocopied article after the guidebook narrative titled, Campbell's Quarry, Hoff, D. T., 1978, Rocks and Minerals, v. 53, no. 6.

As a general summary for this guidebook, the Valley quarry is geologically similar to the railroad cut exposure at Stop 5. However, we will not see the unaltered sediments and diabase in the larger exposure at this stop as we are dealing with a geological event of much greater proportions.

This quarry exposes gray hornfels near the bottom of the Gettysburg diabase sheet. In this general area, the Gettysburg sheet is comprised entirely of York Haven-type diabase, and is approximately 1/2 mile thick and dips about 20° WNW as mapped by Stose and Bascom (1929). Robert C. Smith (personal communication, April 15, 1987) reported that an X-ray diffractometer scan of a sample from gray hornfels chips collected on the Valley quarry stockpiles gave the hornfels mineralogy as follows: Plagioclase such as albite, andradite-grossular, a chlorite, a mica such as muscovite, quartz, possible trace epidote but no calcite or prehnite, and probable magnetite detected with a hand magnet.

Hoff (1978) reported a skarn-magnetite zone in the northwest corner of the Valley (Campbell) quarry. It was further noted that a calcium carbonate rich sediment was the probable host rock for silicate and magnetite replacement.

During a recent trip to this quarry, Bob Ganis and Don Hoff discovered unreplaced crystalline limestone in the skarn. This discovery gives credence to the concept that the magnetite-skarn zone was a lacustrine, calcareous sediment which experienced contact metamorphism and metasomatism relative to the diabase intrusion.

Today, the skarn zone can be examined by standing on the quarry floor. Notably absent are the stratiform magnetite, large epidote vugs, abundant orthoclase and other interesting specimens that were blasted out of this zone during the mid-1970's. The skarn zone can now be divided into an upper non-friable zone about 62 in. thick, and a lower friable zone about 32 in. thick.

The upper zone is characterized by abundant, relict, sedimentary laminae, some of which are calcareous. Of rare occurrence is lamina of almost pure, medium gray, crystalline limestone. Andradite-grossular is very conspicuous in the upper zone, while bormite and "chalcocite" as grains and blebs are moderately distributed, and copper "bloom" is sparse in occurrence.

Examination of a small portion of the lower friable zone revealed abundant andradite-grossular and epidote, and a 0.5 in. thick lamina of light gray diopside. Bornite, chalcopyrite, and bornite with chalcopyrite occur as abundant grains and blebs, and arborescent native copper can be found as microspecimens. Analyses of a 32 in. channel sample from the lower zone gave the following results:

Ag	0.21 troy oz/ton
Au	less than .005 troy oz/ton
Pt	less than .005 troy oz.ton
Co	.003%
Cu	1.32%
Ni	.005%
Pb	less than .001%
Zn	.01%
Mo	.011%
W	.009%

Analyses performed by Hazen Research, Inc. by atomic absorption.

The Gettysburg Quarry produces type A PennDOT aggregate for use in Portland cement concrete and asphaltic concrete. The great variation in rock composition from hornfels to skarn and the variable response to weathering of these materials necessitates a highwall height that permits a composite blend of these variations. The mining progresses toward the dip and a fracture (or joint) set which strikes parallel to the face orientation and dips 79° toward the face has the affect of "locking in" the natural blocks of rock formed by the intersection of the bedding and fractures. This allows for a safe highwall.

Leave Stop 6. Turn right onto PA Route 97 at Valley quarry entrance.

0.75 54.74 Turn left onto ramp to U.S. Route 15 north. Return to Harrisburg Area Community College, east parking lot for end of field trip.

REFERENCES CITED

Berg, T. M., and others (1983; 2nd printing, revised, 1986), Stratigraphic correlation chart of Pennsylvania, Pa. Geol. Survey, 4th ser., General Geology Report 75.

Brown, A. (1973), Geology and the Gettysburg Campaign, Pa. Geol. Survey, 4th ser., Educational Series No. 5, 15 p.

Hoff, D. T. (1978), Campbell's quarry, a complex mineral locality in Gettysburg, Pennsylvania, Rocks and Minerals, v.53, no. 6, p. 247-253.

Palache, C., Berman, H., and Frondel, C. (1951), The system of mineralogy, 7th ed., v. 11, New York, John Wiley and Sons, 1124 p.

Root, S. (1978), Geology and mineral resources of the Carlisle and Mechanicsburg quadrangles, Cumberland County, Pennsylvania, Pa. Geol. Survey, 4th ser., Atlas 138 ab.

Smith, R. C., II, Rose, A., and Lanning, R. (1975), Geology and geochemistry of Triassic diabase in Pennsylvania, Geological Society of America Bulletin, v. 86, p. 943-955.

Stose, G. (1932), Geology and mineral resources of Adams County, Pennsylvania, Pa. Geol. Survey, 4th ser., County Report 1, 153 p.

Stose, G. and Bascom, F. (1929), Description of the Fairfield and Gettysburg quadrangles, U.S. Geol. Survey Atlas 225, 22 p., 8 maps.

Van Houten, F. (1969) Late Triassic Newark Group, north central New Jersey and adjacent Pennsylvania and New York, in Subitsky, S., ed., Geology of selected areas in New Jersey and eastern Pennsylvania, New Brunswick, N.J., Rutgers Univ. Press, p. 314-347.

Geology and Geochemistry of Triassic Diabase in Pennsylvania

ROBERT C. SMITH II[*]
ARTHUR W. ROSE
ROBERT M. LANNING[*]
Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania 16802

ABSTRACT

Based on chemical composition and mineralogy, three types of Triassic diabase are recognized in Pennsylvania. The probable oldest type (Quarryville type) occurs as an olivine tholeiite dike swarm. The York Haven type is a quartz tholeiite, forming sheets, dikes, and a few flows. The youngest Rossville type is also quartz tholeiite that occurs as sheets and dikes. Within samples of the same type, chemical composition is very uniform. In content of major elements, rare earths, and Ba, the Rossville type resembles island-arc tholeiites. The York Haven type is similar to continental tholeiites.

Based on calculated cooling rates and the homogeneity within each type of magma, plus paleomagnetic data, we conclude that each type was emplaced within a relatively short time period, and that all sheets, dikes, and flows of a single compositional type are essentially contemporaneous. The trend of Triassic diabase dikes in Pennsylvania parallels the trend of Precambrian and Paleozoic dikes, suggesting that trends of dikes may reflect pre-existing structural weaknesses in the basement rather than being an exact indicator of stress orientation during Triassic time.

The two quartz tholeiites can be formed by crystallization of 30 to 45 percent of the olivine tholeiite magma as olivine, minor clinopyroxene, and plagioclase or spinel, accompanied by assimilation of orthopyroxene, probably from the mantle. Rare-earth and Sr-isotope data suggest that the York Haven type probably assimilated as much as 20 percent crustal material, whereas the Rossville type assimilated little or none. These phenomena of multiple-stage fractionation and reaction of the magma with mantle and crust probably apply to most magmas. *Key words: igneous petrology, geochemistry, magma genesis, trace elements, Triassic, Pennsylvania.*

INTRODUCTION

Prior to about 1970, Triassic diabase bodies of the eastern United States had been considered uniform in chemical and mineralogical composition (Dana, 1873; Walker, 1940; Hotz, 1953; Smitheringale and Jensen, 1963; De Boer, 1967). However, recent studies of chemistry and field relations reveal that the Triassic diabase belongs to three or more very distinct populations (Smith and Rose, 1970; Weigand and Ragland, 1970; Smith, 1973). In this paper we summarize detailed studies in Pennsylvania on the field relations, chemistry, and mineralogy of these types, compare these diabases to other types of basaltic magmas, and suggest an origin of the magmas. Many additional details of the study are given by Smith (1973), who also discusses differentiation within the diabase sheets.

TRIASSIC BASINS

The Triassic basins of eastern North America extend discontinuously from Nova Scotia 2,000 km southwest to South Carolina. These basins, which are filled with continental sediments and are intruded by diabase, are roughly parallel to the edge of the continental shelf. The Newark-Gettysburg basins have a total length of approximately 500 km, connected by a narrow corridor, and form an arc across southeastern Pennsylvania with a length of approximately 225 km. The width of the present basin outcrop in Pennsylvania varies from about 6 km along its east-west–striking portion to 50 km along the Delaware River on the east (Fig. 1).

The diabase in Pennsylvania occurs within the Triassic basin as sheets ("sills"), dikes, and flows, and as dikes south of the basin. One dike extends well to the north of the basin. A typical diabase sheet has the gross shape of a saucer with upturned margins (Hotz, 1952). Sheets are most commonly between 60 and 600 m thick. The southeastern portions of typical sheets are approximately conformable to the bedding of the enclosing gently northwest-dipping Triassic sedimentary rocks, but the other three margins commonly are crosscutting. In a few places, the sheets extend outside the Triassic basin and intrude Precambrian and Paleozoic rocks; however, the sheetlike form is usually retained.

Diabase dikes are common within the Triassic basin, but some extend into Paleozoic and Precambrian rocks for tens of kilometers. The dikes are usually not wider than a few tens of meters and are typically fine grained throughout, although borders are finer grained than centers, and some dikes show flow differentiation in the centers (Lanning, 1972). Basalt flows as much as 30 m thick occur at two localities in Pennsylvania in the uppermost part of the preserved Triassic section.

SAMPLE COLLECTION AND PREPARATION

To study the composition of the magma and to avoid the complications of differentiation in place, which is well known at the Palisades, New Jersey (Walker, 1940; Walker, 1969), and at Dillsburg, Pennsylvania (Hotz, 1953), sampling for this study has been of the chilled borders of the sheets and dikes. A special effort was made to visit possible exposures of the contacts. At each site, the least-altered material was selected from as close to the actual contact as possible. Many samples were collected at distances <0.5 m from the diabase–country rock contact. Where exposed contacts were lacking, as was the case for many of the smaller dikes, float samples were broken open until a specimen of very fine grained diabase was found. Details of sample locations are given by Smith (1973).

A block 2.5 × 4.5 × 1.5 cm was cut from unaltered, unfractured, unweathered diabase and was used for chemical analysis and a thin section. Altered samples (mainly those containing a few percent chlorite or sericite) were rejected unless needed for study of chemical variation with distance from a contact. Approximately 110 sam-

---

[*] Present address: (Smith) Pennsylvania Geological Survey, Harrisburg, Pa. 17120; (Lanning) U. S. Navy, Corpus Christi, Texas.

Geological Society of America Bulletin, v. 86, p. 943–955, 7 figs., July 1975, Doc. no. 50710.

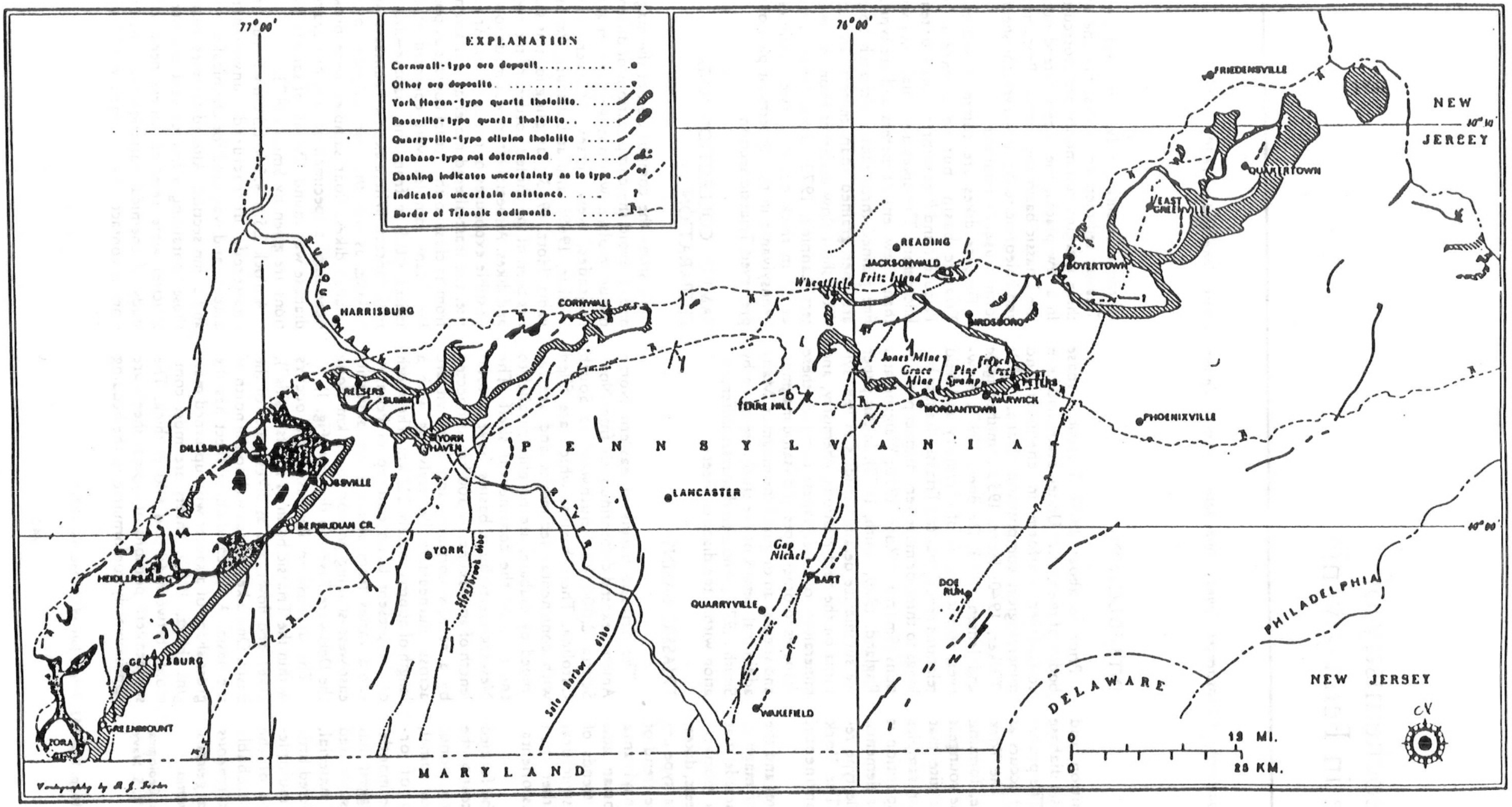


Figure 1. Distribution of three types of diabase in Pennsylvania. Map based on field observations and chemical analyses by R. C. Smith II and R. M. Lanning, state geological map (Gray and others, 1960), Longwill and Wood (1965), Peter W. Weigand (1970, personal commun.), D. B. MacLachlan (1973, personal commun.), and other sources.

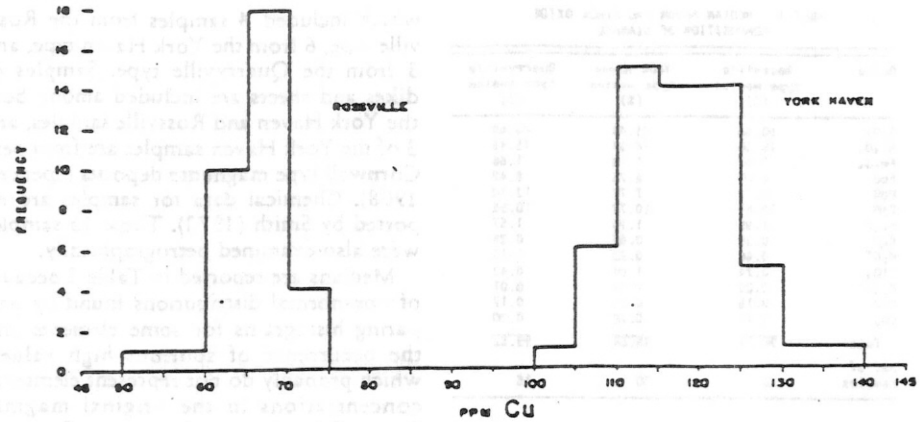


Figure 2. Frequency distribution of Cu for all fresh, chilled, Triassic quartz-normative tholeiite samples.

ples were used for the study and were processed with special care to avoid trace-metal contamination (Smith, 1973).

ANALYTICAL METHODS

The elements Co, Cr, Cu, Ni, and Zn (and, for some samples, Ti) were determined by atomic absorption analysis of solutions derived by a HF-HC10$_4$ decomposition (Rose, 1971), using standards consisting of trace elements added to a synthetic matrix with the composition of USGS W–1 (Ingamells and Suhr, 1963). Replicate analyses gave coefficients of variation of less than 3 percent for Co, Cu, Ni, and Zn and 6 percent for Cr. Accuracy is established by comparison with U.S. Geological Survey reference samples (W–1, BCR–1, AGV–1) analyzed along with the samples (Smith, 1973).

Major elements (Si, Al, Ti, Fe, Mn, Mg, Ca, K) and selected trace elements (P, S, Cl, Sr, Rb) were determined on many of the chilled samples by x-ray fluorescence analysis of $LiBO_2$ fusions. Two samples were analyzed for major elements (by J. B. Bodkin and J. C. Devine) using standard wet silicate analytical methods, and the results were used to make minor corrections to the x-ray fluorescence values for Si, Al, and Mg. Major elements in 15 samples of chilled olivine tholeiite were determined by the method of Medlin and others (1967).

Thirteen samples were analyzed for 55 elements, using the above methods plus emission spectrography, neutron activation, specific-ion electrode, vapor atomic absorption, gamma-ray spectrometry, isotope dilution, wet chemistry, and other methods as described by Smith (1973). In most cases, agreement with accepted values for accompanying USGS reference samples was good; for Cs and Rb, adjustments were made to agree with accepted values.

DISTINCTION OF THREE TYPES OF DIABASE

The Cu and Ti data for the samples suggest that three populations exist (Figs. 2, 3). The two most abundant populations of diabase (denoted Rossville and York Haven) have median Cu contents of 66 and 121 ppm and mean TiO_2 contents of 0.74 percent and 1.10 percent. No overlap in Cu or Ti content between these two populations was found. A third type of diabase (Quarryville) is distinctive in having a mean TiO_2 content of 0.44 percent, with 102 ppm Cu.

Some chilled zones contained sparse, centimeter-size plagioclase phenocrysts (anorthite to bytownite). All samples of chilled diabase contain plagioclase phenocrysts belonging to the lower-Cu and intermediate-Ti population (Rossville), and samples of normal chilled diabase with no plagioclase phenocrysts belong to the higher-Cu and higher-Ti population (York Haven). The lowest-Ti population (Quarryville) was distinctive because it contains abundant fresh olivine microphenocrysts.

The analyses in conjunction with field and thin-section data show that the Ti content is an extremely reliable indicator of the diabase type, but that Cu is affected by slight weathering or alteration in some samples. No differences could be found between the upper and lower contacts, and no indication of chemical reaction with country rock has been detected in chilled diabase. For example, samples D–6, D–7, D–9, D–10, and D–11 were collected from a small sheet of lower-Cu diabase east of Heidlersburg, Adams County. Samples D–6 and D–7 (0 to 3 cm and 7 to 10 cm from the upper contact, respectively) contain 70 and 66 ppm Cu; sample D–10 (1 m from the lower contact) contains 66 ppm, indicating no difference between upper and lower contacts. However, sample D–9, from within 8 cm of the lower contact, is slightly weathered and contains only 37 ppm; and D–11, a coarser sample from the interior of the sheet, contains 55 ppm. In samples from a higher-Cu sheet, samples at 12 to 15 cm and 6 m from the contact contain 116 and 115 ppm Cu, but a sample at the contact contained a trace of alteration and 250 ppm Cu. These three samples contained 1.11, 1.13, and 1.12 percent TiO_2. Several other pairs of samples confirm these generalizations about weathering and alteration. No differences attributable to different types of country rock could be found, indicating rapid chilling and lack of assimilation. The

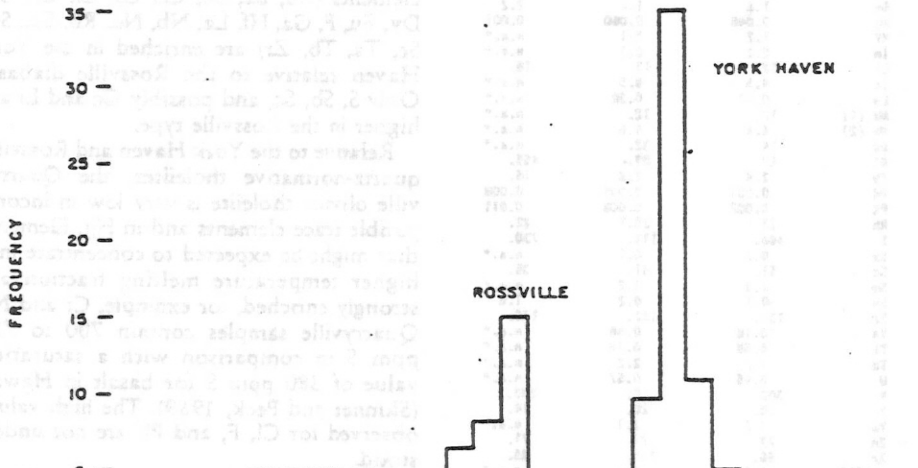


Figure 3. Frequency distribution of TiO_2 for all fresh, chilled, Triassic diabase samples.

small range of values within types also argues against such effects. No effects of weathering or alteration on Ti content could be recognized.

The histograms of Cu and Ti content (Figs. 2, 3) show that (1) two and three distinct populations exist for Cu and Ti, respectively; (2) in the Cu diagram, there is no overlap in the populations after removal of a few altered and weathered samples; (3) in the Ti diagram, there is no overlap in the populations; and (4) the range of values within each population is somewhat larger than the estimated sum of sample preparation and analytical errors but is still small compared to the ranges typically expected in studies of igneous plutons and similar bodies. This uniformity for samples as much as 225 km apart indicates an extremely homogeneous magma.

Type localities where good exposures occurred were selected for each of the three types of Triassic diabase found in Pennsylvania. The corresponding geographic names will be used hereafter in place of "higher-Cu" or "lower-Cu."

Excellent exposures of the higher-Cu diabase (York Haven type) are found above the Penn Central railroad grade along the west side of the Susquehanna River at York Haven, York County, and good exposures immediately across the river at Falmouth, Lancaster County. During dry periods, fair exposures also occur in the middle of the river (in Dauphin County). Together, these constitute the York Haven type locality.

The lower-Cu, intermediate-Ti type of diabase (Rossville type) is well exposed in a road cut along Pennsylvania Route 74, 0.6 km southeast of Rossville, York County. At the Rossville type locality, upper and lower contacts of an approximately 3-m-thick appendage of a larger sheet to the north are exposed. The hornfels that makes up the bulk of the exposure is very tough and, except for the plagioclase phenocrysts in the diabase, close examination is needed to distinguish the diabase from the baked sediments.

A good exposure of the Quarryville type (lowest TiO_2, olivine bearing) has been found by Lanning (1972) in a railroad cut 2.1 km east of Quarryville, Lancaster County. Here the main dike is 30 m thick and dips steeply to the west.

CHEMICAL COMPOSITION OF DIABASE

Table 1 lists the median major and minor oxide composition of chilled borders from the Rossville, York Haven, and Quarryville types of diabase. The York Haven type is a typical quartz-normative tholeiite, and the Rossville type is similar except for higher Al_2O_3. These two diabase types are significantly different only for Al_2O_3, MgO, K_2O, TiO_2, and P_2O_5. The Quarryville type contains olivine in both the mode and norm and is distinctly lower in SiO_2 and high in MgO.

TABLE 1. MEDIAN MAJOR AND MINOR OXIDE COMPOSITION OF DIABASE

Oxide	Rossville type median (%)	York Haven type median (%)	Quarryville type median (%)
SiO_2	50.56	51.84	46.60
Al_2O_3	16.56	14.34	15.45
Fe_2O_3	1.07	1.18	1.66
FeO	9.02	8.75	8.42
MgO	6.79	7.72	13.10
CaO	10.81	10.73	10.55
Na_2O	1.95	1.96	1.57
K_2O	0.39	0.60	0.35
H_2O^+	0.46	0.23	1.15
TiO_2	0.74	1.09	0.43
P_2O_5	0.09	0.12	0.07
MnO	0.18	0.20	0.17
CO_2	0.12	0.08	0.00
Total	98.74	98.84	99.52
No. of samples	20	30	15

For Co, Cr, Cu, Ni, and Zn, the medians in Table 2 are based on analysis of more than 100 samples. For the remaining elements, the medians are based on analyses of a representative subgroup of 13 samples, which included 4 samples from the Rossville type, 6 from the York Haven type, and 3 from the Quarryville type. Samples of dikes and sheets are included among both the York Haven and Rossville samples, and 3 of the York Haven samples are from near Cornwall type magnetite deposits (Spencer, 1908). Chemical data for samples are reported by Smith (1973). These 13 samples were also examined petrographically.

TABLE 2. TRACE-ELEMENT COMPOSITION

Element	Rossville type median (ppm)	York Haven type median (ppm)	Quarryville type median (ppm)
Au	0.0022	0.0035	n.a.*
B	8.	8.	n.a.*
Ba	115.	160.	97.
Be	0.2	0.6	<0.1
Ce	16.	33.	n.a.*
Cs	1.0	1.3	n.a.*
Cl	48.	66.	150.
Co	46.	47.	67.
Cr	205.	302.	1,020.
Cu	66.	121.	102.
Dy	4.0	4.7	n.a.*
Eu	0.92	1.22	n.a.*
F	135.	195.	300.
Ga	16.	18.	19.
Ge	1.8	1.4	2.2
Hg	0.048	0.060	0.001
Hf	1.2	2.1	n.a.*
In	0.2	0.2	n.a.*
Li	17.	13.	18.
La	4.5	8.5	n.a.*
Lu	0.49	0.50	n.a.*
Nb (1)	10.	12.	n.a.*
Nb (2)	6.6	9.6	n.a.*
Nd	24.	32.	n.a.*
Ni	63.	89.	455.
Pb	2.4	2.8	16.
Pd	0.001	0.005	0.008
Pt	0.007	0.008	0.011
Rb	21.*	25.†	22.
S	486.	112.	730.
Sb	0.2	<0.1	n.a.*
Sc	51.	41.	38.
Sm	1.9	3.2	n.a.*
Sn	<0.1	0.2	1.6
Sr	137.	187.	136.
Ta	0.18	0.48	n.a.*
Tb	0.50	0.78	n.a.*
Th	1.7	2.2	n.a.*
U	0.45	0.57	n.a.*
V	300.	310.	200.
Y	20.	20.	14.
Yb	2.2	2.1	n.a.*
Zn	79.	77.	71.
Zr	66.	115.	25.
δS^{34}§	-3.9	+0.1	n.a.*

Note: Nb (1) values determined by authors. Nb (2) values determined by Jack J. Rowe, U.S. Geol. Survey.

* Not analyzed.

† X-ray fluorescence values corrected to make W-1 agree with accepted value of 21 ppm.

§ Data compiled from Smitheringale and Jensen (1963).

Medians are reported in Table 2 because of non-normal distributions found by preparing histograms for some elements and the occurrence of spurious high values, which probably do not represent elemental concentrations in the original magma. Some of the samples from near Cornwall type ore deposits have been enriched in Cs, Cl, and Ag.

For many elements, the two quartz-normative types are distinctly different. For Au, Ba, Be, Ce, Cu, Dy, Eu, Hf, La, Nb, Nd, S, Sb, Sc, Sm, Sr, Ta, Tb, and Zr, no overlap exists between the Rossville and York Haven types. Based on the nonparametric "U" test of Hoel (1954), B, Co, Ge, Hg, In, Lu, Pb, Th, U, V, Y, Yb, and Zn do not differ significantly at the 95 percent confidence level. Little can be concluded from the three Pd and Pt analyses, because each diabase type was represented by only one sample.

In general, the elements that differ significantly between the Rossville and York Haven types are the ones whose size, charge, and polarizability preclude their ready substitution in significant amounts into the major igneous rock-forming minerals believed present in the upper mantle (olivine, aluminous pyroxenes). In other words, they are the incompatible elements of Green and Ringwood (1967). Most trace elements (Au, Ba, Be, Ce, Cs, Cl, Cr, Cu, Dy, Eu, F, Ga, Hf, La, Nb, Nd, Rb, Sm, Sn, Sr, Ta, Tb, Zr) are enriched in the York Haven relative to the Rossville diabase. Only S, Sb, Sc, and possibly Ge and Li are higher in the Rossville type.

Relative to the York Haven and Rossville quartz-normative tholeiites, the Quarryville olivine tholeiite is very low in incompatible trace elements and in Hg. Elements that might be expected to concentrate in a higher temperature melting fraction are strongly enriched, for example, Cr and Ni. Quarryville samples contain 700 to 750 ppm S in comparison with a saturation value of 380 ppm S for basalt in Hawaii (Skinner and Peck, 1969). The high values observed for Cl, F, and Pb are not understood.

In their study of sulfur isotopes in Triassic diabase, Smitheringale and Jensen (1963) gave precise sample localities. Their data for Pennsylvania permit calculation of δS^{34} values for the two most abundant

TABLE 3. TYPICAL MINERALOGY OF DIABASE FROM CHILLED BORDERS

	York Haven	Rossville	Quarryville
Texture	Variety of textures but most often intergranular to subophitic	Intergranular to subophitic	Subophitic microphenocrystic
Felsic minerals	Groundmass plagioclase laths An[illegible], based on Michel-Levy maximum extinction method	Groundmass plagioclase laths An[illegible]; centimeter-sized euhedral bytownite-anorthite phenocrysts present in most hand specimens but not in each thin section	Groundmass plagioclase laths An[illegible]; approximately 56% by volume
Mafic minerals	Approximately 1 to 2% olivine microphenocrysts of Fo[illegible] (2V~90 ± 5°); euhedral when fresh; more altered microphenocrysts have iddingsite core and chlorite rim; most microphenocrysts are subhedral augite, some with simple twinning; sparse, euhedral hypersthene microphenocrysts in some samples; where groundmass pyroxene is coarse enough to be identified, it is pigeonite	Approximately 1% olivine microphenocrysts of Fo[illegible] (2V~90 ± 5°) now half-altered to iddingsite; anhedral augite (2V~50 ± 10°), with either hypersthene or pigeonite, comprises groundmass pyroxene	Approximately 15% anhedral olivine microphenocrysts of Fo[illegible] (microprobe analysis, Lanning, 1972); olivine cut by fractures along which fine opaques have developed; approximately 30% is groundmass augite (2V~55 ± 10°); no orthopyroxenes observed
Accessory minerals	Apatite as prisms and acicular crystals in samples with well-crystallized groundmass; no apatite visible in extremely fine-grained samples; approximately 2% biotite in samples from contacts with clastic rocks; essentially no biotite in samples from contacts with carbonate rocks	Tiny, acicular apatite crystals in plagioclase; approximately 1% total biotite present in pyroxene, as partial rims on opaque oxides, replacing olivine, and interstitial	No apatite or biotite observed; therefore, both probably much less than 0.1%; tiny, golden brown, euhedral (Cr spinel) octahedra are present in olivine microphenocrysts
Sulfides	Subrounded chalcopyrite blebs and irregular pyrite grains	Subrounded blebs of pyrrhotite, some with a chalcopyrite lamella; some chalcopyrite as discrete grains; pyrite as subrounded blebs and stringers	Tiny, subrounded, mixed blebs of pyrrhotite and pentlandite (?); abundant, very fine grained (2μ) yellow sulfides (chalcopyrite?)
Oxides	Approximately 3 to 5%, separate, homogeneous, subrounded grains of ilmenite and magnetite with ilmenite roughly twice as abundant	Approximately 2% interstitial, subhedral to anhedral ilmenite and magnetite in roughly equal amounts	Approximately 2 to 3% anhedral magnetite with traces of ilmenite

types. Their data show higher δS^{34} in the York Haven type. Smitheringale and Jensen regarded the rocks with lower δS^{34} (now known to be from the higher-S Rossville type) as volcanic to hypabyssal and regarded the rocks with higher δS^{34} (now known to be from the lower-S York Haven type) as having been from deeper intrusions. There is, however, no field evidence to support shallower emplacement for Rossville magma; in fact, the only known extrusive rocks of Triassic age in Pennsylvania are of York Haven tholeiite.

MINERALOGY OF DIABASE SAMPLES

The typical mineralogy of 13 samples from the chilled borders of Rossville, York Haven, and Quarryville tholeiites is presented in Table 3, based on x-ray diffraction patterns plus examination of a thin section and a polished section. Optical properties were usually obtainable only on the larger mineral grains, and the descriptions may be biased as a result.

The Quarryville type has weakly aligned olivine crystals and an incipient fracture cleavage best developed in olivine-rich zones. Point counting suggests a composition of 13 percent olivine, 30 percent clinopyroxene, 56 percent plagioclase, and 1 percent opaque minerals. As noted above, Rossville type diabase is characterized by anorthite-bytownite phenocrysts.

DISTRIBUTION AND AGE RELATIONS OF DIABASE IN PENNSYLVANIA

The gross structure and intrusive history of the Triassic basin in Pennsylvania is controversial (Faill, 1973). Lapham (1971) and others postulated that all Triassic diabase was derived from a single magma type that appeared first as flows, then as sheets, and last as dikes. Van Houten (1969) stated that the dikes

> . . . commonly extend beyond the basin border but are not offset along its faulted margin. Thus, these dikes are younger than the sills and flows, their subsequent tilting, and the major faulting of the basin.

The structural history has been worked out from this inferred sequence of events and from the fact that intrusion occurs along planes of weakness. Sanders (1963), for example, related the above sequence to a complicated full-graben model in which there was great relief adjacent to the normal faults bounding the basin. Faill (1973) denied the existence of a major fault bounding the northwest margin of the basin and explained the dip and facies distribution of the sediments by synclinal downwarp.

Our data do not support the hypothesis that the order of emplacement of diabase in Pennsylvania was flows, then sheets, then dikes. We conclude that the order of events was (1) intrusion of the Quarryville olivine tholeiite dike group; (2) emplacement of York Haven quartz-normative tholeiite flows, sheets, and dikes over a short time period; and (3) emplacement of Rossville quartz-normative tholeiite sheets and dikes over a short time period.

The York Haven diabase occurs as sheets and dikes along the entire Triassic basin in Pennsylvania and as flows near Reading and Heidlersburg (Fig. 1). The Rossville type occurs as sheets in the area between Gettysburg and Dillsburg and as dikes extending at least as far east as Jacksonwald. The Quarryville type occurs as a dike swarm near Quarryville.

The chemical data demonstrate that the sheets, dikes, and flows of a single type are essentially identical in composition. For instance, sheets, dikes, and flows of the York Haven type average 1.09 percent, 1.11 percent, and 1.13 percent TiO_2, respectively, and 90, 90, and 98 ppm Ni, respectively (the value for flows is based on only three analyses). For the Rossville type, averages of sheets and dikes are 0.74 percent and 0.74 percent TiO_2 and 65 and 61 ppm Ni, respectively.

Retention of a large body of homogeneous magma for long periods of time within the crust or upper parts of the mantle without change in composition is very unlikely. The temperature at the base of the crust is estimated to be between 400° and 700°C (Wyllie, 1971, p. 31). Basaltic magma at these pressures has a liquidus of 1050°C or higher, and a body of basaltic magma at the base of the crust would, therefore, be 350° to 650°C hotter than its surroundings and would tend to crystallize. Based on equations developed by Irvine (1970), a sheet of basaltic magma 2 km thick and 400°C above its surroundings would be half crystallized in about 20,000 yr. Olivine is almost certain to crystallize from a basaltic magma derived from olivine-bearing mantle (Green and Ringwood, 1967; O'Hara, 1965), and crystallization of even 5 percent of the magma as olivine would deplete the remaining magma in nickel. On this basis, storage of a homogeneous, unfractionated body of magma in the crust for periods of even 20,000 yr does not seem possible. Therefore, the lack of any difference in Ni content between sheets, dikes, and flows suggests that these three forms of occurrence were emplaced from a homogeneous reservoir at almost the same time, probably within a few thousand years of each other. It is noteworthy in comparison that other sequences of basaltic magmas, such as the Columbia River basalts, show distinct changes in composition from one flow to the next, apparently reflecting differentiation of the parent magma (Gunn and Watkins, 1970; Wright and others, 1973).

As a second alternative, the magma might be stored in the mantle where temperatures are higher and crystallization would be slower (though still not negligible). In this case, however, the density difference between basaltic magma and mantle is much larger, and the magma would tend to rise if it occurred in a large body. On the other hand, a large well-mixed body seems the only simple means of attaining a large amount of very homogeneous magma. Therefore, storage of magma without changes in composition for any geologically long period of time is unlikely.

A third alternative is generation of several batches of magma with identical composition. The diversity of trace-element abundance in basaltic magmas compared to the uniformity in the three types makes this alternative difficult to accept. We conclude that the three types of diabase represent three events, with little age difference between sheets, dikes, and flows within each type.

QUARRYVILLE DIKE GROUP

The main Quarryville dike swarm extends from near Morgantown to the Susquehanna River near Wakefield (Fig. 1). Lanning (1972) showed that the main dike terminates at the southern edge of the Triassic basin. However, he found a separate olivine tholeiite dike at Terre Hill, 5 km west of the main Quarryville dike, which extends several kilometres into the Triassic basin. This dike indicates that the Quarryville event is younger than deposition of the lower Stockton Formation of Late Triassic age (or younger than the lower New Oxford Formation).

At about half the locations examined by Lanning (1972), the olivine tholeiite has a fracture cleavage. A cleavage in diabase was not observed at any of the approximately 500 examined contacts of the Rossville and York Haven dikes, sheets, or flows, including Rossville type dikes intruding the main Quarryville dike swarm. This difference suggests that the Quarryville is the oldest type. In addition, based on float distribution, Lanning (1972) concluded that the Quarryville dike is cut by Rossville dikes.

GETTYSBURG SHEET

The "Gettysburg sill" (Stose, 1932; Stose and Jonas, 1939) is a complex, multiple-intrusion sheet (Fig. 1) composed of one-third Rossville and two-thirds York Haven diabase. In general, York Haven diabase forms the concordant base of the sheet on the southeast side of the generally northwest-dipping intrusion. The upper portion of the sheet and the westward discordant projections are predominantly Rossville type. Diabase dikes examined on the west side of the Gettysburg sheet are Rossville type, and all but one of those, within an area extending 16 km southeastward from the sheet, are York Haven type. Within the northwesterly prongs of the sheet are two small lava flows, both York Haven type.

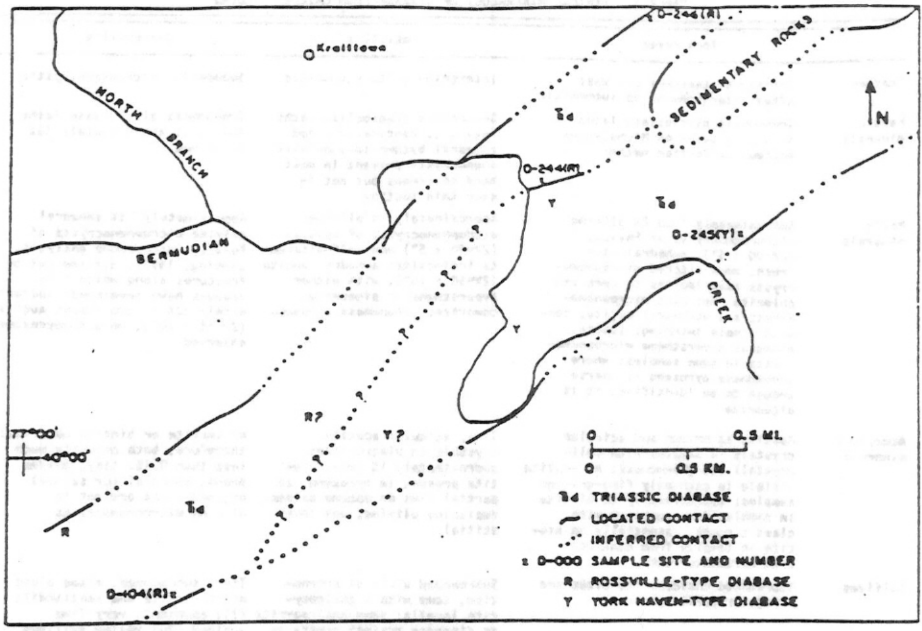


Figure 4. Geologic sketch map of diabase in the vicinity of Bermudian Creek, Wellsville 7½' quadrangle, York County, Pa., showing field relations of Rossville and York Haven types of diabase.

The data of Hotz (1950, 1953) indicate that both the York Haven and Rossville types of diabase are present in the vicinity of the Dillsburg magnetite deposits. TiO_2, Al_2O_3, P_2O_5, and S contents of the chilled contacts (Hotz, 1953) indicate that the thin upper sheet is Rossville diabase, and that the thick lower sheet encountered in drill holes is York Haven diabase. The interpretation by Hotz (1950) that the upper sheet is an offshoot of the underlying sheet is not correct, because the two sheets are different chemical types. Sedimentary rocks probably lie between the upper and lower sheets from the Dillsburg deposits to the northeastern edge of the Gettysburg sheet.

From the northeast corner of the Gettysburg sheet to Bermudian Creek, 18 km to the southwest, the sill is separated parallel to its strike by a nearly continuous inlier of sedimentary rocks. The diabase northwest of the sedimentary inlier is Rossville type; that to the southeast is York Haven type. Along the steep northeast bank of Bermudian Creek, a chilled zone of Rossville diabase in contact with coarse-grained York Haven diabase and granophyre is exposed (Fig. 4). The chilled contact of Rossville cutting across York Haven diabase shows that Rossville is younger than York Haven by at least the few thousand years required for cooling of the York Haven magma, as found from heat-flow calculations (Irvine, 1970). Three kilometres southwest of Bermudian Creek, the sheet is composed only of Rossville diabase.

Because Rossville and York Haven diabase are likely present at the upper and lower contacts, respectively, another internal contact may pass through the Gettysburg sheet where it widens east of Heidlersburg (Fig. 1), but the location of this contact is inferred. From this point southwest to the Maryland border, the concordant southeast portion of the Gettysburg sheet is composed of York Haven diabase. Near Greenmount, the sheet of York Haven diabase is cut by a dike of Rossville diabase that has chilled contacts. As shown in Figure 1, the ringshaped sheet southwest of Gettysburg and its northward projection are inferred to be Rossville diabase, in this case mainly granophyric.

Samples D–102 and D–235 were collected from two basalt flows along the northwest border of the Triassic basin northwest of Heidlersburg. Samples that were only slightly vesicular were chosen for analysis because of their relative lack of alteration. The respective values for samples D–102 and D–235 are TiO_2, 1.09 and 1.15 percent; Cr, 310 and 290 ppm; Co, 49 and 46 ppm; Ni, 101 and 86 ppm; Cu, 121 and 120 ppm; and Zn, 77 and 118 ppm. Of these elements, only Zn in D–235 is slightly atypical for York Haven diabase. Fe_2O_3 and H_2O^+ are higher than in samples of intrusive rocks, but other major elements are similar to York Haven diabase.

ST. PETERS–BIRDSBORO SHEET

The St. Peters–Birdsboro sheet is composed of York Haven diabase. Although the limb of the sheet near Birdsboro (Fig. 1) has normal York Haven type chilled zones, felsic differentiates are more abundant within the sheet than in other York Haven sheets,

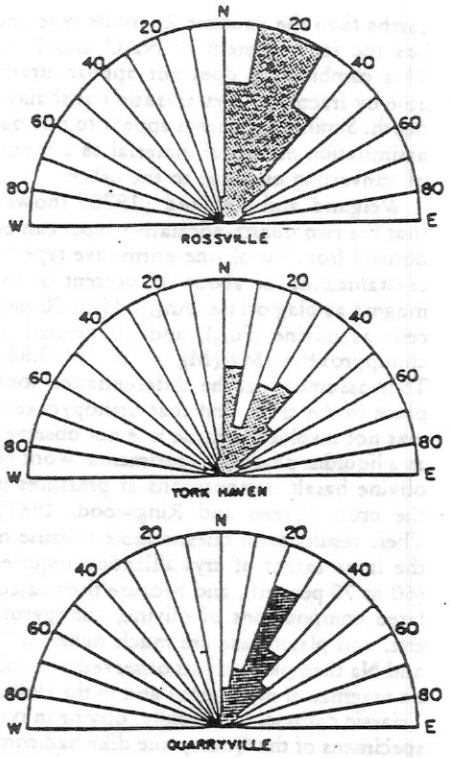


Figure 5. Rose diagrams for strike of Triassic diabase dikes of three types by 2-mi segments.

and the paleomagnetic measurements of Beck (1965) suggest that some may approach the younger Rossville age (Smith, 1973).

The northeast-trending dike southwest of Birdsboro is Rossville type and, from distribution of float, is inferred to cut across the T-shaped dike identified as York Haven type. Thus, the Rossville dike is younger than the York Haven dike.

Between Birdsboro and Jacksonwald, a small arcuate sill is separated from a parallel overlying 150-m-thick basalt flow by a layer of Triassic Brunswick Formation. Both the sill and the flow are composed of normal York Haven diabase. Following the igneous activity, the small sill, the Jacksonwald flow, and the enclosing Triassic sandstone and conglomerate were deformed into a northwest-plunging syncline, which is cut off by a fault along the northwest border of the Triassic province. Wherry (1910) mapped a dike that disappears at the base of the sill and appears again northeast of it. This Rossville dike may cut across the small sill or pass along its base. The order of events for the Jacksonwald area is emplacement of the small York Haven type sill and Jacksonwald basalt flow, then synclinal folding and contemporaneous or later faulting along the northwest side, with an uncertain age of intrusion of the Rossville dike relative to the latter two events.

Because Rossville igneous activity took place after York Haven activity, and because the three known York Haven basalt flows in Pennsylvania occur in the uppermost preserved Triassic sediments, it is unlikely that Rossville flows, if any ever existed, are preserved within the Triassic basin of Pennsylvania.

DIKES IN PRECAMBRIAN TERRANE

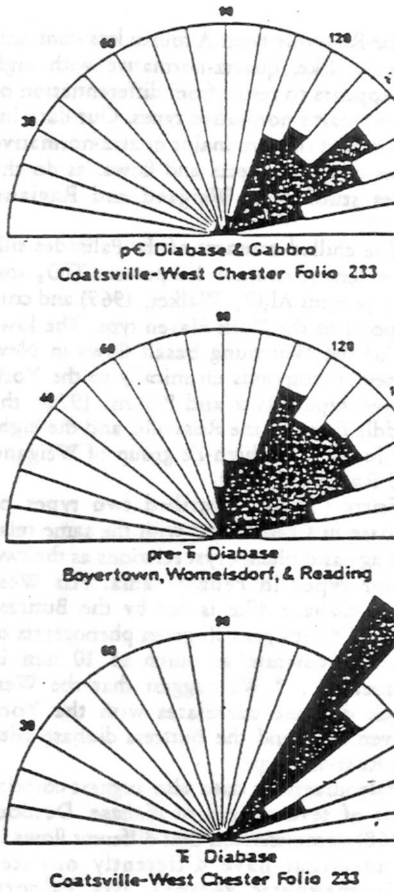
Six samples of chilled diabase from Precambrian terrane have compositions unlike those of the chilled diabase within the Triassic basin in Pennsylvania. Relative to Triassic samples, the samples from Precambrian terrane are altered, contain abundant opaque minerals, are high in total Fe, K_2O, TiO_2, P_2O_5, Cl, S, and Zn, and are low in MgO, Cr, and Ni (Smith, 1973). Several such dikes contain abundant sulfides (in one case as globules) or occur near sulfide occurrences of the Phoenixville area. The only diabase of similar composition found within the Triassic basin is a differentiate within a normal York Haven diabase sheet. Probably the dikes in Precambrian terrane are Precambrian or Ordovician in age.

DIABASE DIKE ORIENTATION

King (1961, 1971), Sanders (1963, 1971), Lapham and Saylor (1970), Lapham (1971), May (1971), and Faill (1973) and others have used orientation of Triassic diabase dikes as evidence to support various structural hypotheses. Rose diagrams were prepared (Fig. 5) using the average strike for 3.2-km intervals, as shown on the map of Gray and others (1960). All three types have approximately the same orientation. The York Haven dikes have a larger spread of orientations than the Rossville dikes and also have an apparent bimodal plot. This bimodal distribution is probably misleading because the Safe Harbor dike of York Haven composition continues 65 km into Maryland with an approximate strike of N. 20° E. (Cohee and others, 1962), which would fill in the minimum between the two maxima.

Rose diagrams were also prepared for Precambrian diabase and gabbro dikes mapped in the Coatesville–West Chester quadrangle (Bascom and Stose, 1932). The northeast trend is also predominant for these Precambrian dikes (Fig. 6). Rose diagrams for diabase dikes in the Boyertown (Buckwalter, 1959), Womelsdorf (Geyer and others, 1963), and Reading (Buckwalter, 1962) quadrangles are also presented in Figure 6. Medians differ slightly, but a strong northeast orientation prevails. This northeast trend appears to reflect an important direction of stress or crustal weakness from the Precambrian through the Triassic.

Roberts (1971) showed that dikes change to sheets where the minimum principal stress direction changes from a horizontal direction at depth to a vertical direction near the surface because of decreasing load of the overlying rocks. Dikes observed at the surface could be feeders or offshoots of the sheets, formed contemporaneously with them as indicated by the chemical data.



p€ Diabase & Gabbro
Coatsville-West Chester Folio 233

pre-Ꞧ Diabase
Boyertown, Womelsdorf, & Reading

Ꞧ Diabase
Coatsville-West Chester Folio 233

Figure 6. Rose diagrams for the strike of Precambrian and Paleozoic diabase dikes in eastern Pennsylvania.

Stose and Bascom (1929, p. 12) and Sanders (1971) assumed a graben model in which the minimum principal stress was perpendicular to the basin margin, and dike intrusion should therefore be parallel to the margin. Most dikes, however, are subnormal to basin margins. This suggests that some reorientation of the stress occurred between the period of subsidence and the formation of dikes and sheets.

TRIASSIC DIABASE OUTSIDE PENNSYLVANIA

Weigand and Ragland (1970), in a study restricted to dikes but including localities throughout eastern North America, also distinguished three main types of diabase on the basis of major- and trace-element analyses. Their olivine-normative type corresponds approximately to the Quarryville type. Their high-TiO_2 quartz-normative type corresponds to the York Haven type and their low-TiO_2 quartz-normative type to the Rossville type. A fourth less-common type of dike, quartz-normative with high Fe, appears to result from differentiation of other quartz-normative types. Our data indicate that the two major quartz-normative types occur as sheets and flows, as do the dikes studied by Weigand and Ragland (1970).

The chilled contacts of the Palisades sill, New Jersey, contain 1.2 percent TiO_2 and 14.5 percent Al_2O_3 (Walker, 1969) and correspond to the York Haven type. The lowest of the Watchung basalt flows in New Jersey corresponds chemically to the York Haven type (Black and Piburn, 1972), the middle flows to the Rossville, and the highest flows to the high-Fe group of Weigand and Ragland (1970).

Fritts (1963) described two types of diabase in Connecticut with the same relative age and phenocryst relations as the two major types in Pennsylvania. His West Rock diabase dike is cut by the Buttress diabase "with grayish-green phenocrysts of calcic bytownite as much as 10 mm in diameter. . . ." We suggest that the West Rock diabase correlates with the York Haven type and the Buttress diabase with the Rossville type.

Paleomagnetic data also suggest correlations of several ages of diabase. De Boer (1968) demonstrated that different flows in Connecticut have differently oriented paleomagnetic vectors. His Talcott, Holyoke, and Hampden events (oldest to youngest) have mean thermoremanent magnetic inclinations from the horizontal of 12°, 25°, and 42°. The Palisades sill and Watchung basalt flows in New Jersey fit the Holyoke event dated at 193 ± 6 m.y. ago. York Haven diabase from Pennsylvania has a latitude-corrected mean inclination of 27° (Beck, 1965), in good agreement with the Holyoke event and with the chemical characteristics of the coeval Palisades diabase. Two samples of Rossville diabase average 38°, in satisfactory agreement with the Hampden event. De Boer also noted that samples of the White Mountain magma series, dated at 180 m.y. or earliest Jurassic, have magnetic inclinations distinctly steeper than the Hampden event, suggesting that all the diabases are Triassic rather than Jurassic.

CLASSIFICATION

Based on CIPW norms (Table 4) and the scheme of Yoder and Tilley (1962), the York Haven and Rossville types are quartz tholeiites, and the Quarryville is olivine tholeiite. However, some aspects of the Quarryville type, namely the presence of traces of olivine in the groundmass and its location on a plot of cation-normative olivine-orthopyroxene-clinopyroxene (Irvine and Baragar, 1971), might qualify it as alkali basalt, especially in the centers of dikes where olivine has been concentrated by flowage differentiation (Lanning, 1972).

TABLE 4. CIPW NORMS

	York Haven (%)	Rossville (%)	Quarryville (%)
Quartz	2.92	1.79	0.00
Orthoclase	3.55	2.31	2.06
Albite	16.59	16.50	13.28
Anorthite	28.56	35.28	34.07
Diopside	19.54	14.63	14.34
Wollastonite	(9.97)	(7.42)	(7.44)
Enstatite	(5.59)	(3.85)	(4.87)
Ferrosalite	(3.98)	(3.37)	(2.04)
Hypersthene	23.32	24.49	9.92
Enstatite	(13.63)	(13.06)	(6.99)
Ferrosalite	(9.68)	(11.43)	(2.93)
Magnetite	1.71	1.55	2.41
Ilmenite	2.07	1.41	0.82
Apatite	0.28	0.21	0.16
Olivine	0.00	0.00	21.28
Forsterite	..	..	(14.55)
Fayalite	..	..	(6.73)
Total	98.53	98.16	98.37
Normative plagioclase	An_{65}	An_{68}	An_{72}

Note: CO_2 not included in calculation.

DERIVATION OF MAJOR-ELEMENT COMPOSITIONS

Basaltic magma is generally considered to originate by partial fusion of the mantle, for which most workers infer a peridotitic composition (Green and Ringwood, 1967; Yoder, 1973; Wyllie, 1971). Yoder (1971, 1973), Kushiro and others (1972), and Nicholls and Ringwood (1973) suggested that quartz-normative tholeiite can form by partial melting of hydrous mantle at pressures of about 20 kb. The amount of water dissolved in the magma under these conditions, however, is at least in the 5 to 10 percent range, and in most of their experiments, much larger. In contrast, the chilled borders of the Triassic diabase contain < 1 percent water, and the Triassic igneous rocks show no indication (extreme vesiculation, explosive eruption, extensive hydrous alteration of diabase or other rocks of the region) of having contained such high amounts of water. Alternatively, Green and Ringwood (1967) suggested that tholeiitic basalt originates as relatively dry olivine-rich picrite at depth in the mantle and fractionates considerable olivine and sometimes other phases on the way to the surface. Although some water undoubtedly was present in the magmas, relatively dry magma seems most reasonable for the Triassic diabase.

A simple relationship between the three types might be as successive liquid fractions formed by differentiation of a single magma or as liquids along two or more differentiation paths from the same parent magma.

Direct derivation of York Haven type from Rossville type magma or vice versa does not seem possible. For instance, the York Haven type has higher MgO, Ni, and Cr and also higher K_2O, Ba, Rb, and rare earths than the younger Rossville type and has the same content of Na_2O and SiO_2. This combination does not appear attainable by fractional crystallization at shallow depth. Similar arguments appear to rule out assimilation of crustal material as a means of converting one type to the other.

Weigand and Ragland (1970) showed that the two quartz-normative types can be derived from the olivine-normative type by crystallization of about 35 percent of the magma as plagioclase (An_{85}), 15 to 20 percent as olivine (Fo_{85}), and 10 percent as clinopyroxene (Mg/[Mg + Fe] of 0.68). They assumed that the differentiation took place in the crust, and that orthopyroxene was not involved because it is not observed as a liquidus phase in experimental work on olivine basalt compositions at pressures in the crust (Green and Ringwood, 1967). Their results seem questionable because of the large extent of crystallization required (60 to 70 percent), and because their calculated compositions of olivine, clinopyroxene, and plagioclase are much richer in Fe and Na than phenocrysts observed in basaltic magmas of other areas and in the chilled Triassic diabase. Specifically, olivine in two specimens of the Quarryville dike had compositions of Fo_{77} and Fo_{82} (Lanning, 1972), and plagioclase phenocrysts in chilled Rossville type diabase are $An_{90\pm5}$ (Smith, 1973).

Because basaltic magmas originate in the mantle, there is no reason to assume that fractionation occurs only in the crust. O'Hara (1965, 1968) summarized evidence for fractionation at all stages from generation to final crystallization. We tested various crystallization processes with this in mind. The following assumptions were made in obtaining the results discussed below: (1) the Quarryville type is the parent and the York Haven and Rossville are derivatives; (2) the molecular ratios of Mg/(Mg + Fe) for olivine, orthopyroxene, and clinopyroxene separating from the magma are identical — this seems a close approximation for temperature conditions in basaltic magma; (3) the crystallizing plagioclase has a composition of An_{85}, near the value observed in the Rossville; (4) all iron is calculated as FeO; (5) the composition of clinopyroxene is approximated by 3 mole percent Al_2O_3 and 30 mole percent $CaSiO_3$, based on analyses of clinopyroxenes from nodules in kimberlite (Boyd and Nixon, 1972) and on the composition of coexisting clinopyroxene and orthopyroxene at temperatures of about 1300°C (Davis and Boyd, 1966); and (6) the assimilation of mantle material may take place as well as crystallization. The minerals considered are olivine, orthopyroxene, clinopyroxene, plagioclase, and spinel, all of which are likely to be present in the upper mantle or are possible crystallizing phases. Garnet did not seem compatible with rare-earth data (discussed below). Hornblende was not included because of its complex composition, and because it does not seem to be important in magmas of low water content.

To find possible assemblages of separated crystals that would yield the observed magmas, starting from the Quarryville composition, equations of the following form were set up relating parent, daughter, and separated crystals:

$$D_i = (P_i - \Sigma a_j C_{ij}) / (1 - \Sigma a_j) ,$$

where P_i, D_i, and C_{ij} are the weight percent of oxide i in the parent, daughter, and separated crystals of mineral j, respectively, and a_j is the proportion of the parent magma crystallized as mineral j. Five equations of this type were set up for SiO_2, Al_2O_3, FeO, MgO, and CaO as oxides, and the amounts of olivine, orthopyroxene, clinopyroxene, and either plagioclase or spinel, plus $FeSiO_3$, were taken as unknowns. For plagioclase as the Al-rich phase, the Mg/(Mg + Fe) ratio of the mafic minerals was then varied until the amount of $FeSiO_3$ was negligible. Table 5–A shows the results using plagioclase after rounding to the nearest 0.1 percent of each of the four minerals. Similar solutions, using an aluminous spinel in place of plagioclase and refined to ±0.03 in Mg/(Mg + Fe), are shown in Table 5–B.

In terms of the amount crystallized, the Mg/Fe of the mafic phases and the plagioclase composition, the solutions in Table 5 are an improvement on those of Weigand and Ragland (1970). The calculated compositions of crystals are very close to those observed for olivine (Fo_{77-83} in Quarryville diabase, from Lanning, 1972, p. 53), bronzite ($En_{78}Fs_{18}Wo_4$ in York Haven diabase, from Smith, 1973, p. 121), and plagioclase (An_{90-85} in chilled Rossville). Because these calculations are sensitive to minor errors in the chemical data, they are certainly not precise, but they do suggest possible methods of deriving the quartz-normative magmas. The slight discrepancies for Na_2O may indicate assimilation (discussed below), too calcic a plagioclase, small analytical errors, or that the spinel case is better. K_2O and TiO_2 will be discussed below as "incompatible elements."

A common feature of the four solutions is the addition of orthopyroxene to the magma, in contrast to crystallization of other minerals. This aspect can be explained in two ways:

1. The Quarryville magma may not be a direct parent of the quartz-normative magmas, but rather one which fractionated from the common parent under conditions in which orthopyroxene was removed. Orthopyroxene occurs on the liquidus of dry olivine tholeiite magmas at pressures of 13 to 20 kb (Green and Ringwood, 1967), so this behavior seems possible, although O'Hara (1968) gave reasons for it being unlikely. The true common parent for all three types would then be found by adding orthopyroxene and perhaps small amounts of other phases. Under this hypothesis, the mineral percentages in Table 5 can be considered as net differences in amounts of phases crystallized to obtain the Quarryville and a quartz-normative magma from the common parent.

2. The alternative explanation is that the Quarryville is the parent, or close to the parent, and that orthopyroxene or equivalent minerals have been assimilated during gradual rise of the magma through the mantle or by assimilation of wall rock during ponding of the magma in the crust. This process is consistent with the observation that in dry basaltic magmas, the field of olivine crystallization expands with decreasing pressure, resulting in crystallization of olivine and the possibility of assimilation of other phases (Green and Ringwood, 1967; O'Hara, 1968). A magma saturated at depth with orthopyroxene would thus tend to assimilate this mineral at shallower depths, as has been suggested by Ito and Kennedy (1968, p. 208) and O'Hara (1968, p. 95). However, the field of orthopyroxene crystallization also expands with decreasing pressure, and in order to avoid saturation with orthopyroxene, it may be necessary to separate olivine by nonequilibrium crystallization caused by continual rise of the magma (O'Hara, 1968) and the resulting pressure decrease. Separation of plagioclase and clinopyroxene, along with additional olivine and perhaps orthopyroxene, might then occur in the crust to explain the observed relationships.

Based on the above discussion, derivation of the two quartz-normative tholeiites from a common parent by differing degrees of crystal fractionation and assimilation of mantle material is a possible explanation for the major-element composition of the quartz tholeiites. Assimilation of crustal material must also be considered, especially in view of the conclusion of Green and Ringwood (1967) that quartz-normative tholeiite can form from dry olivine-normative tholeiite only at depths of 15 km or less (that is, in the crust).

The maximum amount of crustal contamination can be estimated from rare-earth abundances and from strontium isotope ratios. A composite shale typical of crustal material contains 30 ppm La, and a composite basalt has only slightly lower La (Haskin and others, 1966), indicating that most crustal materials would contribute similar amounts of rare earths if assimilated. Note, however, that assimilation of basalt would be relatively ineffective in changing the major-element composition of the magma. Given 4.5 ppm La in the Rossville diabase and 3.5 ppm in olivine-normative diabases of the Quarryville type (Ragland and others, 1971), a limit of about 4 percent crustal contamination (composite shale) is indicated for the Rossville. The higher La content of York Haven diabase allows nearly 20 percent crustal contamination. Even if the parent magma had the very low rare-earth content of oceanic tholeiite (2 ppm La), the limit of possible crustal contamination is only about 10 percent for the Rossville and 25 percent for the York Haven. Although unusual crustal materials might have somewhat lower La, assimilation of such materials seems a questionable general solution for magmas intruded along the entire length of the eastern United States (Weigand and Ragland, 1970).

Strontium isotope data allow similar limits for contamination of the York Haven. The available results (Gast, 1967) for initial Sr^{87}/Sr^{86} on five samples of Triassic diabase average 0.706. The five samples appear to be similar in composition to York Haven diabase. If the primary diabase magma had an initial Sr^{87}/Sr^{86} of 0.703, typical of oceanic tholeiite unaffected by crustal contamination, calculations indicate that the maximum amount of nonmafic crustal material that can have been assimi-

TABLE 5. COMPARISON OF OBSERVED MAGMA COMPOSITIONS WITH CALCULATED COMPOSITIONS AND PHASES DEPLETED

A. Aluminous phase removed: plagioclase

	York Haven observed*	York Haven-calculated†	Rossville observed*	Rossville calculated†
SiO_2	52.80	52.81	51.71	51.72
Al_2O_3	14.61	14.61	16.94	16.98
FeO	10.08	10.05	10.21	10.15
MgO	7.86	7.87	6.94	6.92
CaO	10.93	10.93	11.06	11.02
Na_2O	2.00	2.20	1.99	2.05
K_2O	0.61	0.64	0.40	0.52
TiO_2	1.11	0.78	0.76	0.64
		% removed from Quarryville†		% removed from Quarryville†
Olivine (% Fo)		26.6 (78)		25.7 (83)
Orthopyroxene (% En)		-10.3 (78)		-13.9 (83)
Diopside (Mg/Mg+Fe)		6.0 (78)		8.2 (83)
Composition of diopside		$En_{53}Fs_{11}Wo_{30}Al_6$§		$En_{50}Fs_{12}Wo_{30}Al_8$
Plagioclase (% An)		21.6 (85)		11.3 (85)
Net % of parent crystallized		43.9		31.3

B. Aluminous phase removed: spinel

(Calculated residual magmas are similar to those above)

Parent Quarryville, daughter York Haven

Phases removed: olivine (Fo_{78}), 8%; orthopyroxene (En_{78}), -6%; clinopyroxene ($En_{62.2}Fs_{10.9}Wo_{30}Al_8$), 25%; spinel ($MgAl_2O_4$), 8%.

Parent Quarryville, daughter Rossville

Phases removed: olivine (Fo_{82}), 17%; orthopyroxene (En_{82}), -12%; clinopyroxene ($En_{66.8}Fs_{13.8}Wo_{20}Al_8$), 17%; spinel ($MgAl_2O_4$), 4%

* All compositions of parent and daughter magmas recalculated to 100% for SiO_2, Al_2O_3, FeO, MgO, CaO, Na_2O, K_2O, and TiO_2 before calculations. For the Quarryville parent this yields 47.57% SiO_2, 15.77% Al_2O_3, 10.12% FeO, 13.37% MgO, 10.77% CaO, 1.60% Na_2O, 0.36% K_2O, and 0.44% TiO_2.

† Residual liquid formed from Quarryville depleted by amounts of phases (orthopyroxene added) listed above.

§ Al = Al_2O_3.

TABLE 6. COMPARISON OF TRACE ELEMENTS AND RATIOS FOR TRIASSIC DIABASE WITH BASALT OF OTHER OROGENIC TYPES

	Oceanic tholeiite*	Island-arc tholeiite*	Continental tholeiite*	Rossville	York Haven	Quarryville
Rb (ppm)	0.2 to 5	3 to 10	10 to 30	22	26	22
Cs (ppm)	0.05	0.1	1.0	1.0	1.3	..
Ba (ppm)	6 to 30	50 to 150	300 to 400	115	160	97
Sr (ppm)	70 to 150	100 to 200	100 to 130	137	187	136
K/Rb	800 to 2,000	450 to 1,100	200 to 400	150	190	132
Rb/Sr	0.02	0.01 to 0.05	0.02 to 0.4	0.16	0.14	0.16
La/Yb	1 to 2	1 to 2	12.2	2.1	4.0	1.7
Th/U	1 to 2	1 to 2	2.8	3.8	3.9	..
$U/K \times 10^4$	0.7	1.1	0.25 to 3	1.4	1.2	..

Note: La/Yb based on data of Ragland and others (1971).
* Based on Jakes and Gill (1970) and Compston and others (1968).

lated by the York Haven magma is 20 percent, similar to the figure obtained for the rare-earth data.

Weigand (1970) calculated the compositions of material necessary for converting one diabase type to another by "contamination" and concluded that, because the compositions are not those of normal rock, contamination is not applicable. However, his procedure considers contamination as a simple mixing of magma and contaminant. The true situation (presented by Bowen, 1928) is that assimilation by a magma involves crystallization of phases with which the magma is saturated. The amounts crystallized are approximately equal to the amount of inclusions assimilated and are accompanied by incorporation into the magma of the most soluble components (that is, components of residual systems). Thus, the net effects of assimilation will be dependent on the difference between the composition of crystallized minerals and added material. Specifically, in the case of olivine tholeiite magma, olivine and perhaps some pyroxene and calcic plagioclase will crystallize, and the magma will be enriched in K, Na, Si, incompatible elements (Rb, Cs, Ba, P, U, Th, Zr, rare earths), and perhaps Fe and Ti. The effects do not seem directly calculable, but crystals analogous to those shown in Table 5 will be produced in smaller amounts. The minerals and mineral proportions of Table 5, therefore, seem applicable in a general way to crustal assimilation, although orthopyroxene might not be involved as a high-silica phase.

DERIVATION OF TRACE-ELEMENT COMPOSITION

Assuming that the quartz-normative magmas had a common magmatic parent or mantle source region, the contents of most trace elements can be explained in three ways that are not mutually exclusive. Most minor and trace elements, and especially the "incompatible elements," are enriched in the York Haven type relative to the Rossville. The origin of such enrichments has been discussed by Jamieson and Clark (1970). If the parents of the two quartz-normative magmas originated by partial fusion in the same region of the mantle at different times, the first magma would deplete that part of the mantle in incompatible elements and would be richer in these elements than the second magma. Crystallization of olivine, pyroxene, and plagioclase would remove very little of these elements from the magma, and at the same stage of crystallization, the differences between magmas would remain. It seems doubtful, however, that two episodes of partial melting of the same portion of mantle would produce such similar major-element compositions.

A second possibility is that the higher trace-element content of the York Haven type was attained by greater assimilation during ascent of the magma toward the surface. Later batches of magma (Rossville) either did not assimilate from the same part of the mantle or crust, perhaps because of more rapid ascent, or passed through the same region at a later time and found it depleted in incompatible elements. The relatively high-Al character of the Rossville magma suggests that it differentiated to a quartz-normative composition at a greater depth than did the York Haven (T. H. Green and others, 1967), allowing less opportunity for assimilation of material enriched in incompatible elements. The K/Rb and rare-earth abundances in many peridotite masses (Frey and others, 1971; Steuber and Murthy, 1966) are similar to those in the Triassic diabase, and assimilation of mantle material may explain some trace-element abundances.

A third possible reason for the differing amounts of trace elements is a different degree of crystallization during rise of the two types of magma, as suggested by O'Hara (1968). For some elements (Ba, rare earths, P_2O_5 in the Rossville), the composition of the Rossville is close to the values expected for "residual" concentration from the Quarryville type by removal of crystals in the amounts shown in Table 5. However, values for York Haven magma are consistently too high for this explanation. Jamieson and Clark (1970) pointed out that eclogite-type crystal-liquid fractionation would produce enrichment of incompatible elements. The crystallization of garnet, however, would drastically modify the rare-earth values from those observed.

Nickel and chromium are too high in the York Haven type relative to the Rossville to fit either of the first two models; neither element would be enriched during assimilation or during the first stage of partial fusion. These elements have the reverse behavior, being concentrated in olivine, spinel, and pyroxene relative to magma. However, the abundances of Ni and Cr in the two derivative types seem explainable by strong depletion during crystallization of olivine, pyroxene, and spinel, coupled with a higher extent of crystallization of minerals other than olivine in forming the York Haven magma.

For the remaining elements, including incompatible elements, a combination of the assimilation and residual concentration processes seems the most reasonable means of attaining the observed trace-element content. Because of the low limits for crustal contamination of the Rossville and the compatibility of Rossville trace-element data with that expected for residual accumulation during crystallization of the Quarryville magma, the Rossville magma is concluded to be the result mainly of processes occurring in the mantle. Crystallization may have occurred in the crust, but little or no crustal assimilation is allowed. Considerable assimilation of orthopyroxene from the mantle is therefore indicated.

The relative abundance of europium and other lanthanides is consistent with the differentiation and assimilation models proposed on the basis of the major elements. Crystallization of 20 percent plagioclase is estimated by Philpotts and Schnetzler (1968) to result in a depletion in europium of about 5 percent relative to other rare earths. Analytical errors of at least 5 percent at the level of two standard deviations are estimated for both our data and that of Ragland and others (1971); thus the separation of 21.6 percent plagioclase (Table 5) in forming the York Haven type might not be detectable by Eu depletion. In fact, the data of Ragland and others (1971) seem to show a small depletion of europium for their equivalent of the York Haven type. If some crustal assimilation has taken place, however, the rare-earth values reflect a major component from the assimilated material. The lack of depletion in heavy rare earths suggests that garnet, which has a strong affinity for heavy rare earths (Schnetzler and Philpotts, 1970), is not an important phase in the genesis of the Triassic magmas, either as a residual phase from partial melting or assimilation of a garnet peridotite or eclogite source rock or as a phase crystallizing from the melt.

Many workers have classified basaltic magmas by orogenic environment (oceanic tholeiite, island-arc tholeiite, continental

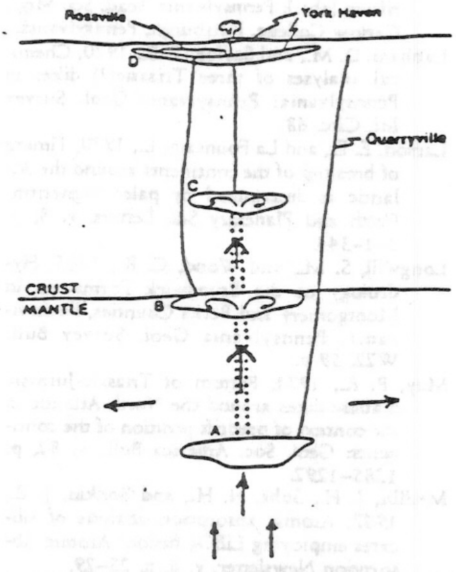


Figure 7. Schematic diagram for origin of magma types. Large arrow and dotted zone indicates assimilation during upward migration or in chamber above. Smaller arrows indicate flowage or migration of mantle material. A, generation and collection of original olivine-rich magma, with intrusion of Quarryville dikes. B, modified magma near Rossville composition formed by assimilation during rise or ponding near base of crust. C, modified magma near York Haven composition formed by assimilation of crustal material.

tholeiite) and have pointed out differences in trace-element content of basalt from these different environments (Jakeš and White, 1971; Jakeš and Gill, 1970; Compston and others, 1968). Table 6 compares the composition of the Rossville, York Haven, and Quarryville types with recognized types of basalt. The Rossville type shows distinct similarities in lanthanide and Ba abundance to island-arc tholeiites (major elements are also very similar), although for K, K/Rb, U, Th, and most other trace elements, it is clearly within the range of continental tholeiite.

DISCUSSION

The following discussion and Figure 7 summarize the most likely explanation of the available data on the origin of Triassic diabase magmas.

The Quarryville magma originated by partial fusion of mantle under relatively dry conditions and rose rapidly into the upper crust. Because of the apparent extensional nature of the Newark-Gettysburg basin, the trend of the basin parallel to the edge of the continent, and the separation of North America from Europe and Africa at about this time (Larson and La Fountain, 1970), it is likely that the process generating the magma was analogous in some respects to that operating in mid-ocean rift zones. If so, the parent material and (or) the overlying mantle and crust were richer in incompatible elements than beneath mid-ocean ridges, and the trace-element abundances of recent oceanic tholeiite were not produced.

Another portion of Quarryville magma rose more slowly through the mantle where it crystallized olivine and assimilated orthopyroxene, then moved into the crust and differentiated at shallow depths yielding the York Haven type by crystallization of olivine, clinopyroxene, plagioclase, and possibly orthopyroxene. A small to moderate amount of crustal assimilation probably occurred at this stage, appreciably increasing the content of incompatible elements and probably silica. The changes in this magma are thus envisioned as a result of a four-stage history: (1) generation in the mantle as olivine tholeiite, (2) crystallization and reaction during ascent through the mantle, (3) crystallization and reaction with crust, and (4) intrusion to the present site, where further differentiation took place after formation of the chilled borders (F. Walker, 1940; Hotz, 1953; W. Walker, 1969; Smith, 1973). Mixing during the third stage was sufficiently thorough to produce relatively homogeneous magmas.

The Rossville magma is inferred to have undergone a similar sequence of events but, judging from the rare-earth data, with little or no assimilation during passage through the crust, perhaps because this episode of differentiation took place at a deeper level in more mafic country rock not as easily assimilated or because of a shorter time spent within the crust. The trace-element contents of the Rossville magma are probably a relatively close representation of the parent of the York Haven magma that resulted from mantle assimilation plus crystallization of olivine and other minerals.

The processes affecting these Triassic magmas do not seem to be unique. For example, Cox and others (1967) distinguished two analogous types of basaltic magma among the Karroo basalt of southern Africa. In a northern province, the basalt is high in incompatible elements but low in alumina, like the York Haven type. In a southern province, the basalt is low in incompatible elements and relatively higher in alumina, crystallizing plagioclase early, like the Rossville type. A similar process of origin seems applicable.

The general nature of the proposed process producing the two quartz-normative Triassic magmas in eastern North America has similarities to the zone-refining concept of Harris (1957) and to the continuous fractionation concept of O'Hara (1965, 1968), in which magma is continually crystallizing and reacting with the mantle as it moves upward. In the case of the York Haven magma, this behavior extended into the crust. If this behavior is generally true of basaltic magmas, then they are far from being simple products of melting in the mantle, but instead their content of both major and trace elements results from a complex series of processes occurring between the source and the final site of intrusion. Not only is the magma modified by these processes, but the mantle is also modified in a direction of increased olivine and decreased incompatible elements in its upper part. Inhomogeneities of the mantle, both laterally and vertically, would result from these processes.

ACKNOWLEDGMENTS

We are grateful to Norman H. Suhr for considerable help with analytical work. Fellowships to Smith were provided under the National Defense Education Act and by the National Aeronautics and Space Administration. Field and laboratory work were supported largely by the Mineral Conservation Section of The Pennsylvania State University. Lanning was supported by a National Science Foundation fellowship.

Analyses for Au and Nb were provided by J. J. Rowe and David Gottfried of the U.S. Geological Survey; Pt and Pd analyses are by W. A. Fuchs. Aid was given by K. M. Khattab on U and Th analyses, by W. A. Jester of the Breazeale Nuclear Reactor at Penn State on neutron activation analyses, and by J. B. Bodkin and J. C. Devine of the Mineral Constitution Laboratory on wet chemical analyses. D. M. Lapham of the Pennsylvania Geological Survey was helpful in suggesting exposures of diabase and discussing genesis. Compositional data on several dikes were furnished by P. W. Weigand. A. L. Boettcher reviewed the manuscript, and C. Wayne Burnham and C. P. Thornton commented on earlier versions of the paper.

REFERENCES CITED

Bascom, F., and Stose, G. W., 1932, Coatesville–West Chester: U.S. Geol. Survey Atlas, Folio 223, scale 1:62,500.

✓ Beck, M. E., Jr., 1965, Paleomagnetic and geologic implications of magnetic properties of the Triassic diabase of southeastern Pennsylvania: Jour. Geophys. Research, v. 70, p. 2845–2856.

Black, W. W., and Piburn, M. D., 1972, Geochemistry of Watchung lavas from the Newark Triassic basin: Geol. Soc. America Abs. with Programs, v. 5, no. 5, p. 378.

Bowen, N. L., 1928, The evolution of the igneous rocks: New York, Dover (repub. 1956), 332 p.

Boyd, F. R., and Nixon, P. H., 1972, Ultramafic nodules from the Thaba Putsoa Kimberlite pipe: Carnegie Inst. Washington Geophys.

Lab., Ann. Rept., p. 362–373.

Buckwalter, T. V., 1959, Geology of the Precambrian rocks and Hardyston Formation of the Boyertown quadrangle: Pennsylvania Geol. Survey Atlas 197.

——1962, The Precambrian geology of the Reading 15' quadrangle: Pennsylvania Geol. Survey Prog. Rept. 161, 49 p.

Cohee, George V., and others, 1962, Tectonic map of the United States: U.S. Geol. Survey and Am. Assoc. Petroleum Geologists, scale 1:2,500,000.

Compston, W., McDougall, I., and Meier, K. S., 1968, Geochemical comparison of Mesozoic basaltic rocks of Antarctica, South Africa, and Tasmania: Geochim. et Cosmochim. Acta, v. 32, p. 129–149.

Cox, K. G., MacDonald, R., and Hornung, G., 1967, Geochemical and petrographic provinces in the Karroo basalts of Southern Africa: Am. Mineralogist, v. 52, p. 1451–1474.

Dana, J. D., 1873, On some results of the earth's contraction from cooling, Pt. IV, Igneous injections, volcanoes: Am. Jour. Sci., v. 106, p. 104–115.

Davis, B.T.C., and Boyd, F. R., 1966, The join $Mg_2Si_2O_6$–$CaMgSi_2O_6$ at 30 kilobars pressure and its application to pyroxenes from kimberlites: Jour. Geophys. Research, v. 71, p. 3567–3576.

De Boer, J., 1967, Paleomagnetic-tectonic study of Mesozoic dike swarms in the Appalachians: Jour. Geophys. Research, v. 72, p. 2237–2250.

——1968, Paleomagnetic differentiation and correlation of the Late Triassic volcanic rocks in the central Appalachians: Geol. Soc. America Bull., v. 79, p. 609–626.

Faill, R. T., 1973, Tectonic development of the Triassic Newark-Gettysburg basin in Pennsylvania: Geol. Soc. America Bull., v. 84, p. 725–740.

Frey, F. A., Haskin, L. A., and Haskin, M. A., 1971, Rare-earth abundances in some ultramafic rocks: Jour. Geophys. Research, v. 76, p. 2057–2070.

Fritts, C. E., 1963, Bedrock geology of the Mount Carmel quadrangle, Connecticut: U.S. Geol. Survey Geol. Quad. Map GQ–199, scale 1:24,000.

Gast, P. W., 1967, Isotope geochemistry of volcanic rocks, *in* Hess, H. H., and Poldervaart, A., eds., Basalts: New York, Interscience, p. 325–358.

Geyer, A. R., Buckwalter, T. V., McLaughlin, D. B., and Gray, C., 1963, Geology of the Womelsdorf quadrangle: Pennsylvania Geol. Survey Atlas 177C.

Gray, C., and others, 1960, Geologic map of Pennsylvania: Pennsylvania Geol. Survey, scale 1:250,000.

Green, D. H., and Ringwood, A. E., 1967, The genesis of basaltic magmas: Contr. Mineralogy and Petrology, v. 15, p. 103–190.

Green, T. H., Green, D. H., and Ringwood, A. E., 1967, The origin of high-alumina basalts and their relationships to quartz tholeiites and alkali basalts: Earth and Planetary Sci. Letters, v. 2, p. 41–51.

Gunn, B. M., and Watkins, N. D., 1970, Geochemistry of the Steen Mountains basalts, Oregon: Geol. Soc. America Bull., v. 81, p. 1497–1516.

Harris, P. G., 1957, Zone refining and the origin of potassic basalts: Geochim. et Cosmochim. Acta, v. 12, p. 195–208.

Haskin, L. A., Frey, R. A., Schmitt, R. S., and Smith, R. H., 1966, Meteoritic, solar, and terrestrial rare-earth distributions: Phys. Chem. Earth, v. 7, p. 167–321.

Hoel, P. G., 1954, Introduction of mathematical statistics (2nd ed.): New York, John Wiley & Sons, Inc., p. 291–293.

Hotz, P. E., 1950, Diamond-drill exploration of the Dillsburg magnetite deposits, York County, Pennsylvania: U.S. Geol. Survey Bull. 969A, p. 1–27.

——1952, The form of diabase sheets in southeastern Pennsylvania: Am. Jour. Sci., v. 250, p. 375–388.

——1953, The petrology of granophyre in diabase near Dillsburg, Pennsylvania: Geol. Soc. America Bull., v. 64, p. 675–704.

Ingamells, C. O., and Suhr, N. H., 1963, Chemical and spectrochemical analyses of standard silicate samples: Geochim. et Cosmochim. Acta, v. 27, p. 897–910.

Irvine, T. N., 1970, Heat transfer during solidification of layered intrusions. I. Sheets and sills: Canadian Jour. Earth Sci., v. 7, p. 1031–1061.

Irvine, T. N., and Baragar, W.R.A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Jour. Earth Sci., v. 8, p. 523–544.

Ito, K., and Kennedy, G. C., 1968, Melting and phase relations in the plane tholeiite-lherzolite-nepheline basanite to 40 kilobars with geological applications: Contr. Mineralogy and Petrology, v. 19, p. 177–211.

Jakeš, P., and Gill, J., 1970, Rare earth elements and the island arc tholeiitic series: Earth and Planetary Sci. Letters, v. 9, p. 17–28.

Jakeš, P., and White, A.J.R., 1971, Composition of island arcs and continental growth: Earth and Planetary Sci. Letters, v. 12, p. 224–230.

Jamieson, B. G., and Clark, D. B., 1970, Potassium and associated elements in tholeiitic basalts: Jour. Petrology, v. 11, p. 183–204.

King, P. B., 1961, Systematic pattern of Triassic dikes in the Appalachian region: U.S. Geol. Survey Prof. Paper 424–B, p. 93–95.

——1971, Systematic pattern of Triassic dikes in the Appalachian region — Second report: U.S. Geol. Survey Prof. Paper 750–D, p. 84–88.

Kushiro, I., Shimizu, N., Nakamura, Y., and Akimoto, S., 1972, Compositions of coexisting liquid and solid phases formed upon melting of natural garnet and spinel lherzolite at high pressures: Earth and Planetary Sci. Letters, v. 14, p. 19–25.

Lanning, R. M., 1972, An olivine tholeiite dike swarm in Lancaster County, Pennsylvania [M.S. thesis]: University Park, Pennsylvania State Univ., 80 p.

Lapham, D. M., 1971, Triassic tholeiitic magma as a fundament of Mesozoic continental rifting [abs.]: Pennsylvania Acad. Sci. Mtg., Carlow College, Pittsburgh, Pennsylvania.

Lapham, D. M., and Saylor, T. E., 1970, Chemical analyses of three Triassic(?) dikes in Pennsylvania: Pennsylvania Geol. Survey Inf. Circ. 68.

Larson, E. E., and La Fountain, L., 1970, Timing of breakup of the continents around the Atlantic as determined by paleomagnetism: Earth and Planetary Sci. Letters, v. 8, p. 341–344.

Longwill, S. M., and Wood, C. R., 1965, Hydrology of the Brunswick Formation in Montgomery and Berks Counties, Pennsylvania: Pennsylvania Geol. Survey Bull. W22, 59 p.

May, P. R., 1971, Pattern of Triassic-Jurassic diabase dikes around the North Atlantic in the context of predrift position of the continents: Geol. Soc. America Bull., v. 82, p. 1285–1292.

Medlin, J. H., Suhr, N. H., and Bodkin, J. B., 1967, Atomic absorption analysis of silicates employing $LiBO_2$ fusion: Atomic Absorption Newsletter, v. 8, p. 25–29.

Nicholls, I. A., and Ringwood, A. E., 1973, Effect of water on olivine stability in tholeiites and the production of silica-saturated magmas in the island arc environment: Jour. Geology, v. 81, p. 285–300.

O'Hara, M. J., 1965, Primary magmas and the origin of basalts: Scottish Jour. Geology, v. 1, p. 19–40.

——1968, The bearing of phase equilibria studies in synthetic and natural systems on the origin and evolution of basic and ultrabasic rocks: Earth-Sci. Rev., v. 4, p. 69–133.

Philpotts, J. A., and Schnetzler, C. C., 1968, Europium anomalies and the genesis of basalt: Chem. Geology, v. 3, p. 5–13.

Ragland, P. C., Brunfelt, A. O., and Weigand, P. W., 1971, Rare-earth abundance in Mesozoic dolerite dikes from eastern United States, *in* Brunfelt, A. O., and Steinnes, E., eds., Activation analysis in geochemistry and cosmochemistry: Universitetsforlaget, p. 227–235.

Roberts, J. L., 1971, On the mechanics of intrusion of sills: Discussion: Canadian Jour. Earth Sci., v. 8, p. 176–179.

Rose, A. W., 1971, Trace metals in stream sediments of southeastern Pennsylvania: Pt. II: Studies of anomalies from Part I: Penn State Univ. Earth and Mineral Sci. Expt. Sta. Bull., no. 86, 14 p.

Sanders, J. M., 1963, Late Triassic tectonic history of northeastern United States: Am. Jour. Sci., v. 261, p. 501–524.

——1971, Regional synthesis of stratigraphy and structure of upper Triassic strata, northeastern North America in light of plate tectonics [abs.]: Pennsylvania Acad. Sci. Mtg., Carlow College, Pittsburgh, Pennsylvania.

Schnetzler, C. C., and Philpotts, J. A., 1970, Partition coefficients of rare-earth elements between igneous matrix and rock-forming mineral phenocrysts — II: Geochim. et Cosmochim. Acta, v. 34, p. 331–340.

Skinner, B. J., and Peck, D. L., 1969, An immiscible sulfide melt from Hawaii, *in* Wilson, H.D.B., ed., Magmatic ore deposits: Econ. Geology Mon. 4, p. 310–322.

Smith, R. C., II, 1973, Geochemistry of Triassic diabase from southeastern Pennsylvania [Ph.D. thesis]: University Park, Pennsylvania State Univ., 262 p. (Available from Dissertation Copies, P.O. Box 1764, Ann Arbor, Mich. 48106, as microfilm or xerox prints.)

Smith, R. C., II, and Rose, A. W., 1970, The occurrence and chemical composition of two distinct types of Triassic diabase in Pennsylvania: Geol. Soc. America Abs. with Program, v. 2, no. 7, p. 688.

Smitheringale, W. G., and Jensen, M. L., 1963, Sulfur isotopic composition of the Triassic igneous rocks of eastern United States: Geochim. et Cosmochim. Acta, v. 27, p. 1183–1207.

Spencer, A. C., 1908, Magnetite deposits of the Cornwall type in Pennsylvania: U.S. Geol. Survey Bull. 359, 102 p.

Steuber, A. M., and Murthy, V. R., 1966, Strontium isotope and alkali element abundances in ultramafic rocks: Geochim. et Cosmochim. Acta, v. 30, p. 1243–1259.

Stose, G. W., 1932, Geology and mineral resources of Adams County, Pennsylvania: Pennsylvania Geol. Survey Bull. C1, 153 p.

Stose, G. W., and Bascom, Florence, 1929, Description of the Fairfield and Gettysburg quadrangles: U.S. Geol. Survey Atlas 225, 22 p., 8 maps, scale 1:62,500.

Stose, G. W., and Jonas, A. L., 1939, Geology and mineral resources of York County, Pennsylvania: Pennsylvania Geol. Survey Bull. C67, 199 p.

Van Houten, F. B., 1969, Late Triassic Newark Group, north central New Jersey and adjacent Pennsylvania and New York, *in* Subitsky, S., ed., Geology of selected areas in New Jersey and eastern Pennsylvania: New Brunswick, N.J., Rutgers Univ. Press, p. 314–347.

Walker, F., 1940, Differentiation of the Palisade diabase, New Jersey: Geol. Soc. America Bull., v. 51, p. 1059–1105.

Walker, K. R., 1969, The Palisades sill, New Jersey: A reinvestigation: Geol. Soc. America Spec. Paper 111, 178 p.

Weigand, P. W., 1970, Major and trace element geochemistry of the Mesozoic dolerite dikes from eastern North America [Ph.D. thesis]: Chapel Hill, N. C., Univ. North Carolina, 162 p.

Weigand, P. W., and Ragland, P. C., 1970, Geochemistry of Mesozoic dolerite dikes from eastern North America: Contr. Mineralogy and Petrology, v. 29, p. 195–214.

Wherry, E. T., 1910, Contributions to the mineralogy of the Newark Group in Pennsylvania: Wagner Free Sci. Inst. Trans., v. 7, p. 5–27.

Wright, T. L., Grolier, M. J., and Swanson, D. A., 1973, Chemical variation related to the stratigraphy of the Columbia River basalt: Geol. Soc. America Bull., v. 84, p. 371–386.

Wyllie, P. J., 1971, The dynamic earth: New York, Wiley, 416 p.

Yoder, H. S., 1971, The join diopside-pyrope-H_2O at 10 kb: Carnegie Inst. Washington Year Book, v. 69, p. 178.

——1973, Contemporaneous basaltic and rhyolitic magmas: Am. Mineralogist, v. 58, p. 153–171.

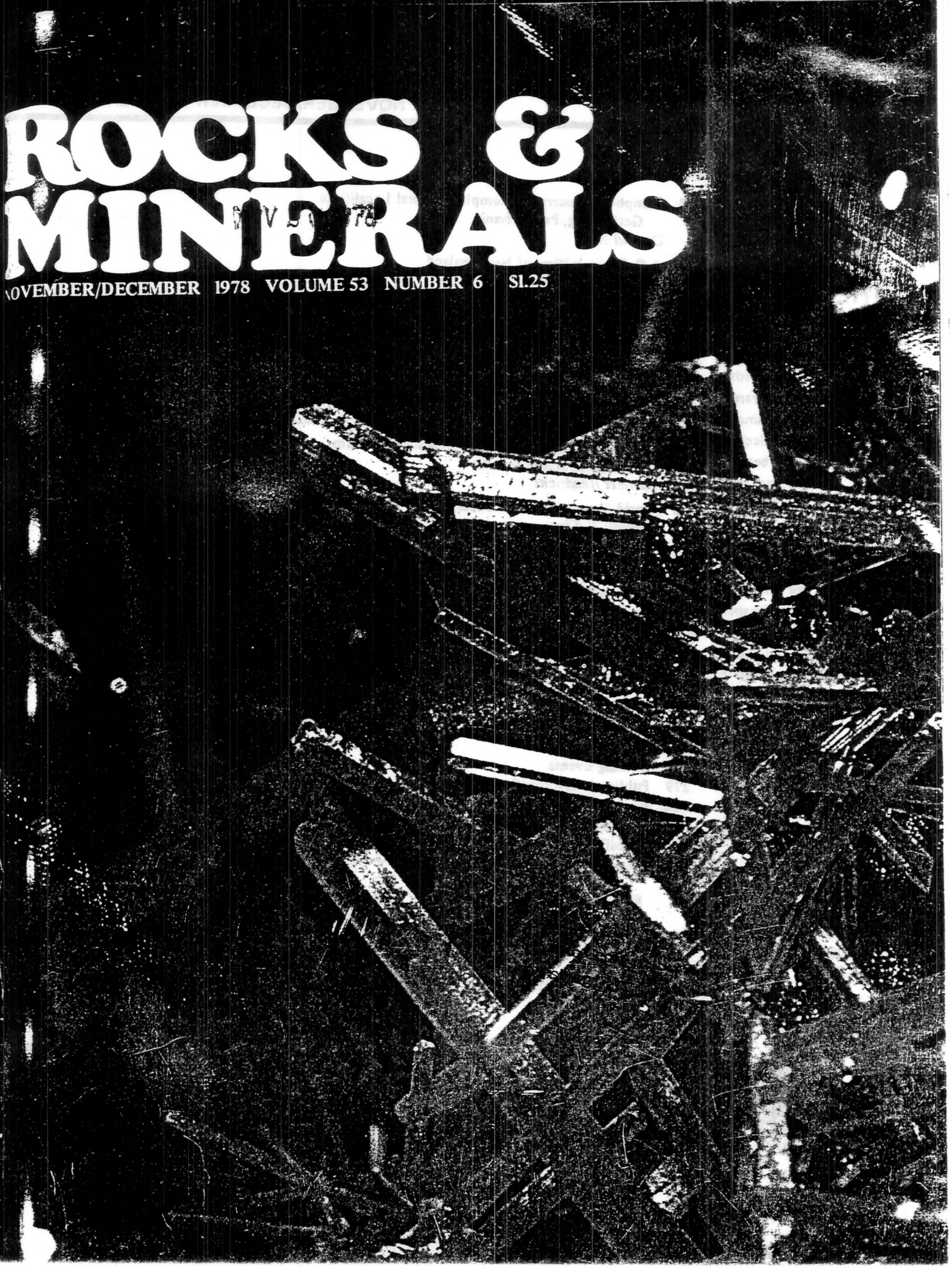
Yoder, H. S., and Tilley, C. E., 1962, Origin of basalt magmas: An experimental study of natural and synthetic rock systems: Jour. Petrology, v. 3, p. 342–532.

MANUSCRIPT RECEIVED BY THE SOCIETY JANUARY 30, 1974

REVISED MANUSCRIPT RECEIVED AUGUST 27, 1974

ROCKS & MINERALS

NOVEMBER/DECEMBER 1978 VOLUME 53 NUMBER 6 $1.25



ROCKS & MINERALS

NOVEMBER/DECEMBER 1978, Volume 53 Number 6

ON THE COVER:

Crocoite ($PbCrO_4$) from Dundas, Tasmania is pictured on this month's cover. One of the rarest of minerals, this mineral is prized by collectors because of its beauty. The crystals on this specimen measure ¼ inch. It was photographed using long bellows rather than a microscope for increased depth of field. The specimen is part of the Smithsonian Collection. Photograph by Joel E. Arem.

FEATURES

DEPARTMENTS

THE EASTERN FEDERATION OF MINERALOGICAL AND LAPIDARY SOCIETIES HAS CHOSEN *ROCKS AND MINERALS* AS ITS OFFICIAL MAGAZINE

Founder:
Peter Zodac

Managing Editor:
Linda Dove

Editorial Assistant:
Karen Deans

Advertising:
Frank C. Turley

Layout:
Jane Rogers

Publisher:
Cornelius W. Vahle Jr.

Published bi-monthly by HELDREF PUBLICATIONS at 4000 Albemarle St., N. W., Washington, D. C. 20016. Telephone: (202) 362-6445. * Annual subscription rates are $10 for institutions and $7 for individuals. Single copy price is $1.25 cents. Add $3.00 for subscriptions outside the U.S. and Canada. Foreign subscriptions must be paid in U. S. dollars.

All orders by individuals should be paid in advance. Institutions may send purchase orders and will be billed. Claims for missing issues made within six months will be made free of charge.

Second class postage paid, Washington, D. C.

* Annual subscription rates are now $38 for institutions and $23 for individuals.

ISSN 0035-7529

The Harry T. Campbell Sons' Co. Gettysburg quarry looking north towards the skarn-magnetite zone. Relic sedimentary bedding in the hornfels dips westerly.

Campbell's Quarry

A Complex Mineral Locality in Gettysburg, Pennsylvania

DONALD HOFF
William Penn Memorial Museum
Box 1026
Harrisburg, Pennsylvania 17120

The Harry T. Campbell Sons' Company crushed stone quarry, a noted Pennsylvania mineral locality, is located approximately 2.2 miles (3.55 km) southeast of Center Square in Gettysburg, Pennsylvania. The entrance road is situated along U.S. Route 140. The locality was opened in 1934 by John S. Teeter and Sons, Inc., and sold to the Campbell Company in 1959. Even now collectors still refer to the locality as Teeter's quarry.

Prior to 1974, the Campbell quarry was a noted zeolite suite locality. However, additional suites of minerals have been discovered in recent years.

Donald Hoff is curator of the Earth Science Division of the William Penn Memorial Museum. He directed the design and fabrication of the new Hall of Geology which opened in July 1976. He is an avid collector of Pennsylvania minerals and is a member of numerous mineral societies including the Pennsylvania chapter of the Friends of Mineralogy and the Pennsylvania Academy of Science.

GEOLOGY AND MINERALIZATION

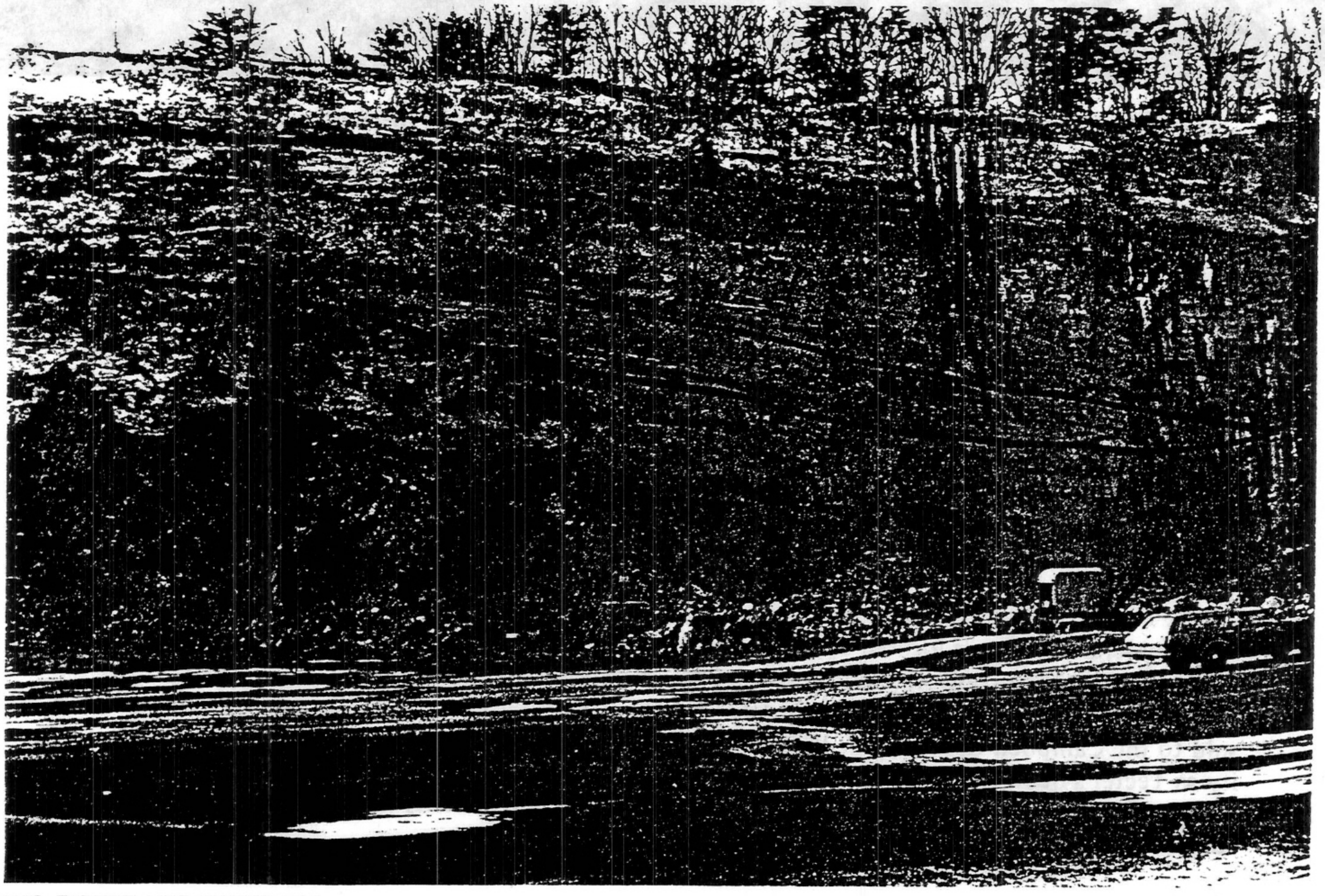
The Campbell quarry is in the south central portion of a long structural basin produced by subsiding crustal movements during Triassic period. This tectonic feature, known as the Gettysburg basin, trends northeast-southwest for approximately 90 miles (145 km) through part of southeastern Pennsylvania and northern Maryland. Its maximum width is 18 miles (29 km). During Late Triassic times, rivers and streams flowing from surrounding highlands deposited sediments into the basin as it subsided and then tilted. Minor lake deposits of essentially the same age occur near the center of the basin.

As a general rule, the sediments of the basin dip gently to the northwest and consist chiefly of shale, sandstone, and conglomerate with minor argillites, limy mudstones, and impure limestones. Sheets and dikes of Upper Triassic diabase intrude the sediments and minor extrusions of basaltic lava accompanied the igneous activity.

Fossils are rather rare in the Gettysburg basin. More notable finds include Upper Triassic dinosaur footprints, metoposaurid amphibians, and phytosaur reptiles.

The Campbell quarry exposes a thermally metamorphosed shale unit of the Triassic Gettysburg Formation near the bottom of a large diabase intrusion known as the Gettysburg sheet. This large northwesterly dipping igneous body trends northeast-southwest, and averages 1,800 feet (549 m) in thickness along its 38 mile (61 km) length (Stose and Bascom, 1929, page 12). As mapped by Stose and Bascom, the diabase sheet has a thickness of approximately ½ mile (805 m) in the quarry area. The present working face of the quarry is located approximately 450 feet (137 m) east of the main body of diabase. However, fracturing and metamorphism at Campbell's was increased by a large convex roll located on the bottom of the diabase body. The roll, which bears a large southerly trending protuberance, occurs approximately 500 feet (152 m) northeast of the quarry. Magmatic heat baked the sediments in the

The skarn-magnetite zone in the northwest corner of Campbell's quarry. The zone is approximately 390 feet (119 m) long as exposed in February, 1978.



THE HORNFELS EPIDOTE–ALBITE–ZEOLITE SUITE

ALBITE–one of the more abundant minerals in the hornfels fractures. It occurs as white to colorless microcrystals, usually twinned, associated with epidote. Sharp, water-clear albites sitting on terminations or prism faces of small green epidote crystals present a micromounters paradise.

CALCITE–Rare fluorescent calcite occurs as small tan-colored rhombohedral crystals on albite, stilbite, and white cleavable calcite.

CHABAZITE–Found in fractures as white to colorless rhombohedral crystals up to .5 centimeters and associated with epidote, albite, laumontite, heulandite, and stilbite. Peculiar vugs in hornfels, sometimes separated by only micro thin walls, are lined with chabazite crystals sometimes associated with stilbite. Pseudomorphs of chabazite after glauberite rarely occur.

CHLORITE GROUP: SPECIES UNKNOWN–Found as rare veinlets of dark green lustrous micro flakes lining fracture walls followed by epidote-albite deposition, or as veinlets in epidote.

EPIDOTE–Pistachio green epidote crystals, as singles or radiated groups up to .7 cm, coat fracture walls in association with albite, heulandite, stilbite, and more rarely chabazite and natrolite. Epidote with chlorite, albite, and stilbite forms vuggy veins in fractures. Crystalline aggregates of epidote often coat and pigment slickensided fault surfaces.

HEMATITE–Dark grey to reddish masses of hematite rarely occur on stilbite. The brilliant black specular variety occurs in and on natrolite and stilbite crystals. Red hematite pigments mirrorlike surfaces on slickensides.

HEULANDITE–Colorless to white prisms of heulandite, up to 1.3 centimeters long, occur on fracture walls often enclosing epidote and albite crystals.

LAUMONTITE–Radiated and stellated groups of small, white obliquely terminated crystal prisms of laumontite most commonly occur with stilbite, and are sometimes enclosed by stilbite crystals.

NATROLITE–occurs rather rarely as radiated groups of elongated, acicular, colorless to pink, single crystals exhibiting a typical square cross section.

QUARTZ–Massive milky quartz is rarely found as vein material in the hornfels.

"SERICITE"–Micro, lustrous, white sericitic scaly aggregates in association with chabazite and stilbite, coat walls of vugs in hornfels. The sericitic mineral could be muscovite, paragonite, or chlorite.

STILBITE–is ubiquitous throughout the hornfels fractures. The mineral occurs abundantly as stellated crystal aggregates cementing very narrow fractures. Typical sheath shaped crystal aggregates which exceed 2.5 cm in length, and spherical aggregates of radiated crystals which exceed 3 cm in diameter, sometimes line vugs in open fractures.

OTHER MINERALS–Rare blebs of chalcocite (?) were found in a thin lense of sandstone interbedded with the hornfels. Lacking x-ray data, this mineral could be djurleite, a similar copper sulfide. Also, rare pyrite occurs as cubic crystals embedded in hornfels and zeolites. The pyrite is often partially altered to "limonite."

quarry area producing a hard, dense, grey, contact metamorphic rock called hornfels. Heating of ground water and thermal remobilization of Ca, Na, Al, Si, and Fe was followed by hydrothermal solution redistribution. Epidote, albite, zeolites, minor calcite and hematite crystallized out of solution in the fractures. Chemical-rich hydrothermal expulsions from the diabase magma were a possible source for some of the hornfels mineralization.

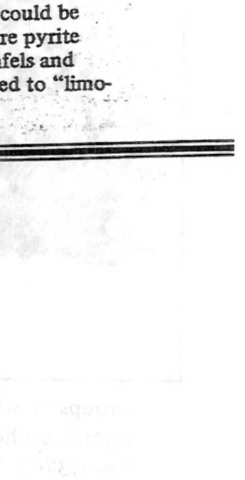
Blasting during 1974 exposed a lenticular shaped body of sulfide bearing skarn and magnetite enclosed in the hornfels. The extent of this zone of contact metamorphism and contact metasomatism is not known at the present time. A calcium carbonate rich sediment was the probable host rock for silicate and magnetite replacement. As none of the unaltered host rock is available for study, this assumption is based on the nature of the deposit and data concerned with deposits of similar genetic regimes as at Cornwall and Dillsburg, Pennsylvania (Lapham and Gray, 1973; Hotz, 1950). Expulsion of fluids from the diabase in place, or fluids working up along the basal diabase-sediment contact from the diabase source magmatic chamber were the source of Fe, Mg, Si, Cu, S, and perhaps much of the K in the replacement zone.

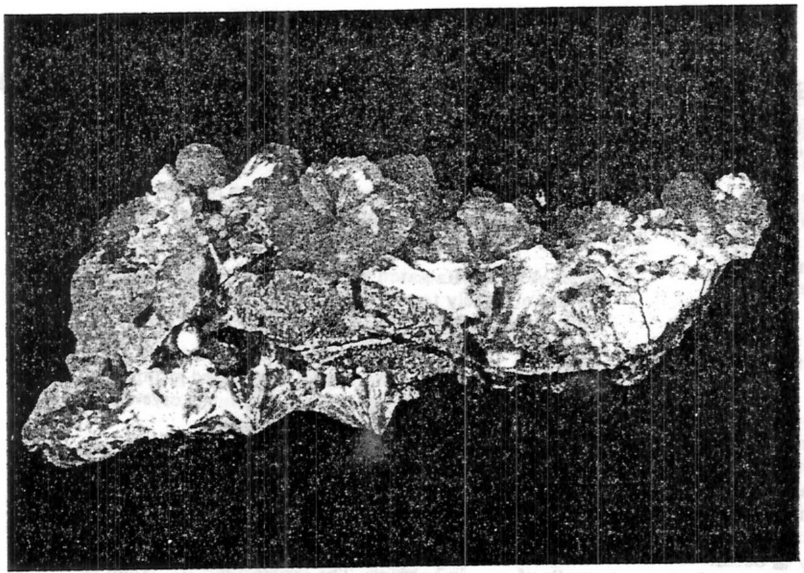
MINERAL DESCRIPTIONS AND ASSOCIATIONS

Mineralogy of the Hornfels

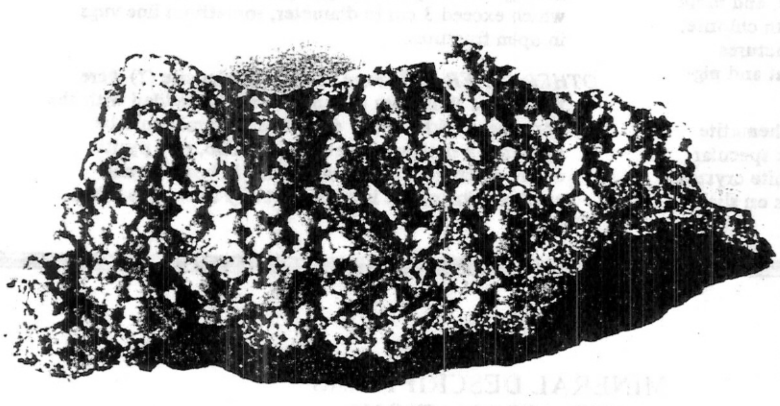
Abundant hornfels mineralization found in place by the author is associated with a fracture set striking an average of N5^{0}W, near vertical to dipping 72^0 easterly, and planar to curved. Throughout the many years, stilbite has been the chief collectable mineral.

Epidote was usually the first mineral to crystallize in the fractures. However, chlorite deposition sometimes preceded and then followed epidote. Albite postdates epidote with colorless albite crystals enclosing green epidote crystals. Zeolites were the next to form in the sequence of mineral crystallization (paragenesis). Laumontite crystallized first, followed by chabazite and then heulandite. Natrolite was not found by the author in association with chabazite, but natrolite deposition postdates heulandite in the one specimen available for study. Stilbite was the last zeolite to form, but is sometimes contemporaneous with natrolite. Rare calcite crystals crystallized on stilbite, and equally rare platy hematite crystals were contemporaneous with, and followed stilbite.





Divergent and radiated tan-colored groups of stilbite crystals on brecciated hornfels. William Penn Memorial Museum specimen No. M4751: 3.5 x 10 cm.



Groups of white stilbite crystals with tiny snow-white laumontite crystals on hornfels fracture wall. William Penn Museum specimen No. M3763: 13 x 30 cm.

CAMPBELL QUARRY COLLECTING PERMISSION

Collecting at Campbell's is permitted only on *Saturdays from 8:00 A.M. to 12 noon.* Only one group is permitted to enter the quarry on any one Saturday morning. Permission to collect *must be obtained before arrival at Campbell's.*

Harry T. Campbell Sons' Company
R.D. # 1, P.O. Box 128
Gettysburg, PA 17325
Tel: A.C. (717) 334-3166

Mineralogy of the Skarn–Magnetite Zone

The recently exposed zone of complex contact metamorphism and metasomatism exhibits a bewildering, zoned array of textures and mineral associations. As textures and relative abundance of various mineral associations change from blast to blast, only a brief summary of the skarn-magnetite zone will be given at this time. This, of course, precludes noting relative abundance of mineral species in this article.

Of special interest to collectors are the epidote vugs which sometimes are abundant in the skarn. Definition of the epidote vugs includes the omnipresent epidote, but not always as the dominant mineral. The greatest dimension of the epidote vugs, not to be confused with the orthoclase vugs, exceeds 14 cm. Epidote vugs and orthoclase vugs are sometimes separated by only 3 centimeters of solid skarn. Orthoclase vugs occur near center in coarsely crystalline orthoclase masses. Epidote is of rare occurrence in the orthoclase vugs.

Concave groups of epidote crystals, and associated minerals, are sometimes completely enclosed in late calcite. Dilute hydrochloric acid may be used to expose these crystal groups. The mineral suite in the calcite infilled occurrences is limited essentially to epidote, tremolite, and albite.

MINERALS OF THE SKARN–MAGNETITE ZONE

***ACTINOLITE*–Gray to very light green, matted actinolite fibers occur in the epidote vugs often associated with pseudomorphs of fibrous actinolite after diopside crystals with residual diopside cores.**

***ALBITE*–Small white albite crystals, as singles or groups, rest on epidote crystals and thickly matted white byssolite.**

***ANDRADITE*–Small to boulder size tabular, lenticular, irregularly shaped crystalline masses of light to very dark brown and reddish andradite occur in skarn. Peculiar curved, dead end "veins" of andradite often extend from the masses which are sometimes interconnected with zigzag veins. Much of the massive andradite is composed of closely intergrown crystals up to 3.5 cm, and exhibits crystal faces when broken. Well formed single crystals of andradite occur in skarn adjacent to massive andradite.**

***APATITE GROUP: SPECIES UNKNOWN*–Occurs in the epidote vugs as tiny white to colorless, terminated hexagonal crystals up to .6 cm long, closely associated with epidote, chlorite, titanite, and quartz. White apatite crystals occur embedded between plates of magnetite after hematite, and with octahedral magnetite microcrystals in vuggy platy magnetite.**

BORNITE–Bornite-chalcocite intergrowths produce a blebby texture in andradite-epidote rich skarn. Blebs of bornite associated with chalcopyrite are found in cleavable calcite and in the epidote vugs.

Bornite, containing blebs of chalcopyrite, forms pinch and swell, and arcuate vein-like masses in skarn up to more than 1 cm wide. The masses pinch when bornite rich and swell when calcopyrite rich, and are sometimes interconnected by zigzag veinlets of bornite-chalcopyrite. Much of this material has oxidized to malachite and chrysocolla.

CALCITE–White to rare Iceland spar, fluorescent, cleavable calcite is found as center fillings in large orthoclase masses, and enclosing epidote and albite crystals in association with tremolite variety byssolite. Small masses of calcite in skarn are sometimes rimmed with magnetite replacement.

CHALCOCITE–occurs as described under bornite.

CHALCOPYRITE–The most extensive development of chalcopyrite consists of large masses, more than 10 cm in the longest dimension, enclosing andradite crystals, and altered in part to "limonite," malachite, and chrysocolla. Masses of chalcopyrite up to 2.5 cm occur along chlorite-epidote boundaries in skarn enclosing and replacing epidote crystals. Chalcopyrite is sometimes abundant in association with gross magnetite replacements, either in the magnetite as masses up to 2 cm, or as veinlets and blebs in adjacent andradite rich skarn.

CHLORITE GROUP: SPECIES UNKNOWN–Occurs as green flakes rimming orthoclase replacements in skarn, and also as inclusions in orthoclase crystals. Green flaky masses of chlorite sometimes enclose orthoclase crystals.

Globular to botryoidal aggregates of chlorite microcrystal flakes are found in the epidote vugs. The chlorite aggregates, up to .5 cm in diameter, enclose byssolite and epidote crystals. Green, gemmy, transparent globular groups of chlorite microcrystals occur included in, and resting on colorless quartz crystals in epidote vugs. The chlorite groups are occasionally shaped like an extended accordion, and then sometimes twisted and bent like too much toothpaste squeezed from a tube.

DIOPSIDE–Rare, light green, transparent diopside crystal prisms occur projecting from epidote vug walls. Bundles of byssolite fibers sometimes project into space from the terminal ends of the tiny diopside prisms, or byssolite bundles projecting from vug walls abruptly become diopside prisms.

Diopside also occurs as described under actinolite.

DJURLEITE–Fairly abundant as grey blebs and masses possessing a high metallic luster in epidote and andradite rich skarn. Djurleite is rarely associated with chalcopyrite.

EPIDOTE–Light yellow-green to dark green singly and doubly terminated epidote crystals up to 1.3 cm long occur in the epidote vugs. The epidote crystals are usually elongated to acicular, and sometimes found as divergent groups of single acicular crystals up to 3.5 cm long. Brilliant, sharp, stubby to equant, dark green epidote crystals occur more rarely as splendent groups. Quartz crystals are often found in abundance with the epidotes.

Epidote crystals are sometimes embedded in calcite near the center of large orthoclase masses. Epidote rarely occurs in the orthoclase vugs. Epidote is a very abundant mineral component of the skarn rocks.

(?)

GROSSULAR–Transparent, light yellow-green garnet microcrystals occasionally occur in the epidote vugs as rhombic dodecahedrons enclosing byssolite fibers.

HEMATITE–Brilliant, black, specular hematite aggregates showing red internal reflections are found in coarsely crystalline andradite-epidote skarn. Specular hematite plates in groups up to 6 x 13 cm and larger, enclose quartz crystals. Platy hematite occurs in the epidote vugs as sharp, single, microcrystals and fairly large aggregates.

Most of the epidote vug hematite was reduced to magnetite. The pseudomorphs of magnetite after hematite bear overgrowths of tiny octahedral magnetite crystals.

HEULANDITE–Tiny, colorless heulandite crystals enclose epidote microcrystals in the skarn epidote vugs.

MAGNETITE–Found in the skarn-magnetite zone as minor to gross replacements, and as platy aggregates after hematite. The platy magnetite occurs in the epidote vugs, or as vuggy masses in skarn associated with apatite and titanite.

A massive magnetite-calcsilicate rock contains platy magnetite with octahedral magnetite and light brown titanite microcrystals near plate boundaries. The magnetite, silicates, calcite, and accessory chalcopyrite-pyrite components of this rock exhibit a texture reminiscent to that of a coarse grained igneous rock.

Magnetite surrounding calcite masses in the skarn has replaced both the calcite and the adjacent contact metamorphic skarn silicates. Excellent octahedral magnetite microcrystals are found on the calcite side of the magnetite replacement.

NATROLITE–Reported as acicular microcrystals occurring in vugs in the skarn-magnetite zone.

ORTHOCLASE–Massive lenticular to vein-like, white to pink orthoclase replacements sometimes cut skarn. Lenticular masses of orthoclase measuring more than 5 x 10 cm contain vugs lined with orthoclase crystals [redacted] 1.5 cm and larger. Epidote, chlorite, quartz, stilbite, and calcite are also found in the orthoclase vugs.

Rare orthoclase crystals occur in the epidote vugs.

PYRITE–Rare pyrite is found associated with magnetite.

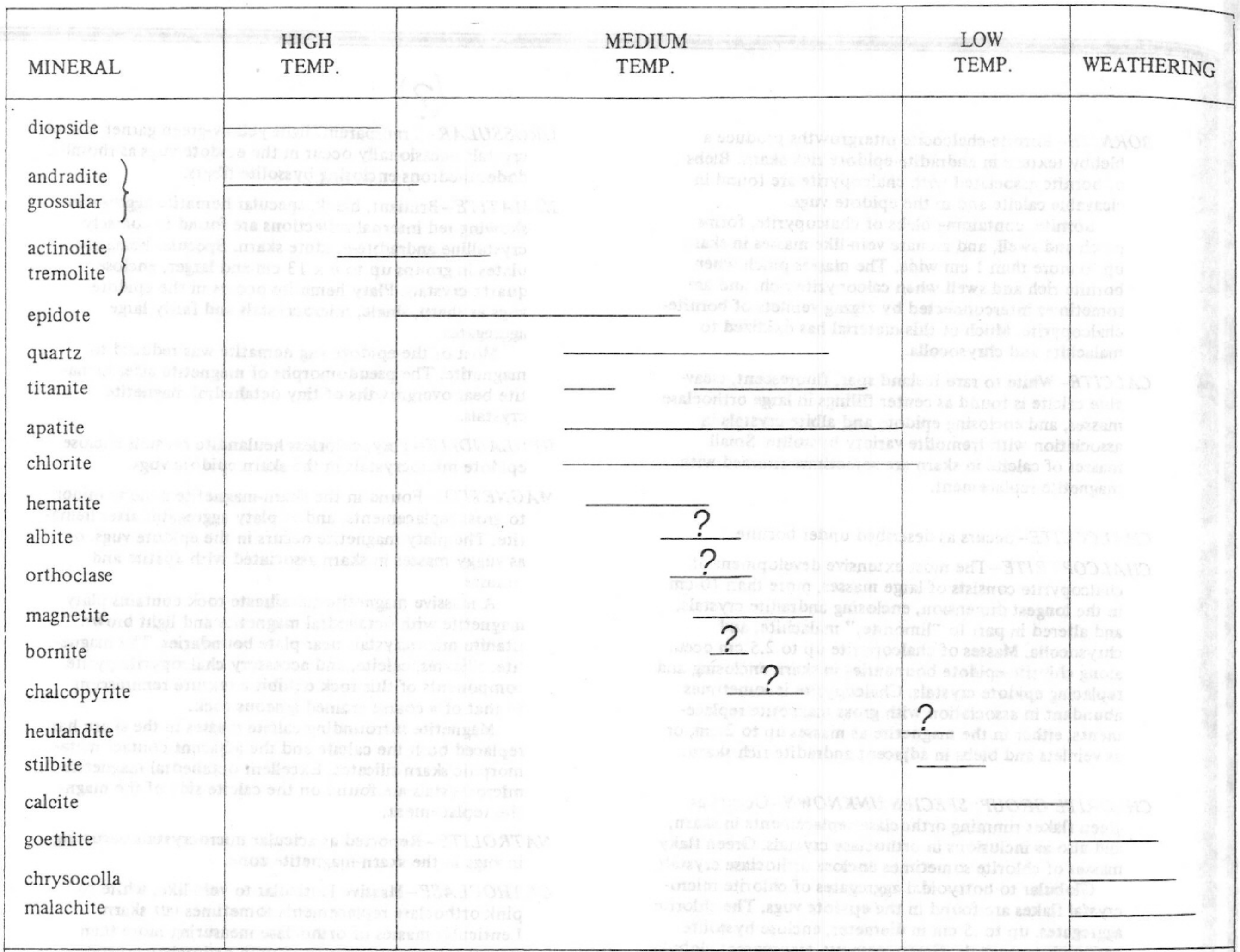
QUARTZ–White to rare colorless terminated quartz crystals up to 2.5 cm long are abundant in the epidote vugs. The quartz crystals contain epidote inclusions, but occasionally near equant late epidote crystals sit on quartz crystal prism faces. Quartz crystals are enclosed by hematite, but late quartz microcrystals rest on platy hematite.

STILBITE–Occurs as micro, colorless prisms in orthoclase vugs, and as white radiated crystal groups in the epidote vugs. Colorless radiated stilbites, in association with other zeolites, fill late fractures in skarn and magnetite.

TITANITE–Found as yellow to light brown and grey microcrystals in the epidote vugs associated with epidote, apatite, quartz and magnetite. Titanite fills space between plates of magnetite after hematite. Vuggy areas in the platy magnetite exhibit titanite microcrystals in association with clusters of sharp, octahedral magnetite microcrystals.

TREMOLITE–Found as snow-white byssolite fibers in the epidote vugs and enclosed in late calcite. The epidote vug byssolite sometimes appears to be black or brown due to coatings of pyrolusite or "limonite."

RELATIVE SEQUENCE OF MINERAL DEPOSITION IN THE SKARN–MAGNETITE ZONE EPIDOTE VUGS



NOTE: Temperature gradients are only relative to deposition of minerals in the skarn epidote vugs. Exact position of feldspars, sulfides, and heulandite in question due to lack of association with many of the listed mineral species.

WEATHERING MINERALS – ENTIRE QUARRY

CHRYSOCOLLA, CUPRITE, GOETHITE (limonite), MALACHITE, and NATIVE COPPER are found in the skarn-magnetite zone as oxidation products of the copper and iron bearing sulfides. Bright green malachite, sometimes as divergent groups of microcrystals, and blue to green chrysocolla occur as fracture surface coatings in sulfide rich skarn. Stellated groups of fibrous malachite crystals possessing light to dark green color banding rarely coat fracture surfaces.

Cuprite is occasionally found as red to impure orange coatings on fracture surfaces and rarely as the variety chalcotrichite in vugs in djurleite rich skarn. Rare native copper occurs as micro arborescent crystal groups in small vugs associated with cuprite microcrystals.

Malachite and chrysocolla occur in small vugs in skarn produced by the dissolving out of massive chalcopyrite and bornite. Massive "limonite" often lines these vugs followed by chrysocolla and malachite deposition. This occurrence yields attractive micro, botryoidal, bright green velvety malachite groups on bright blue botryoidal chrysocolla.

* ~~PYROLUSITE~~ occurs as dendrites on orthoclase crystals and fracture surfaces throughout Campbell's quarry. The black sooty coatings on epidote, byssolite, and other minerals in the skarn epidote vugs in probably pyrolusite.

* Manganese oxide or oxides

Rare "limonite" pseudomorphs after pyrite are found in the hornfels rock or embedded in zeolites found in hornfels fractures.

MONTMORILLONITE(?) occurs as pink to white earthy masses near zeolites in hornfels fractures.

ACKNOWLEDGMENTS

The author extends a note of appreciation to Dr. Robert C. Smith of the Pennsylvania Geological Survey, Harrisburg, Pennsylvania, for his x-ray diffraction identification of djurleite, chalcocite, and diopside. Dr. Smith collected the first djurleite specimen at Campbell's quarry. This discovery was the first for djurleite in Pennsylvania.

The author is also grateful to the Harry T. Campbell Sons' Company for giving collectors permission to enter their Gettysburg quarry.

REFERENCES

Geyer, A. R.; Smith, R. C., II; and Barnes, J. H. 1976. Mineral collecting in Pennsylvania. *Pennsylvania Topographic and Geologic Survey Bulletin* G 33: 28-30

Glaeser, J. D. 1966. Provenance, dispersal, and depositional environments of Triassic sediments in the Newark-Gettysburg basin. *Pennsylvania Topographic and Geologic Survey Bulletin* G 43: 168.

Hotz, P. E. 1950. Diamond-drill exploration of the Dillsburg magnetite deposits, York County, Pennsylvania. *U. S. Geological Survey Bulletin* 969-A: 27.

Krumbein, W. C., and Sloss, L. L. 1963. *Stratigraphy and sedimentation*. 2nd ed. San Francisco: W. H. Freeman and Company.

Lapham, D. M., and Gray, C. 1973. Geology and origin of the Triassic magnetic deposit and diabase at Cornwall, Pennsylvania. *Pennsylvania Topographic and Geologic Survey Bulletin* M 56: 343.

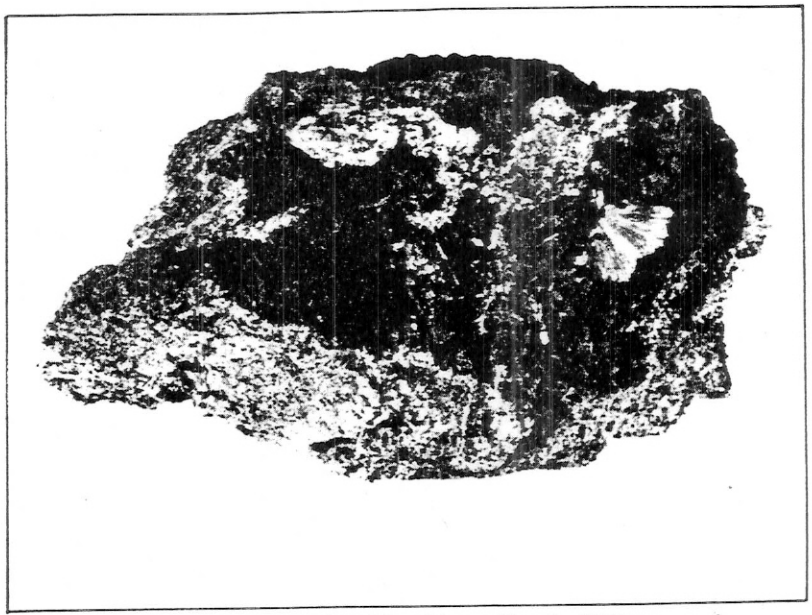
Park, C. F., Jr., and Mac Diarmid, R. A. 1970. *Ore deposits*. 2d ed. San Francisco: W. H. Freeman and Company.

Smith, R. C., II; Rose, A. W.; and Lanning, R. M. 1975. Geology and geochemistry of Triassic diabase in Pennsylvania. *Geol. Soc. Am. Bull.* 87: 943-955.

Stose, G. W., and Bascom, F. 1929. Description of the Fairfield and Gettysburg, Pennsylvania 15' Quadrangles. *U. S. Geological Survey Folio* 225: 22, geologic maps and sections.

Turner, F. J., and Verhoogen, J. 1960. Igneous and metamorphic petrology. 2d ed. New York: McGraw-Hill Book Company, Inc.

For more information on other Pennsylvania collecting sites, see the June 1978 issue of ROCKS AND MINERALS devoted to the state of Pennsylvania. Back issues are available from the publisher.



Dark green epidote crystals with white radiated stilbite group in skarn epidote vug. William Penn Museum specimen No. M4256: 7 x 11 cm.

White to pink orthoclase crystals lining skarn orthoclase vug. William Penn Museum specimen No. M4298: 9.5 x 11 cm.