39TH. ANNUAL FIELD CONFERENCE OF PENNSYLVANIA GEOLOGISTS

GUIDEBOOK

GEOLOGY OF THE PIEDMONT OF SOUTHEASTERN PENNSYLVANIA

King of Prussia, Pa.
October 4 & 5, 1974

Host:
Bryn Mawr College

GUIDEBOOK for the 39th ANNUAL FIELD CONFERENCE OF PENNSYLVANIA GEOLOGISTS

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Field Trip Leaders:

Roddy V. Amenta, LaSalle College*, Philadelphia, Pa.
Maria Luisa Crawford, Bryn Mawr College, Bryn Mawr, Pa.
William A. Crawford, Bryn Mawr College, Bryn Mawr, Pa.
William B. Fergusson, Villanova University, Villanova, Pa.
William R. Parrott, Jr., Bryn Mawr College, Bryn Mawr, Pa.
Frank H. Roberts, Delaware County Christian School, Newtown Square, Pa.
Edward J. Trojan, Pennsylvania Department of Transportation, Radnor, Pa.
Mary Emma Wagner, University of Pennsylvania, Philadelphia, Pa.

Host: Bryn Mawr College

Headquarters Motel: George Washington Motor Lodge, King of Prussia, Pa.

Guidebook Distributed by:

Bureau of Topographic and Geologic Survey
Department of Environmental Resources
Harrisburg, Pennsylvania 17120

Arthur A. Socolow, State Geologist

*Current address: Madison College, Harrisonburg, Va.

With affection and appreciation
We dedicate this Guidebook to

EDWARD H. WATSON

He was, to most of us, a mentor,
friend, and guide through the
complexities of the local geology.

His former students
and colleagues.

CREDITS FOR PREPARATION

Typing: Helen L. Guy
Mary Ann Miller

Drafting: John G. Kuchinski
Virginia Milewski
Albert Van Olden

Field Trip Arrangements: Donald M. Hoskins

Guidebook Editors: William A. Crawford
Maria Luisa Crawford

Reviewer: Thomas O. Wright

Historical Notes: William A. Crawford

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION TO THE GEOLOGY OF THE CRYSTALLINE ROCKS OF SOUTHEASTERN PENNSYLVANIA

M. L. Crawford

The rocks which lie south of the Triassic Basin and east of 76° W longitude can be subdivided into three groups (see Table 1 for formation names and stratigraphic succession and Fig. 1 for a geologic sketch map).

A. Paleozoic and younger rocks of known ages. This category includes basal Cambrian clastic sediments, Cambro-Ordovician carbonates and Triassic clastic rocks and diabase. The older rocks are weakly to moderately metamorphosed (to greenschist facies) (see Fig. 2 and Fig. 3 for metamorphic conditions in the area).

B. Intermediate to high-grade metamorphic pelitic, volcanic and volcaniclastic, psammitic, and calcareous rocks (greenschist to granulite facies) of unknown age but possibly late Precambrian to Ordovician. These rocks overlie the Grenville basement (Group C) and may correspond in part to the Paleozoic rocks in group A. Ultramafic and granodioritic bodies which occur in these rocks are also metamorphosed.

C. Grenville basement of amphibolite and granulite facies metamorphic grade probably composed of both metaigneous and metasedimentary rocks. These are cut by diabase dikes which may be correlative with some of the metaigneous rocks of group B.

The basement rocks in the region, first mapped by Bascom (1909) are generally considered to be Precambrian in age. She identified two main rock types: a granitic and a gneissic facies, which she interpreted as metasediments; these were intruded by gabbro, possibly correlative with mafic rocks in the Wissahickon Formation. Bascom named the granitic rocks Baltimore gneiss because of their resemblance and similar stratigraphic position to the basement gneisses in the Baltimore domes. Subsequent mapping in the basement blocks (Armstrong, 1941; Wagner, 1972) has shown a greater complexity than suggested by the early work. Bascom's gneissic facies of the Baltimore gneiss corresponds to mylonites developed along faults which border the gneiss blocks as well as to mylonite zones within the blocks. The other rock types within the Baltimore gneiss are now known to include mafic, intermediate and felsic granulites, retrograded granulite, amphibolite and migmatite. The granulites are intruded by diabase dikes (Wagner, 1972). The field relations and metamorphic history suggest that the amphibolites and migmatites may be younger than the granulites; the latter were metamorphosed during the Grenvillian Orogeny (980 m.y. based on U-Pb isotopic dating of zircon, Grauert *et al.*, 1973; Tilton *et al.*, 1960) (Fig. 4). A new nomenclature is desirable for the basement gneisses but, until mapping in progress is completed, the name Baltimore gneiss will be retained for all rocks which underlie known Glenarm series formations, except cross-cutting diabase dikes.

South of the Chester Valley, approximately between longitude 75°15'W and 75°38'W the Baltimore gneiss is in direct contact with the Wissahickon Formation

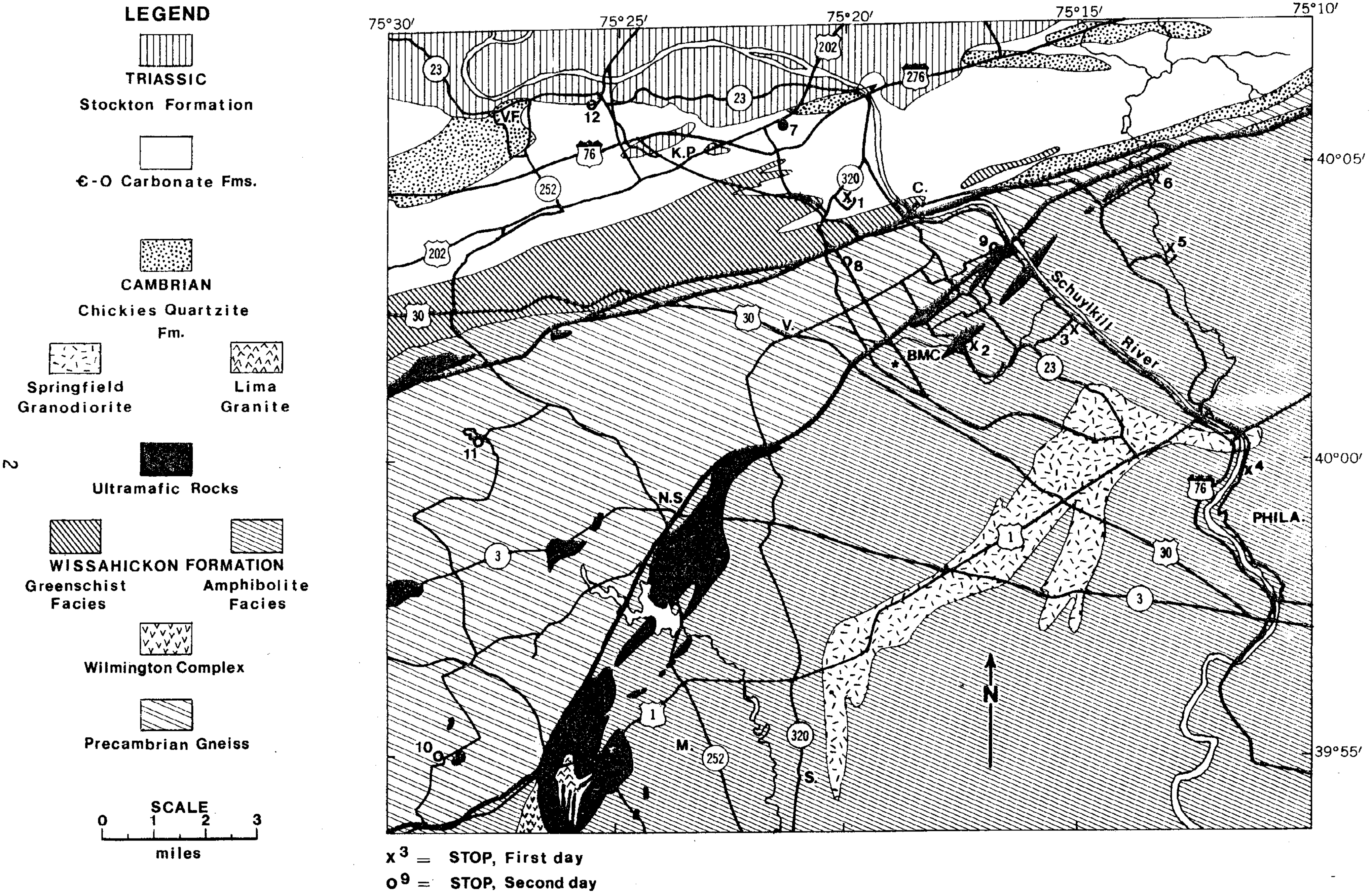


Figure 1. Generalized geologic map of southeastern Pennsylvania showing STOP locations.

of the Glenarm Series, or with ultramafic rocks intruded or faulted into the Wissahickon Formation. In this region the contacts between the Baltimore gneiss and the Glenarm series are mapped as faults. West of this region the basement gneiss is overlain by Setters quartzite succeeded by Cockeysville marble. East and north of the central region, the overlying succession starts in Cambrian clastics and continues into Cambro-Ordovician carbonates. In recent years most geologists working in the Glenarm Series have concluded that those formations are correlative with the unmetamorphosed lower Paleozoic of the Lancaster Valley (Watson, 1957; Higgins, 1972).

In the piedmont of Pennsylvania, the metamorphic grade in Paleozoic and Glenarm Series rocks increases to the southeast, from greenschist facies along the Chester Valley to upper amphibolite and granulite facies rocks along the fall line between Philadelphia and Wilmington. The upper amphibolite facies rocks, characterized by the assemblage sillimanite-orthoclase, are limited to the area around the Springfield granodiorite and the Wilmington Complex (Fig. 2). The latter consist of amphibolites and metagraywackes or metavolcanic rocks in the upper amphibolite and granulite facies (Ward, 1959). U/Pb isotopic analysis of zircons from the Wilmington complex (Grauert and Wagner, 1974) (Fig. 4) suggest that the Wilmington complex granulite facies metamorphism occurred about 440 m.y. ago, during the Taconic orogeny. This is the best evidence thus far for the age of the post-Grenville metamorphism in Southeastern Pennsylvania. Preliminary results of Rb/Sr whole-rock analysis of the Arden granite and trondhjemite which is intrusive into the Wilmington Complex rocks (Ward, 1959) yield an isochron of about 560 m.y. (Foland, personal communication). This date, as well as the apparent gradational transition from the granulite facies portion of the Wilmington Complex into amphibolites which can be traced into Maryland, suggests that the Wilmington Complex may be the high-grade metamorphic equivalent of the James Run Formation (Higgins, 1972).

Work currently in progress (Parrott, this guidebook) is aimed at determining the relation of the Wilmington Complex rocks and the amphibolite facies metavolcanic, metavolcaniclastic and metasedimentary rocks which form the southern part of the Baltimore gneiss block immediately to the north of the northern end of the Wilmington Complex. The amphibolite facies rocks in the Baltimore gneiss block appear to overlie the Grenville age granulite facies rocks of the northern block of basement gneiss (Wagner, 1972, and this guidebook). U/Pb ages from zircons (Grauert *et al.*, 1973) (Fig. 4) from the amphibolite facies rocks are difficult to interpret. One possibility is that the rocks represent the metamorphic derivatives of rocks deposited after 980 m.y. (the age of the granulite facies metamorphism of the basement gneiss) and subjected to episodic lead loss at 240 m.y.

There is evidence that the Taconic metamorphism also affected the Baltimore gneiss (Wagner, 1972; Wagner and Crawford, 1973) but the relation between the metamorphic isograds and the basement blocks is not simple. At the western end of the basement gneiss blocks, in the vicinity of West Grove and Avondale, the isograds in the Wissahickon Formation appear to wrap around the gneiss blocks. Further east, in the area to be visited during the conference, the Cream Valley fault system on the northern side of the Baltimore gneiss (Fig. 2) juxtaposes staurolite-bearing schists (Wissahickon Formation, amphibolite facies) against

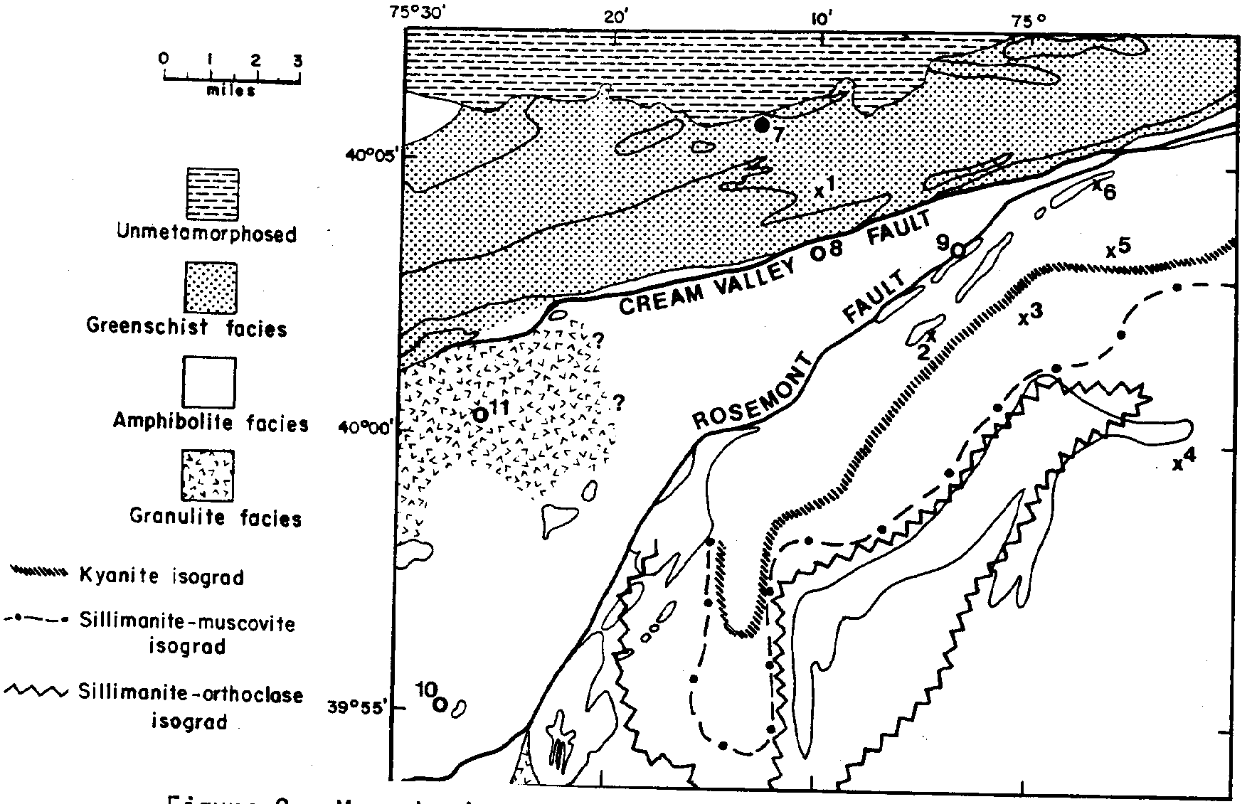
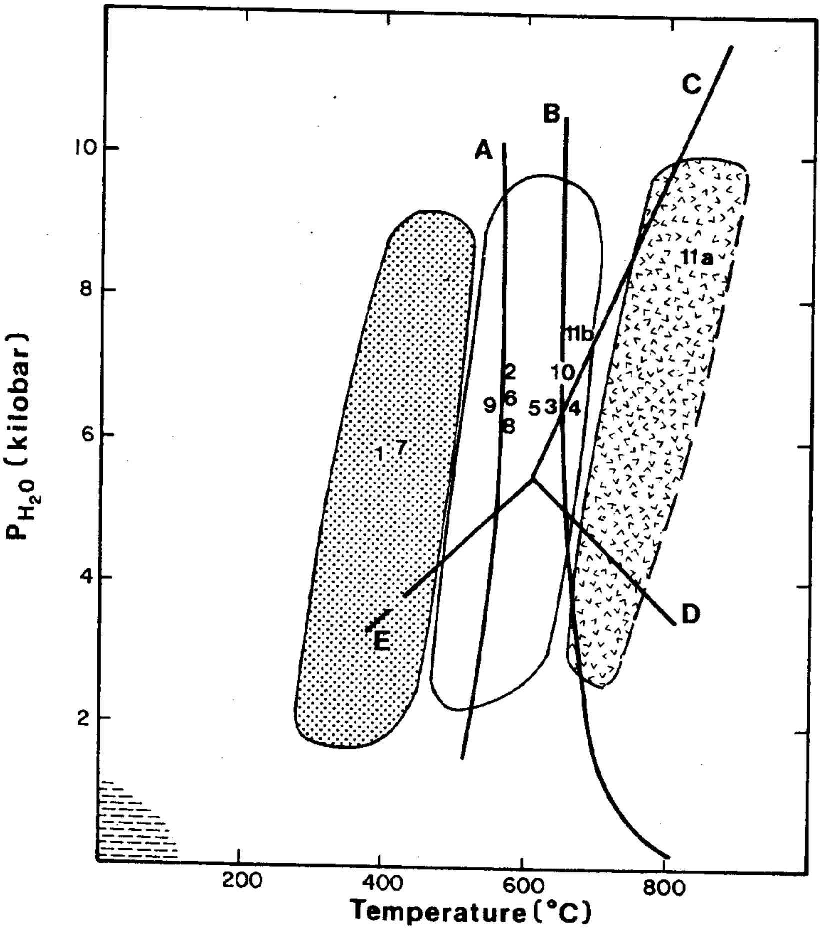


Figure 2. Map showing metamorphic facies and metamorphic isograds in the Philadelphia region. Adapted from Wyckoff (1952) and Wagner (1972). x, first day stops; o, second day stops.



Stability curves, low T assemblage on the left of the equations.

A – chlorite + muscovite = staurolite + biotite + quartz + vapor

B – granite minimum melting curve

C – kyanite = sillimanite

D – andalusite = sillimanite

E – kyanite = andalusite

1, 2 ·· Estimated P, T conditions for each field trip stop.

Figure 3. Pressure and temperature conditions affecting the metamorphic rocks in the Philadelphia region showing the estimated P-T conditions for each stop.

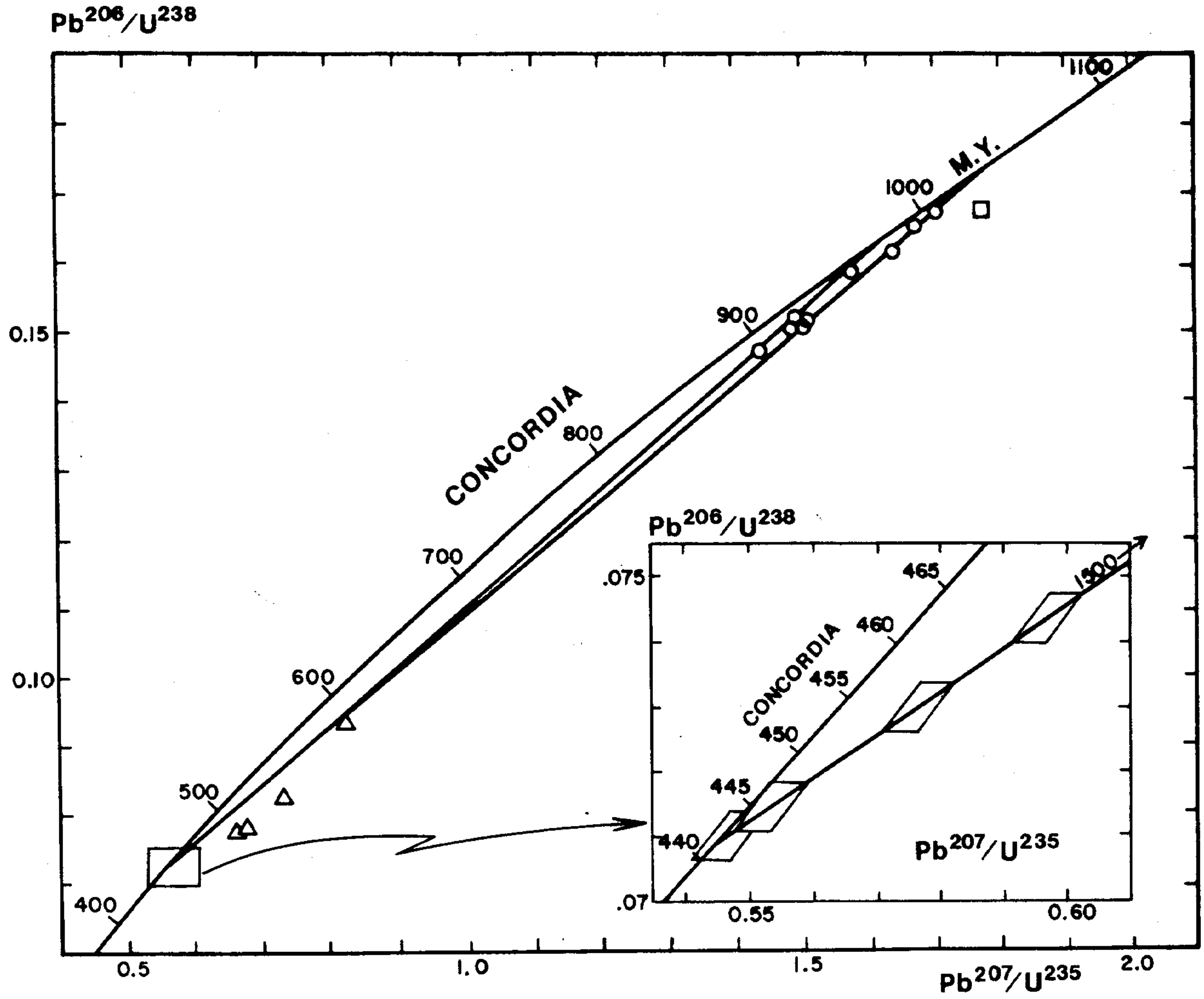


Figure 4 - Concordia diagram showing the isotopic data on zircons from rocks in the Pennsylvania Piedmont adapted from Grauert *et al.* (1973) and Grauert and Wagner (1974).

Baltimore gneiss ○ granulite facies rocks

☐ data from Tilton *et al.* (1960)

△ amphibolite facies rocks

Wilmington complex (inset): ▱

muscovite-chlorite phyllites (Wissahickon Formation, greenschist facies). The grade of metamorphism continues to rise south of the Rosemont fault which marks the southern boundary of the basement gneiss block (Fig. 2).

The ultramafic rocks which intrude or are faulted into the Wissahickon Formation are concentrated on either side of the Wilmington Complex, near the borders of the Baltimore gneiss blocks, and, in some places, are mapped within the Baltimore gneiss. At least some of the latter, particularly the three ultramafic bodies along Pa. Rte. 3, appear to lie along a fault and do not actually intrude the gneisses. The metamorphism of the ultramafic rocks (Roberts, 1969) and their internal structure suggests they were emplaced prior to the metamorphism of the Wissahickon Formation. Amenta (1974 and this guidebook) suggests, however, that there were two episodes of metamorphism in the Wissahickon Formation, both of amphibolite facies, and the ultramafic rocks were emplaced between the two episodes.

Felsic igneous rocks: the Springfield and Ridley Park granodiorites, the Lima granite, and small, unnamed dikes of similar composition, intrude the schist of the Wissahickon Formation. Around the margins of the Springfield granodiorite the schist was "granitized" by metasomatic introduction of potassium resulting in the development of microcline porphyroblasts. These felsic igneous rocks are all metamorphosed and deformed to some degree. The Lima granite includes xenoliths of ultramafic bodies. The oldest dates obtained on the Springfield granodiorite, 480 and 460 m.y. (reported in Lapham and Root, 1971) suggest that the intrusion was coeval with the Taconic metamorphism which affected the rocks of the area.

Pegmatites which are common in the Wissahickon Formation appear to be of two varieties. The first consist of minerals identical to the mineralogy of the surrounding schist. These pegmatites are frequently small segregations or narrow veins, usually folded with the country rock; but they may be more massive, cross-cutting bodies. The second type are commonly cross-cutting veins or dikes and apparently always contain microcline, generally absent from the first variety (Cohen, 1973). The microcline-bearing pegmatites possibly are associated with the igneous activity which produced the intrusive felsic rocks whereas the plagioclase pegmatites could represent segregations from the schist due to incipient melting.

The most prominent structural feature in the quartzofeldspathic granulites of the basement is a lineation which trends between N 60° E and due E. In the most mafic rocks a faint foliation defines a girdle whose axis trends parallel to the lineation in the felsic rocks. These features suggest that the northern part of the basement block in the trip area is an asymmetric anticline whose axial plane dips steeply south and is approximately parallel to the Cream Valley fault which forms its northern boundary (Wagner, 1972). The Wissahickon Formation shows a complex deformational history as outlined by Amenta (1974 and this guidebook). This included early folding followed by a second deformation which coincides with movement along the boundary fault on the southern margin of the basement gneiss (Rosemont fault) and a third period of folding which he interprets as being related to the intrusion of the Springfield granodiorite. Presumably the fault at the northern boundary of the basement gneiss blocks (Cream Valley fault) formed simultaneously with the Rosemont fault; however, according to Amenta (personal communication), there may have been later movements along the Cream Valley Fault. Mylonites within and along the borders of the basement gneisses and in the adjacent Wissahickon Formation formed at this time.

A tentative correlation of these deformations with the structural history deduced by Freedman *et al.* (1964) and Wise (1970) further west suggests that the early isoclinal folding in the Wissahickon Formation of the Philadelphia region coincides with flow folding to the northwest and possible major basement thrusting identified by Freedman *et al.* (1964) along the Susquehanna River. The second deformation in both the Philadelphia and Susquehanna regions involves the upward movement of large basement blocks: the Mine Ridge Anticline in the west, and the basement gneisses north of the Rosemont Fault in the Philadelphia region. There is evidence for post-metamorphic movements along the Cream Valley Fault north of the basement gneisses in the Philadelphia region, including juxtaposition of staurolite-bearing rocks with chlorite-muscovite phyllite and mylonization of staurolite-garnet schists. This suggests renewed movements of basement blocks after the three major episodes of holding in the Wissahickon of the Philadelphia region as mineralogical evidence (Amenta, 1974; this guidebook) suggests high grade metamorphic recrystallization accompanied and followed the third of these deformations. It is not possible to state with certainty whether the basement uplift documented along the Susquehanna should be correlated with the early or the later phase of basement movements in the Philadelphia region.

A number of K/Ar dates on micas (Lapham and Bassett, 1964; Lapham and Root, 1971) cluster around 330 m.y. suggesting that the rocks remained at fairly high temperatures well into the Acadian, or were reheated at that time. The late movements on the Cream Valley Fault and a late deformation which resulted in strained but not recrystallized micas in the Wissahickon Formation, as well as in the felsic rocks intruded into the schists, (Amenta, 1974 and this guidebook) could well be associated with this 330 m.y. date. This possibly represents the gradual uplift of the Piedmont province and the initiation of the feature which resulted in the Alleghanian deformation in the Paleozoic cover rocks further west.

The arkosic sandstones of the Stockton formation contain fragments of K-feldspar and muscovite several mm in diameter. The concentration of high percentages of fresh feldspar and the high proportion of feldspar at the southern outcrop edge of the Triassic rocks (Glaeser, 1966) suggest a nearby source: probably the felsic gneisses and igneous rocks of the adjacent crystalline Piedmont. At present the Piedmont rocks are contributing detritus to the New Jersey coastal plain.

Table 1

Stratigraphic column - Chester Valley and North*

Geologic Age	Formation	Description	Igneous Rocks
Triassic	Stockton Formation	Light colored sandstone, arkosic sandstone, and conglomeratic sandstone, includes red to purplish-red sandstone, shale and mudstone; beds of conglomerate are most numerous near the base of the formation.	Diabase
Ordovician	Conestoga Limestone	Medium-gray, impure limestone with shale partings; in Chester Valley includes micaceous limestone, phyllite and alternating limestone and dolomite.	
Cambrian	Elbrook Limestone	Light-gray to yellowish-gray, finely laminated, siliceous limestone with interbeds of dolomite.	
	Ledger Dolomite	Light-gray, massive, pure, coarsely crystalline dolomite; siliceous in part.	
	Kinzers Formation	Micaceous limestone containing interbedded calcareous mica schist.	
	Vintage Dolomite	Dark-blue granular dolomite with a wavy, knotted texture due to differential weathering of impurities.	
	Antietam Formation	Grey, buff-weathering quartzite and quartz schist.	
	Harpers Phyllite	Green-gray phyllite and schist containing beds of quartz schist and thin-bedded quartzite.	
	Chickies Quartzite	Vitreous to granular metaquartzite with interbedded quartzose schist; conglomeratic at base.	
Precambrian	Baltimore Gneiss		Diabase

*Stratigraphic description taken from McGlade *et al.*, (1972) and Poth (1968).

Table 1 (Continued)

Stratigraphic column - South of Chester Valley*

Geologic Age	Formation		Description	Igneous Rocks
Triassic				Diabase
Ordovician to Precambrian	Glenarm Series	Peters Creek Schist (=Metagraywacke facies of Wissahickon Formation (Higgins, 1972))	Fine-grained finely laminated, nonfissile mica schist, characterized by numerous thin beds of quartzite which are interleaved with muscovite-rich layers.	Springfield and Ridley Park granodiorites
		Wissahickon Formation	Pelitic rocks ranging from phyllite through schist to gneiss as the metamorphic grade increases. In places contains numerous beds of quartzite.	Lima granite Ultramafic and mafic rocks
		Cockeysville Marble	Medium to coarse-grained saccharoidal rock, ranging in color from white to light blue-gray, often banded with flakes of golden-brown phlogopite.	
		Setters Formation	Chiefly quartzite or quartzitic schist but in places may be a mica gneiss.	
Age not known, correlative with or older than Wissahickon Fm.?	Wilmington Complex metavolcanics and metasediments			Arden granite
UNCONFORMITY				
Precambrian	Baltimore Gneiss			Diabase

*Stratigraphic descriptions taken from McGlade *et al.* (1972) and Poth (1968).

RELATIVE TIMING BETWEEN DEFORMATION AND METAMORPHISM IN THE WISSAHICKON FORMATION NEAR PHILADELPHIA

Roddy V. Amenta

Introduction

The Wissahickon Formation near Philadelphia exhibits a variety of diachronous minor structures consisting of folds, cleavages and lineations. The sequence in development of these structures has been established and is based on the following types of observations:

(1) cleavages and lineations overprinting older structures,

(2) cleavages and lineations folded by younger folds,

(3) differences in orientations between generations of structures,

(4) degree of recrystallization of minerals in cleavages and

(5) fabric relationships between cleavages and porphyroblasts.

Near Philadelphia the basement gneiss complex, bounded by high angle faults, (Fig. 1) form an axis which separates fold belts with opposite senses of overturning in younger rocks on either side. In the Cambro-Ordovician carbonates northwest of this axis the folds are overturned northwest, but in the Wissahickon Formation southeast of this axis the dominant folds (F_2) are overturned southeast (see Table 2 for explanation of terminology). Ultramafic rocks are found close to and within the fault zones which separate the basement gneisses from younger rocks. Cataclastic rocks and related isoclinal folds in the Rosemont fault zone are transitional southeast to F_2 folds. The F_2 folds show no mineral evidence indicating that high grade metamorphism was synchronous with their development; but they deform older structural elements and metamorphic fabrics (M_1) consisting of mineral growth lineations (L_1), rare isoclinal similar folds (F_1) and "bedding plane" schistosity (S_1) which is parallel to F_1 fold axial planes (Fig. 5).

The main episode of metamorphism (M_2) overprinted the F_2 folds and established zones of staurolite, kyanite, sillimanite (Weiss, 1949; Wyckoff, 1952) and granitization (Postel, 1940) consecutively southeast. Recumbent folds (F_3) and subhorizontal cleavage (S_3) developed locally probably due to stresses related to granitization. That such stresses existed is also suggested by the fact that all pre-D_3 structures near the granitized zone appear to be disoriented (Amenta, 1974, in press). Open folds (F_4) with axial plane cleavage (S_4) dipping southeast developed after the peak of metamorphism (M_2). F_4 and S_4 become more intensely developed northwest, but at the present time it is uncertain whether F_4 or F_2 folds are dominant in the carbonates. D_5 structures are local and consist of steeply plunging folds and lineations in schists marginal to the granitized zone.

Below is a summary of my conclusions in regard to the structural and metamorphic history: (Those who wish more detail are referred to Table 3):

(1) There are 5 generations of structures and 2 episodes of amphibolite facies regional metamorphism, M_1 and M_2.

(2) F_2 folding in the Wissahickon Formation (and probably in the carbonates) was synchronous with basement uplift along vertical faults with diapiric emplacement of ultramafic rocks.

(3) Apparently the grade of metamorphism during D_2 was low, probably no higher than greenschist facies; but M_1 preceded and M_2 occurred after D_2. I therefore suggest that:

   (a) M_1 and D_1 were an early phase of the Taconic orogeny,

   (b) D_2 was a late, post-metamorphic phase of the Taconic orogeny associated with (pre-Silurian?) diapirism of ultramafic rocks,

   (c) M_2 and D_3 were a phase of the Acadian orogeny and

   (d) D_4 and D_5 were late phases of the Acadian orogeny or phases of the Alleghanian orogeny.

Table 2

EXPLANATION OF TERMINOLOGY

S_0: bedding, compositional layering.

D_1: first generation deformational event.

F_1: first generation fold or fold axis.

S_1: axial plane or axial plane schistosity of F_1 fold.

L_1: first generation lineation parallel to F_1 axis.

D_2: second generation deformational event.

F_2: second generation fold or fold axis.

S_2: axial plane or axial plane cleavage of F_2 fold.

L_2: second generation lineation parallel to F_2 axis.

etc.:

M_1: first episode of metamorphism.

M_2: second episode of metamorphism.

Table 3

DETAILED STRUCTURAL AND METAMORPHIC HISTORY OF THE WISSAHICKON FORMATION NEAR PHILADELPHIA

PHASE	MESOSCOPIC STRUCTURES	FABRICS	METAMORPHISM
D_1	FAIRMOUNT F_1: isoclinal, similar folds in bedding, S_0. S_1: schistosity parallel to axial planes and bedding. L_1: mineral lineations, ribbing, elongate augen.	Habit alignment of micas and hornblende in S_1 and L_1, rotation axes of snowball garnets in L_1, fibrolite needles in L_1 in augen.	M_1: synkinematic, amphibolite facies.
D_2	SCHUYLKILL F_2: dominant, tight to isoclinal, plane noncylindrical, flattened parallel folds in S_0 and S_1; axial planes dip NW. Upright, isoclinal, plane cylindrical, similar folds in Rosemont fault zone. S_2: axial plane crenulation cleavage, transposition schistosity in fault zone. L_2: axes of small folds, crenulation lineations, rods and mullions, compositional banding (S_0/S_2 intersection) in fault zone.	Micas and hornblende in S_1 and L_1 deformed, S_2 transposition schistosity and cataclastic textures in fault zone. Fabrics recrystallized, staurolite and kyanite cut across S_2, no synkinematic minerals found.	Grade (?), on negative evidence probably no higher than greenschist facies.
D_3	WISSAHICKON CREEK F_3: recumbent, open to close, plane noncylindrical, parallel folds. S_3: axial plane crenulation and fracture cleavages. L_3: crenulation lineations.	S_2 and S_1 deformed, fabrics recrystallized. Kyanite, fibrolite, garnet and muscovite lie across and parallel to S_3, staurolite rotated by S_3.	M_2: prekinematic to postkinematic with respect to D_3. Amphibolite facies with grade increasing SE toward granitized zone.
D_4	GLADWYNE F_4: gentle to open, parallel folds in S_1; close to tight folds in S_2 in fault zone; axial planes dip SE. S_4: axial plane crenulation cleavage, development intensifies NW. L_4: crenulation lineations plunging gently NE and SW.	S_3, S_2, and S_1 deformed. Fabrics recrystallized in SE but not recrystallized in NW, no synkinematic minerals found.	Waning stage of M_2
D_5?	BARMOUTH F_5: steeply plunging, close to tight folds in cataclastic zone marginal to granitized schists. S_5: axial plane crenulation cleavage. L_5: compositional banding (S_0/S_5 intersections) and mullions in cataclastic zone; conjugate pair (?), steeply raking, crenulation lineations in S_1 in NW.	Cataclastic textures marginal to granitized schists, unrecrystallized, no synkinematic minerals found.	Waning stage of M_2

SCHEMATIC CROSS SECTIONS DEPICTING FOLDS AND S-SURFACES IN THE PIEDMONT NEAR PHILADELPHIA

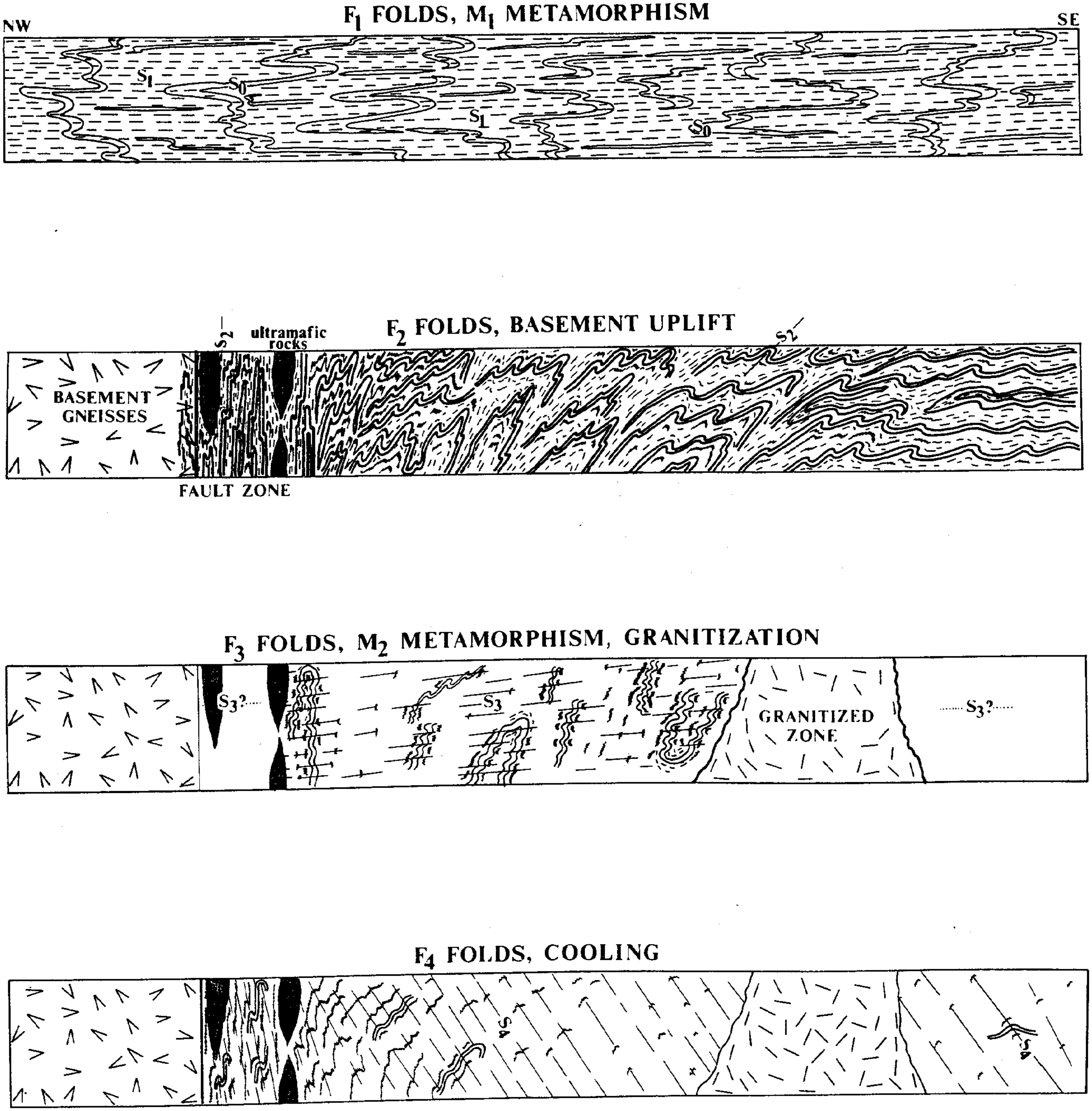


Figure 5. Schematic cross-sections depicting folds and S-surfaces in the Piedmont near Philadelphia.

METAMORPHISM OF ULTRAMAFIC ROCKS OF SOUTHEASTERN PENNSYLVANIA

Frank H. Roberts and William A. Crawford

Many bodies of alpine-type ultramafic rocks occur along the eastern margin of the North American continent. In southeastern Pennsylvania these bodies have been grouped under the general heading "serpentinite and related rocks" on previously published maps, thus giving the false impression that serpentinite is the predominant rock type. Whereas that is true for some bodies, a large number consist of pyroxenite or norite, rimmed by zones of anthophyllite rock grading into chlorite-talc schist and serpentinite on the outer perimeter as shown in the idealized map of an ultramafic body (Fig. 6).

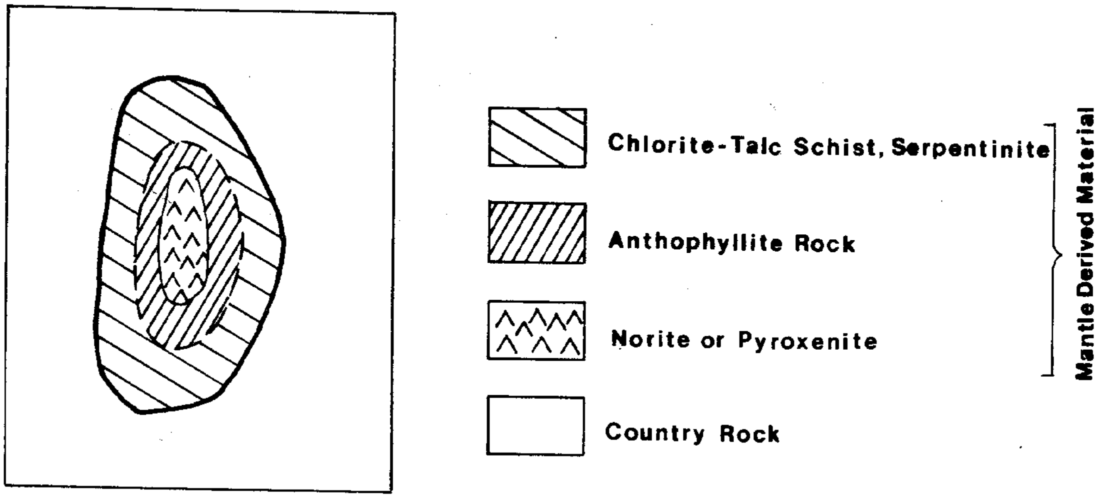


Figure 6. Idealized ultramafic body.

The occurrences of ultramafic rocks in the field trip area are located on Fig. 7. Most of the ultramafic bodies occur within the Wissahickon schist in close proximity to its contact with the Precambrian gneiss. For ease of reference the bodies have been grouped in bands designated by a letter with the individual body labeled by number. A single band (A in Fig. 7) occurs north of the Precambrian gneiss. Some pods of ultramafic rocks (B in Fig. 7) lie within the gneiss and on line with a projection of the "Unionville" septum of the Wissahickon schist. Two spatially distinct bands of rock (C and D in Fig. 7) merge together toward the southwest. The fifth band E contains only body number 1. The field conference will visit bodies C 1 and D 1 which are stops 6 and 9.

Tables 4a and 4b contain a list of ultramafic rock bodies shown on the regional map (Fig. 7) and presents the petrography and chemistry of the various rock types found in each. Pyroxenite and norite remain as unmetamorphosed cores in some metamorphosed ultramafic bodies. The former presence

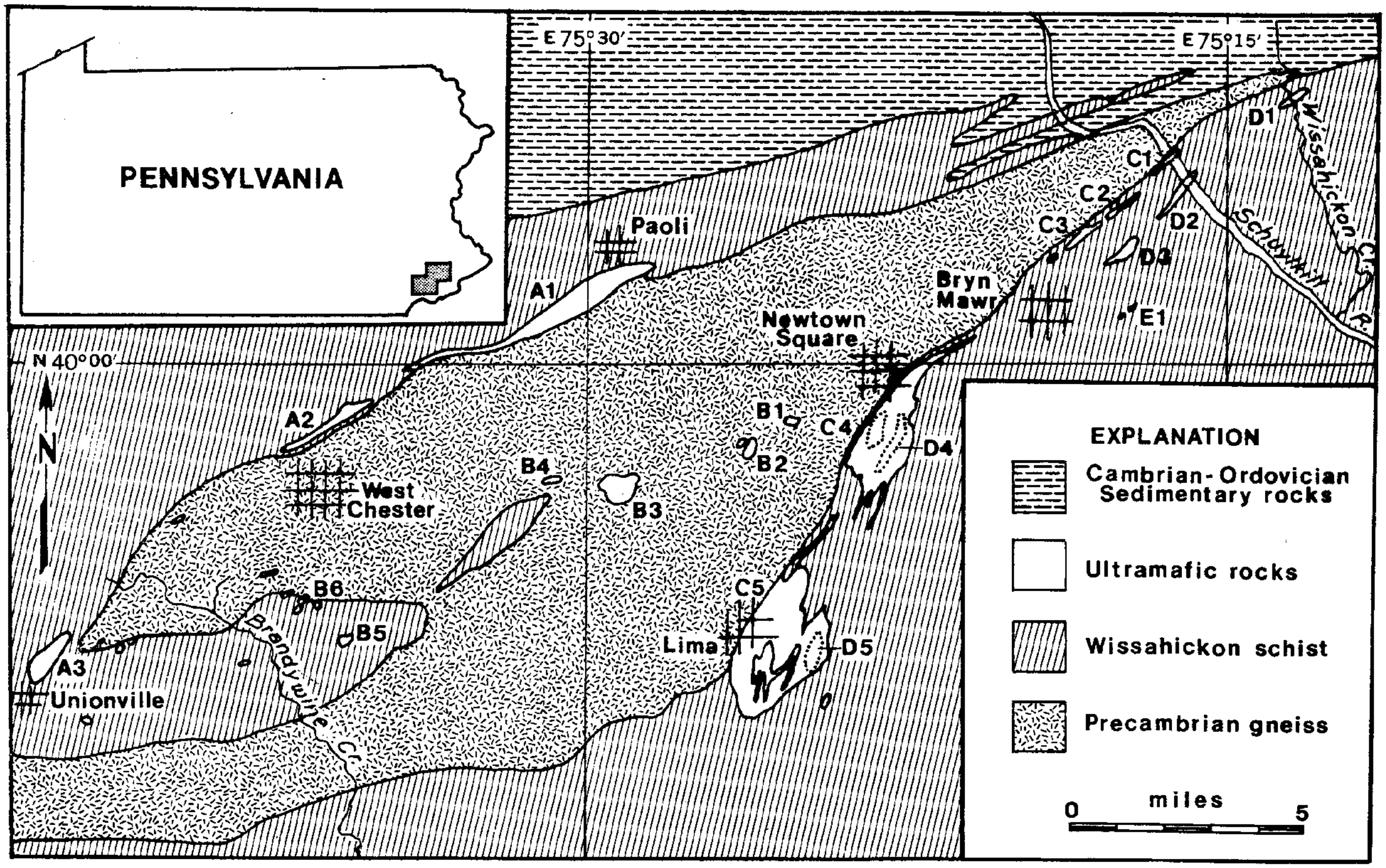


Figure 7 - Occurrences of ultramafic rocks near Philadelphia.

of peridotite and dunite in others is inferred from the mineralogy and microtextures of these bodies.

Ultramafic mass C-D 4 exhibits interfingering with the Wissahickon schist. The attitudes of foliations and lineation demonstrate the structures in the ultramafic rocks are conformable with and similar to those of the surrounding country rocks. It is most probable the ultramafic rocks were emplaced before, or during, the deformation of the Wissahickon schist.

Table 4a

PETROGRAPHY OF ROCK TYPES FOUND IN EACH ULTRAMAFIC BODY

ROCK TYPES	ULTRAMAFIC BODY (see Figure 1)																			
	A			B						C			D			C	D	C	D	E
	1	2	3	1	2	3	4	5	6	1	2	3	1	2	3	4	4	5	5	1
NORITE[1]																X				
PYROXENITE[2]					X												X		X	
ANTHOPHYLLITE ROCK[3]				X	X							X				X	X		X	X
CHLORITE-TALC SCHIST[4]										X	X		X	X	X		X			
SERPENTINITE[5]	X	X	X			X	X	X	X		X		X	X	X	X	X	X		

Mantle-Derived Source Rock

Sequence of Metamorphic Zones

[1] NORITE: The coarsely crystalline, brown and white speckled norite contains 65 percent or more bronzite $(En_{84\pm6})$ with minor augite, 35 percent or less bytownite (An_{85-90}) and 1 to 3 percent chrome-rich magnetite occurring interstitially between pyroxene and plagioclase and also as inclusions within the pyroxene grains. The pyroxene exhibits incipient alteration to anthophyllite.

[2] PLAGIOCLASE-BEARING PYROXENITE: The coarsely crystalline, brown, pyroxenite contains 90 percent or more bronzite; the remainder being bytownite and minor chrome-rich magnetite.

[3] ANTHOPHYLLITE ROCK: This rock containing colorless, fibrous, grains of anthophyllite, relicts of pyroxene, accessory magnetite, and traces of chlorite is the high temperature metamorphic product of the norite and pyroxenite. Anthophyllite rock may be quite massive without foliation or it may be schistose in response to deformation.

[4] CHLORITE-TALC SCHIST: These rocks vary in composition from almost pure talc to a chlorite-magnetite mixture. Talc rich portions of this schist often contain quartz either as veins or intermingled with the talc grains giving the impression that quartz and talc crystallized simultaneously during metamorphism.

[5] SERPENTINITE: Antigorite and chrysotile with accessory chrome-rich magnetite and small grains of relict olivine comprise the serpentinite. The rock's texture is reminiscent of that of dunite.

Table 4b

CHEMICAL ANALYSES OF ROCK TYPES FOUND IN EACH ULTRAMAFIC BODY

OXIDE WEIGHT PERCENTS

OXIDE	NORITE (Avg., 5 Anal.)	PYROXENITE (Avg., 4 Anal.)	ANTHOPHYLLITE ROCK (1 Anal.)	CHLORITE-TALC (1 Anal.)	SERPENTINITE (Avg., 3 Anal.)
SiO_2	53.6	58.4	58.0	56.3	43.7
Al_2O_3	10.4	2.3	2.2	0.7	0.2
Fe_2O_3	1.3	1.9	-	1.5	6.6
FeO	9.3	10.3	13.6	8.0	0.9
MnO	0.2	0.3	0.3	0.2	0.1
MgO	14.8	23.3	22.7	24.4	38.4
CaO	10.4	1.8	1.1	1.9	-
Na_2O	0.4	0.2	0.2	0.6	-
K_2O	-	0.2	0.1	0.1	-
H_2O	1.4	1.3	2.5	3.5	12.2
TOTAL	101.9	100.0	100.7	97.2	102.1

CATION NORM

MINERAL					
Orthoclase	-	1.0	-	-	-
Albite	3.5	2.0	1.5	2.5	-
Anorthite	26.5	4.7	4.3	-	-
Magnetite	1.3	1.9	-	0.7	1.2
Wollastonite	9.8	1.8	-	-	-
Enstatite	40.6	63.8	-	-	-
Ferrosilite	13.8	15.0	-	-	-
Hypersthene	-	-	33.2	8.4	-
Quartz	4.5	9.7	13.8	13.3	1.6
Biotite	-	-	1.1	1.1	-
Actinolite	-	-	-	13.1	-
Serpentine	-	-	46.0	57.4	97.1
Riebeckite	-	-	-	3.4	-
	100.0	99.9	99.9	99.9	99.9

The following hydration reactions are suggested as among those which involve the adjustment of mantle-derived material to the country rock environment and are summarized diagramatically in Table 5. All these reactions involve an increase in volume of the rocks, which would be favored by a lowering of pressure as retrograde metamorphism proceeds. Each of these reactions involves only the addition of water and oxygen which might have been available from the country rock sediments now termed the Wissahickon schist. Iron oxide produced appears as magnetite grains in the metamorphic rocks and silica appears as quartz veins cutting these rocks.

(1) The metamorphism of pyroxenite or the orthopyroxenes of norite to anthophyllite rock occurs in the inner portions of the ultramafic bodies. The key reaction is the production of anthophyllite and magnetite from Opx, water and oxygen:

$6Mg_3Fe[SiO_3]_4 + 3H_2O + 1/2\ O_2 = 3Mg\ Fe[Si_8O_{22}](OH)_2 + Fe_3O_4$

Opx + Water + Oxygen = Anthophyllite + Magnetite

(2) Farther from the centers of the mass continuing hydrous retrograde metamorphism produces the chlorite-talc schist from anthophyllite rock and the remnants of the original pyroxenite and norite. Among the important reactions are the breakdown of anthophyllite to talc and magnetite and the derivation of chlorite, quartz and magnetite from aluminous clinopyroxene:

(A) $3Mg_6Fe[Si_8O_{22}](OH)_2 + 3H_2O + 1/2\ O_2 = 6Mg_3[Si_4O_{10}](OH)_2 + Fe_3O_4$

Anthophyllite + Water + Oxygen = Talc + Magnetite

(B) $3Mg_3Fe[Si_3AlO_{12}] + 6H_2O + 1/2\ O_2 = 3Mg_3[SiAlO_5](OH)_4 + 6SiO_2 + Fe_3O_4$

Clinopyroxene + Water + Oxygen = Chlorite + Quartz + Magnetite

(3) Serpentinite may be derived from primary pyroxenite, peridotite or dunite, or serpentinite may be derived from anthophyllite rock. Three possible reactions are illustrated below:

(A) $3Mg_3Fe[SiO_3]_4 + 6H_2O + 1/2\ O_2 = 3Mg_3[Si_2O_5](OH)_4 + 6SiO_2 + Fe_3O_4$

Opx + Water + Oxygen = Serpentine + Quartz + Magnetite

(B) $3Mg_3Fe[SiO_4]_2 + 6H_2O + 1/2\ O_2 = 3Mg_3[Si_2O_5](OH)_4 + Fe_3O_4$

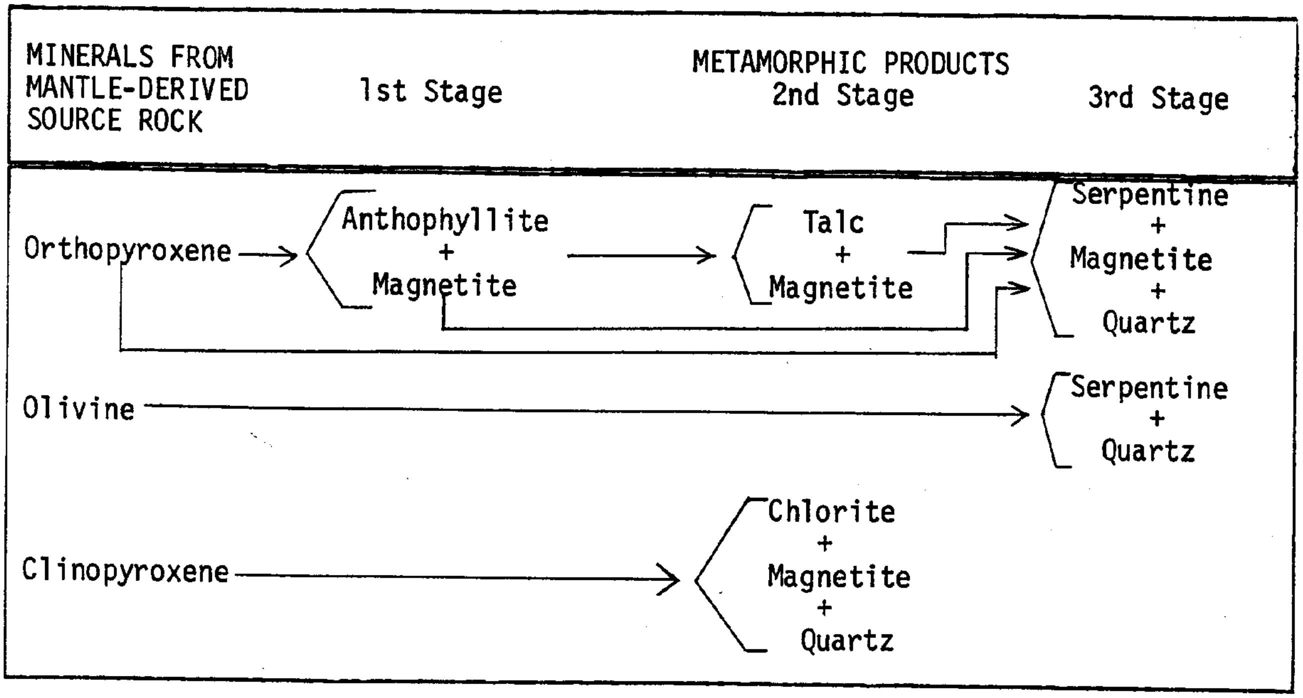
Olivine + Water + Oxygen = Serpentine + Magnetite

(C) $3Mg_6Fe[Si_8O_{22}](OH)_2 + 9H_2O + 1/2\ O_2 = 6Mg_3[Si_2O_5](OH)_4 + 12SiO_2 + Fe_3O_4$

Anthophyllite + Water + Oxygen = Serpentine + Quartz + Magnetite

Table 5

SUMMARY OF HYDRATION REACTIONS INVOLVING THE ADJUSTMENT OF MANTLE-DERIVED MATERIAL TO COUNTRY ROCK ENVIRONMENT



It is proposed that ultramafic rocks originally existing at conditions of very high temperature and moderate pressure were uplifted and moved into an environment of lower temperature and pressure, coming into contact with water derived from the sediments now metamorphosed and termed Wissachikon schist. The metamorphic zoning from norite or pyroxenite to chlorite-talc schist or serpentinite is the result of mineralogical adjustment of the ultramafic rocks to new conditions, those of the almandine-amphibolite facies of the Wissahickon schist. The absence of metamorphism in the cores is thought to be due to both a lack of water and insufficient activation energy.

BALTIMORE GNEISS

Mary Emma Wagner

The Precambrian Baltimore Gneiss in southeastern Pennsylvania is a heterogeneous sequence of rocks of unknown age which, in an area studied in detail, distinctly records two separate episodes of metamorphism. The area of detailed study lies in the block known as the West Chester prong.

The area was subjected to granulite facies metamorphism during Grenville time approximately 1000 m.y. ago. At that time rocks of basaltic composition recrystallized to pyroxene granulites, some of which contain two pyroxenes plus plagioclase (andesine) (±biotite, ±hornblende) and others contain garnet plus clinopyroxene plus plagioclase (oligoclase). The garnet-clinopyroxene association is dependent on the degree of silica saturation and also on the Mg/Fe ratio. Olivine does not occur in any of the granulites, although many are olivine normative. Quartzofeldspathic rocks recrystallized to garnet-hypersthene-plagioclase-orthoclase quartz granulites or garnet-hypersthene-mesoperthite-quartz granulites, while quartz-rich rocks of unusual composition recrystallized to sillimanite-quartz or garnet-quartz rocks. The mineral assemblages indicate P-T conditions transitional between intermediate-pressure granulite and high-pressure granulite facies (Green and Ringwood, 1967), approximately 775-850°C, 8-9 kb.

At some period following the Grenville metamorphism, the Precambrian rocks were intruded by diabase dikes. Both the granulite facies rocks and the diabase dikes were later metamorphosed during a second metamorphism. The only effect of this second metamorphism in most of the granulites was the formation of garnet coronas on mafic minerals wherever they had been in contact with plagioclase. The coronas are almost ubiquitous on hypersthene, magnetite, ilmenite, biotite and hornblende, less common on clinopyroxene, garnet and apatite. Plagioclase adjacent to the garnet coronas frequently shows a narrow zone of less calcic composition. Where the coronas surround hypersthene, there is often a zone of fine-grained clinopyroxene and quartz between the hypersthene and the garnet corona. This indicates a reaction typical of the transition from intermediate pressure granulite to high-pressure granulite facies:

Anorthite + hypersthene = garnet + clinopyroxene + quartz

In those quartzofeldspathic gneisses most affected by the second metamorphism the garnet coronas became very thick and in places surround symplectites of biotite-quartz or biotite-clinopyroxene-quartz instead of hypersthene. In the final stages of this process most or all of the hypersthene has disappeared, the garnets are larger and are more randomly distributed, with only a trace of coronal configuration, and the assemblages are typical of the amphibolite facies.

The diabase dikes contain garnet coronas similar to those in the granulites. Other effects of the second metamorphism in the diabases are the partial replacement of large grains of augite by fine-grained pale green clinopyroxene or pale brown hornblende and the recrystallization of laths of plagioclase (labradorite-bytownite) to fine-grained aggregates of oligoclase-andesine. However, in many of the dikes recrystallization is incomplete and portions of the original igneous minerals remain. Ophitic texture is preserved in most of the dikes.

The complete gradation from rocks in which the only effect of the second metamorphism was the formation of coronas with assemblages typical of high-pressure granulites to rocks completely recrystallized to assemblages stable in the amphibolite facies leads to the conclusion that reaction was incomplete and high-pressure granulite assemblages formed where the rocks were dry, whereas amphibolite facies assemblages formed and reactions were more complete wherever water was available. In the quartz-rich rocks, pseudomorphs of kyanite after sillimanite suggest the sillimanite inverted to kyanite during the second metamorphism. P-T conditions were approximately 650-700°C, 7-8 kb.

The time of the second metamorphism is thought to be Taconic on the basis of discordant ages on zircons from the gneiss, which fall along a chord whose upper intersection with the concordia curve is approximately 1000 m.y. and whose lower intersection is about 450 m.y. (Grauert *et al.*, 1973). (Fig. 4)

GLEN MILLS QUARRY

W. R. Parrott, Jr.

A. HISTORICAL SETTING: First operated in 1884, the quarry was taken over by the General Crushed Stone Company in 1905. It is now the largest quarry in the Philadelphia area, and is approximately -100' elevation at its lowest level. Despite its depth and the proximity of Chester Creek at the top of its western side, water seepage is minimal, most water entering the quarry as runoff. Last year 1,700,000 tons of crushed stone were moved, the rock used primarily for road- and railroad bed-metal, as well as for asphalt produced on the premises.

B. GEOLOGIC SETTING:

1. The first detailed geologic mapping in this area was by Bascom (Bascom, *et al.*, 1909), who mapped the rocks as Precambrian granitic gneisses intruded ("injected") by gabbro.

2. Later work, primarily by and under the direction of Edward H. Watson (Watson, 1957; Thurston, 1965), reinterpreted the rocks as follows:

   a. rock types:
      1) mafic rocks
         a.) pyroxene-rich type
         b.) plagioclase amphibolite
      2) intermediate rocks
         a.) former sediments
         b.) alterations of mafic rocks
      3) felsic rocks
         a.) igneous granites, hypersolvus and subsolvus types
         b.) pegmatites
            1. parallel to foliation (banding) and deformed, sometimes in boudins; microcline rich
            2. cross-cutting and slightly deformed, often garnet rich
            3. cross-cutting, undeformed, microcline and calcite rich

   b. sequence of events:

      1) interlayered graywackes, carbonates; graphitic gneiss; intermediate to basic igneous rocks

      2) granitization, migmatites, early pegmatitic segregations; major deformation and metamorphism, syntectonic

      3) later deformation

4) crushing and hydrothermal alteration

Watson believed the granitization was syntectonic, largely *in situ*; Thurston that the granitic material was not generated *in situ*.

3. Levin (1956) sampled 2 felsic rocks for zircon analysis and dating to compare with another locality in the Baltimore gneiss. The analysis indicated a sedimentary origin for most of the zircons, and dating (Pb-alpha, Larson method) gave dates of 375 and 421 m.y. (Watson, 1957).

4. Grauert (Grauert, *et al.*, 1973) sampled a Glen Mills rock for U-Pb dating; the sample plotted near the concordia, about 450 m.y., w other amphibolite facies rocks. (Fig. 4)

5. Present Study. (Fig. 35)

    a. the present study is part of an overall reinvestigation of primarily amphibolite facies rocks originally mapped as gabbros within the basement complex, bounded on the south by pelitic rocks, banded gneisses and amphibolites of the Wissahickon Formation and the Wilmington Complex (Ward, 1959), and by ultramafic rocks (Roberts, 1969; Roberts and Crawford, this guidebook) and on the north by granulite facies rocks (Wagner, 1972; Wagner and Crawford, 1974; Wagner, this guidebook).

    b. the rocks in the vicinity of the quarry are amphibolites and banded gneisses, generally migmatized to varying degrees.

    c. the contact relationships to the south are complex:

        1) the contact mapped as the Rosemont Fault is frequently only expressed as a topographic depression, is nowhere exposed; mylonitization is not well developed.

        2) the amphibolites along the southern boundary appear to interfinger with the Wissahickon schist, at least locally.

        3) the Wilmington Complex rocks of banded gneisses and amphibolites are strikingly similar to those being studied.

        4) the ultramafic rocks lying along the contact bear uncertain relation to the rocks on both sides (band A of Fig. 7).

    d. the relation to granulite facies rocks to the north described by Wagner is not clear. A zone (band B of Fig. 7) of ultramafic, mylonitic and schistose rocks lies between the study area and that of Wagner. Nevertheless, there may be a gradational transition in rock type and metamorphic grade.

e. these amphibolite facies rocks may be of one, or several ages. The retrograded granulite facies rocks in the north may be of the same age as the amphibolite facies rocks at the quarry. The amphibolites at the quarry may be of the same age as those in the Wissahickon and/or Wilmington Complex.

C. LITHOLOGY

1. There is considerable variation of rock types within the quarry. From 14 measured sections in the quarry, Watson (1935) published figure 8, showing the spectrum of composition; this figure does not take account of the calcsilicate rock on the east wall of the quarry.

2. The several rock types include:

   a. calcsilicate rocks
   b. felsic to intermediate quartzofeldspathic gneisses
   c. mafic rocks, including amphibolitic rocks and meta-diabases with preserved ophitic and subophitic textures
   d. ultramafic rock: weathered serpentine
   e. pegmatitic segregations
   f. mylonites (very local)

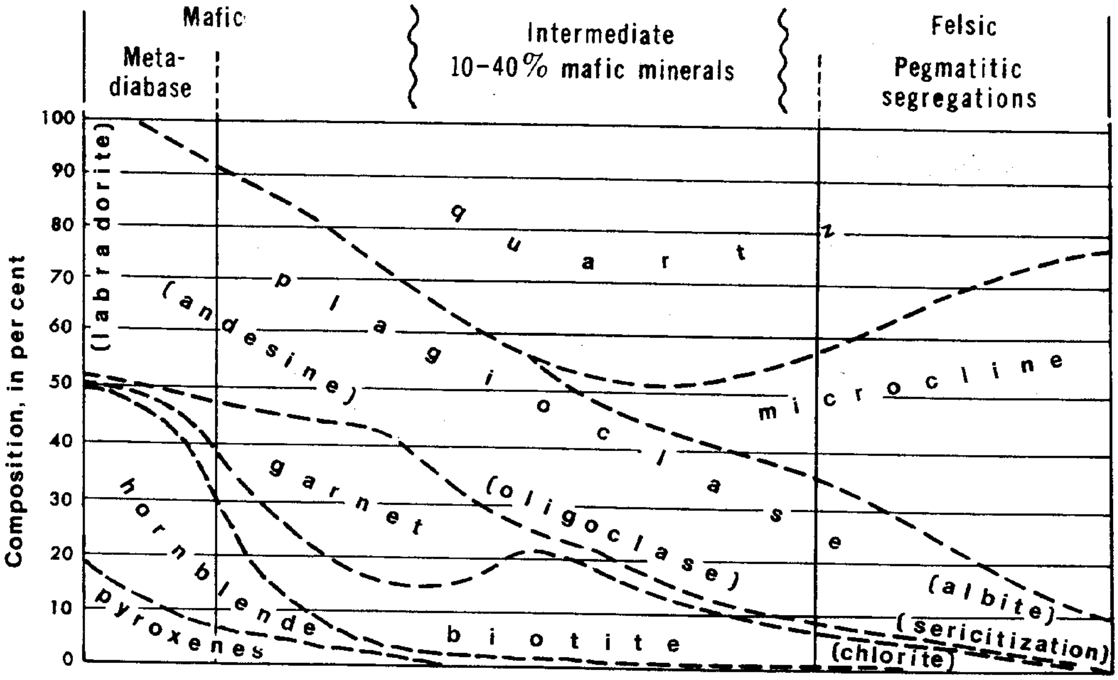


Figure 8 - Variation in rock composition at Glen Mills Quarry based on 14 measured sections by Watson (1935).

D. MINERALOGY

1. The characteristic mineralogy of the major rock types is as follows:

   quartz
   plagioclase
   potassium feldspar
   hornblende
   garnet
   biotite

   Plagioclase composition ranges from An_{11} to An_{42} in felsic and intermediate types, and reaches labradorite in the metadiabases (Watson, 1957; Thurston, 1965). Potassium feldspar includes microcline and microperthite. Garnets of the intermediate rock type have been analyzed as: almandine, 66%; pyrope, 7.5%; grossular, 23%; spessartine, 2% (Watson, 1957).

2. Other minerals present include: calcite, hypersthene, augite, epidote, muscovite, pyrite, magnetite and ilmenite.

3. Accessories include: sphene, apatite, zircon, rutile and sericite.

4. Thurston (1965) reports sillimanite in biotite rich layers of some intermediate rocks; Levin (1965) also reported sillimanite and noted trace amounts of kyanite in a garnetiferous felsic band.

E. METAMORPHISM

The assemblage hornblende-plagioclase-garnet-epidote is characteristic of the amphibolite facies of metamorphism; migmatitic rocks show several degrees of partial melting.

See Fig. 2 and Fig. 3 for the relationship of the metamorphic grade of these rocks to those of other stops.

F. STRUCTURE

The structure of the quarry is complex (Figs. 35 and 9). The prominent foliation is isoclinally folded compositional banding, which may be either original bedding or metamorphically induced banding; the predominant northeast strike and southeast dip of the foliation is shown in Fig. 9 as is the southeast plunge of the major lineation. Locally there is considerable complication of the structure, primarily due to later broad folding and the effects of partial melting; the most notable example of this complication is a synform with minor structures along the eastern side of the quarry, where shallow dips and dip reversals are common. Boudinage is very well developed along both the south and north walls.

G. A POSSIBLE SEQUENCE OF EVENTS:

The following is one possible interpretation; as work continues, however, it remains open to revision:

1. sedimentary and igneous rocks; some possibly already metamorphosed; banding seen in quarry
2. isoclinal folding
3. main metamorphism, with migmatization; continued deformation
4. pegmatitic segregation; continued deformation
5. late pegmatitic segregation
6. fracturing

According to this interpretation most of the events recorded in the quarry were Paleozoic, in accord with the dating by Levin and Grauert. This does not preclude that the original rocks were older. One major phase of metamorphism and intense deformation is postulated; compare with Amenta (1974, and this guidebook).

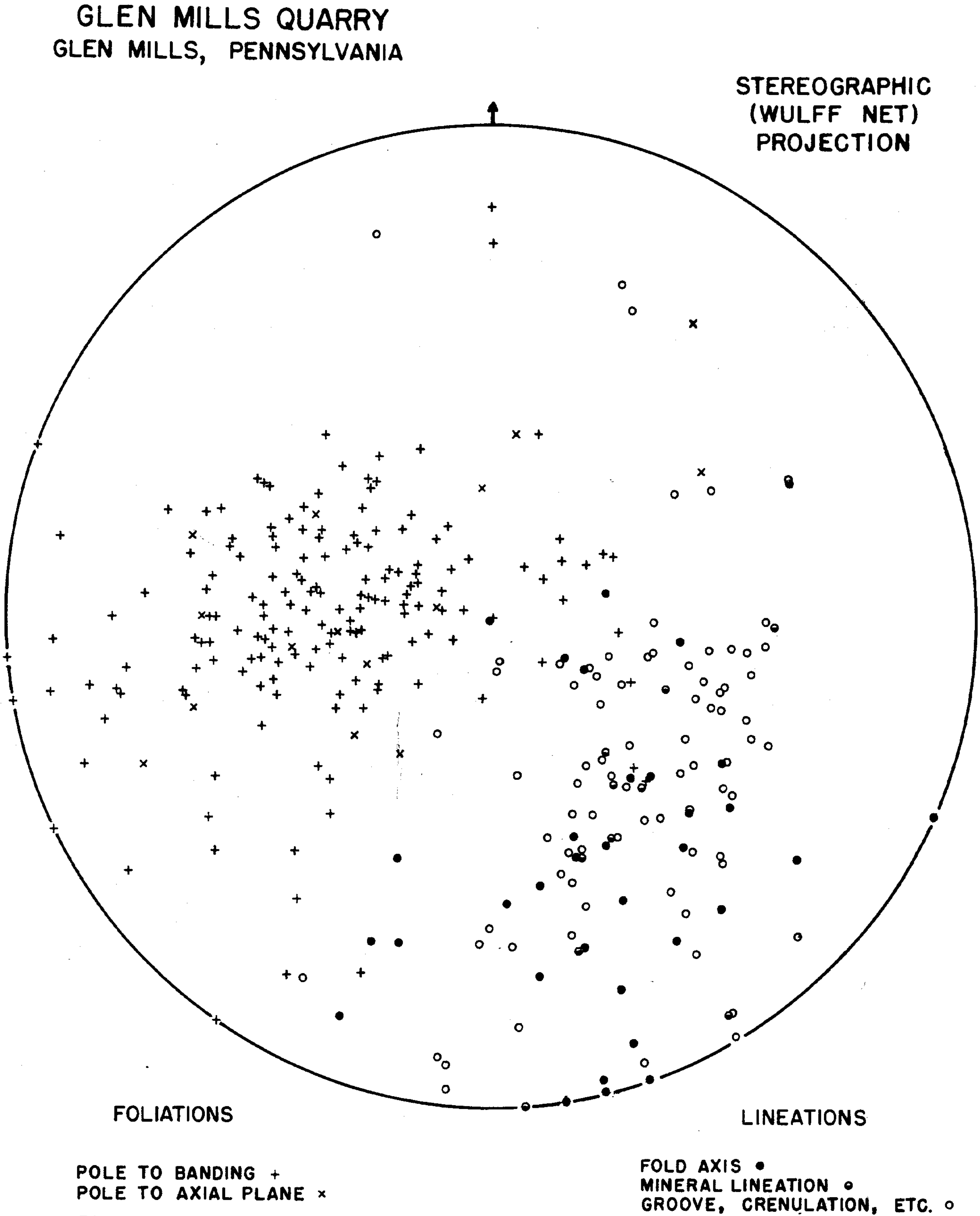


Figure 9. Stereographic projection of foliations and lineations, Glen Mills Quarry.

SINKHOLES

William B. Fergusson

Limestone terrains in humid climates have always been choice sites for human settlement, agriculture, industry, and presently urban and suburban growth. Broad rolling valleys, fertile soil, and usually adequate to great yields of groundwater are all conducive and attractive to human pursuits. It is easy to maintain road grades in a carbonate valley; the Chester Valley is no exception. The predecessor of the Penn Central System laid their Main line tracks down the valley about 140 years ago, following the Philadelphia to Lancaster Turnpike which was built in 1774 and which, in turn, followed the old Indian trails.

Stops 1 and 7 are located in the Chester Valley which extends through Montgomery, Chester, and Lancaster Counties over a distance of about 50 miles. This narrow valley, rarely attaining a width of two miles, is floored with metamorphosed carbonate rocks belonging to the Ledger, Elbrook, and Conestoga Formations. The rolling topography of the valley ranges between 100 and 200 feet above sea level; it is flanked on the north and south by hills of more durable metamorphic rocks ranging in elevation between 400 and 600 feet. The southern border of the valleys was once bounded by a famous fault, the Martic Overthrust, but the fault has been removed from the literature and the southern border is now the Martic line delineating the contact between carbonates and phyllites. The major streams cross the valley along its entire length and only the minor tributaries parallel the valley for short distances. Thus the Chester Valley appears not to be the result of stream erosion but rather an example of a valley formed mostly by solution of carbonate rocks.

Solution features have been of slight consequence in the valley's cultural past; and in fact residents in rural areas sometimes welcome the appearance of a sinkhole. Sinkholes have been greatly utilized as solid waste disposal centers for the minor amounts of farm refuse in the past. Now that urbanization and suburbanization are rapidly traveling down the valley solution features are becoming an environmental and engineering problem.

Beneath the rolling topography and within the rich soil, masked from view, are pinnacles and potential sinkholes. Many pinnacles and sinkholes are located within the small section of the valley covered by this field trip (Fig. 17).

Pinnacles are formed by the solution of carbonate rocks along open joints and bedding planes at the soil rock interface. Here, as throughout the Appalachians, solution features follow the strike of the beds. Therefore, almost all pinnacles in the region parallel the strike of the rocks, and possess a serrated appearance where cross joints are susceptible to solution. In general, fine grained, pure limestones are more susceptible to solution than dolomitic limestones, arenaceous limestones, and dolomites characteristic of the Chester Valley, so there are no "large" caverns in the area; but the subsurface has a multitude of openings making the groundwater hydrology complex. Many workers believe that most solution features occur in thick bedded carbonate units, and the thinner units are not susceptible to large scale solution. There appears to be no basis for this belief, and Rauch and White (1970) in their detailed study of solution of carbonate rocks in the Nittany Valley found no correlation between the amount of solution and the thickness of the beds. The sequence of events leading to sinkhole formation in steeply dipping carbonate rocks is well illustrated by the modification of the work of McGlade, Geyer and Wilshusen (1972) shown in Fig. 10.

It appears that the collapse of the soil arch into the subsurface void is inevitable, although a lengthy process. Sinkhole formation from Steps 4 to 5 is easily hastened by the works of man, particularly at construction sites. Grading of building sites thins out the soil arches between the pinnacles and over the undetected voids. Lowering of the water table causes soil arches to desiccate rapidly and hasten collapse. Frequently collapse of the soil arch occurs during heavy rains when surface runoff becomes channeled onto a soil arch and washes the arch into the void. Paving over an arch, or pouring a foundation on it, can cause collapse because of the extra weight; or by drying out of the arch because of the impervious cover provided by the construction.

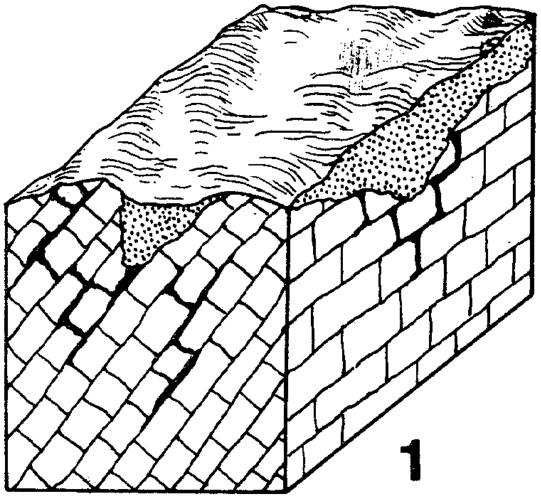
If an incipient or actual sinkhole is located before construction it is best to excavate the sinkhole until solid rock is exposed, place a steel mat or beams across the hole and make a concrete platform across the opening. This was the technique used for the sinkhole depicted in Fig. 11. In the event that the solid rock rim of the sinkhole cannot be found frequently the hole is filled with rock rubble and grouted. If the sinkholes formed after construction most frequently the sinkhole is grouted. None of these techniques are infallible, and frequently sinkholes are only partially "cured".

Detection of incipient sinkholes by ordinary field techniques is at best difficult. If there are sinkholes and shallow soil depressions in an area; and the sinkholes and depressions follow the strike of the rocks; and cross the property in question, the odds are extremely high that sinkholes will form during construction.

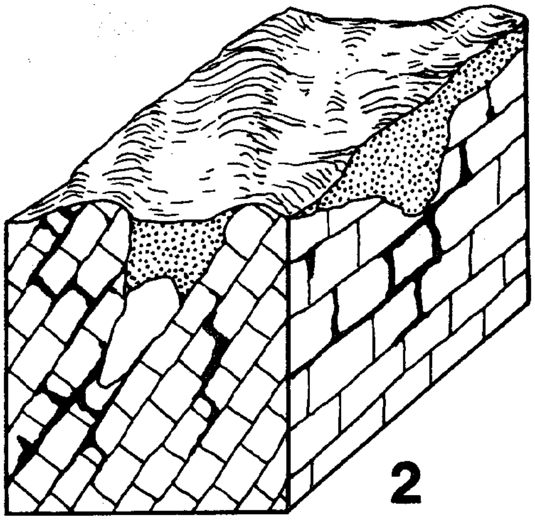
Potential sinkholes are frequently found by close spaced drilling. Drilling is difficult in that core recovery will be very poor, drilling water is lost in the subsurface voids; and what little core is recovered is usually oxidized, pitted, and ground up by the drill as it alternately travels through soil, voids, and limestone pinnacles.

Standard subsurface procedures also frequently miss detection of these subsurface voids, and the potential sinkhole is discovered too late. Some researchers believe that geophysical techniques show little promise for the detection of subsurface solution problems (Knight, 1971); other workers believe geophysical techniques show some promise (McGlade, Geyer and Wilshusen, 1972); and others have demonstrated where geophysics, particularly resistivity techniques may be an invaluable aid to the detection of subsurface solution problems (Richards, 1971).

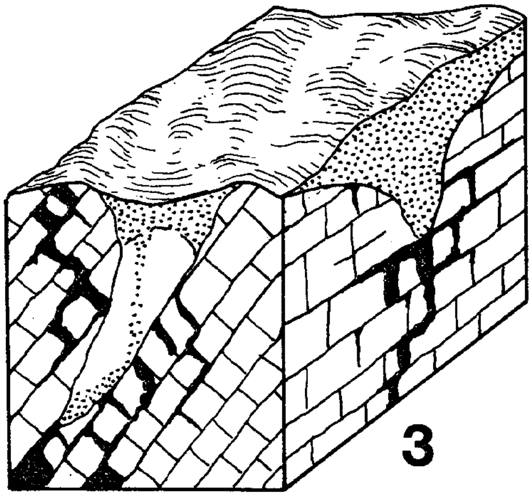
The groundwater hydrology of the carbonate rocks in this area is quite complex because of the varieties of openings which may occur in the subsurface. The initial porosity of carbonate rocks is very low to nil; more groundwater is



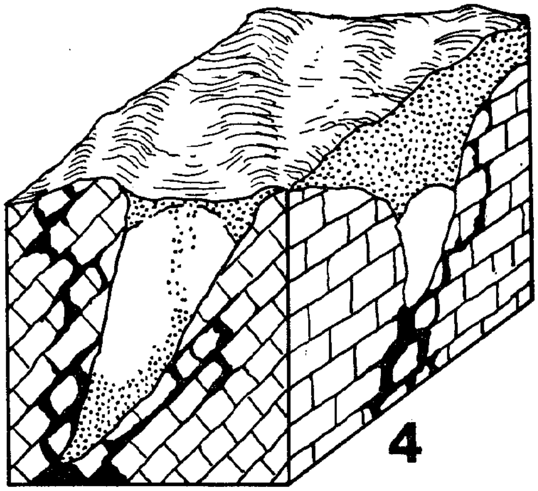
Pinnacle development begins on the edges of steeply dipping beds at the soil-rock interface. The main body of the pinnacle parallels the strike of the beds, and solution on cross joints lends a serrate appearance to the pinnacle.



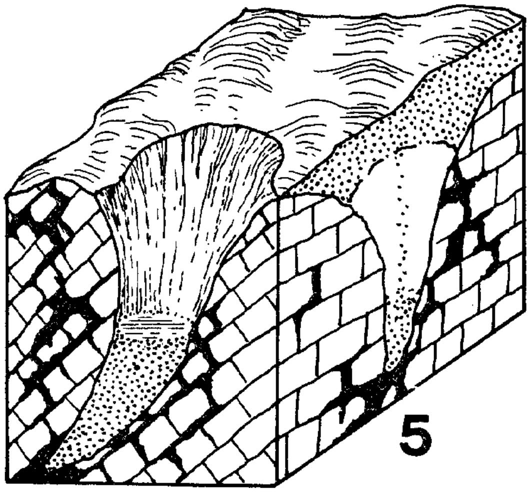
A cavity forms beneath the soil cover, between the pinnacles, as solution advances down dip. A soil arch forms above the void and provides a foundation for the soil above the void.



The soil arch desiccates as the void enlarges, and the soil falls into the void. This further enlarges the void and weakens the thinning soil arch.



Prior to collapse the soil arch is very thin.



After collapse a new sinkhole is added to the landscape.

Figure 10. Sinkhole development (after McGlade, Geyer, and Wilshusen, 1972)

transmitted through joints than through pore space. The groundwater flow may be low to moderate along joint openings, in solution openings it may be great. The greater flows may be turbulent. This turbulence would enhance the solution openings through subsurface erosion. In addition subsurface solution along joint planes and bedding planes complicates the direction of subsurface flow.

Of course there is no practical way to determine what type or types of subsurface openings may be present beneath a particular site. The following data were developed from published records of water wells drilled in the carbonate rocks within the general field trip area (Newport, 1971; D.E.R., 1973). Fourteen wells were drilled in Cambrian Age rocks of the Ledger and Elbrook Formations; and thirty wells were drilled in the Conestoga Formation of Ordovician Age. The wells range in depth between 50 and 820 feet. The 50 foot deep well was drilled in the Elbrook Formation and yielded 50 GPM; and the 820 foot deep well was drilled in the Conestoga Formation and yielded 79 GPM. The highest yield is from the Ledger Formation, two miles west of Stop 7, from a 275 foot deep well with a yield of 1810 GPM. Of all the wells studied within a two mile radius of Stops 1 and 7, the mean depth is 274 feet, median depth 230 feet; and the majority of wells were about 200 feet deep. The mean yield from these wells is 210 GPM, median yield 100 GPM; and the majority of wells produced about 100 GPM. It appears that subsurface openings range from joint openings in the eight wells that yielded less than 50 GPM, to joints enlarged by solution in the fifteen wells whose yield was from 50 to 200 GPM; and "large" solution cavities in the twenty-one wells that produced over 200 GPM. There is, of course, no relation between well depth and well yield.

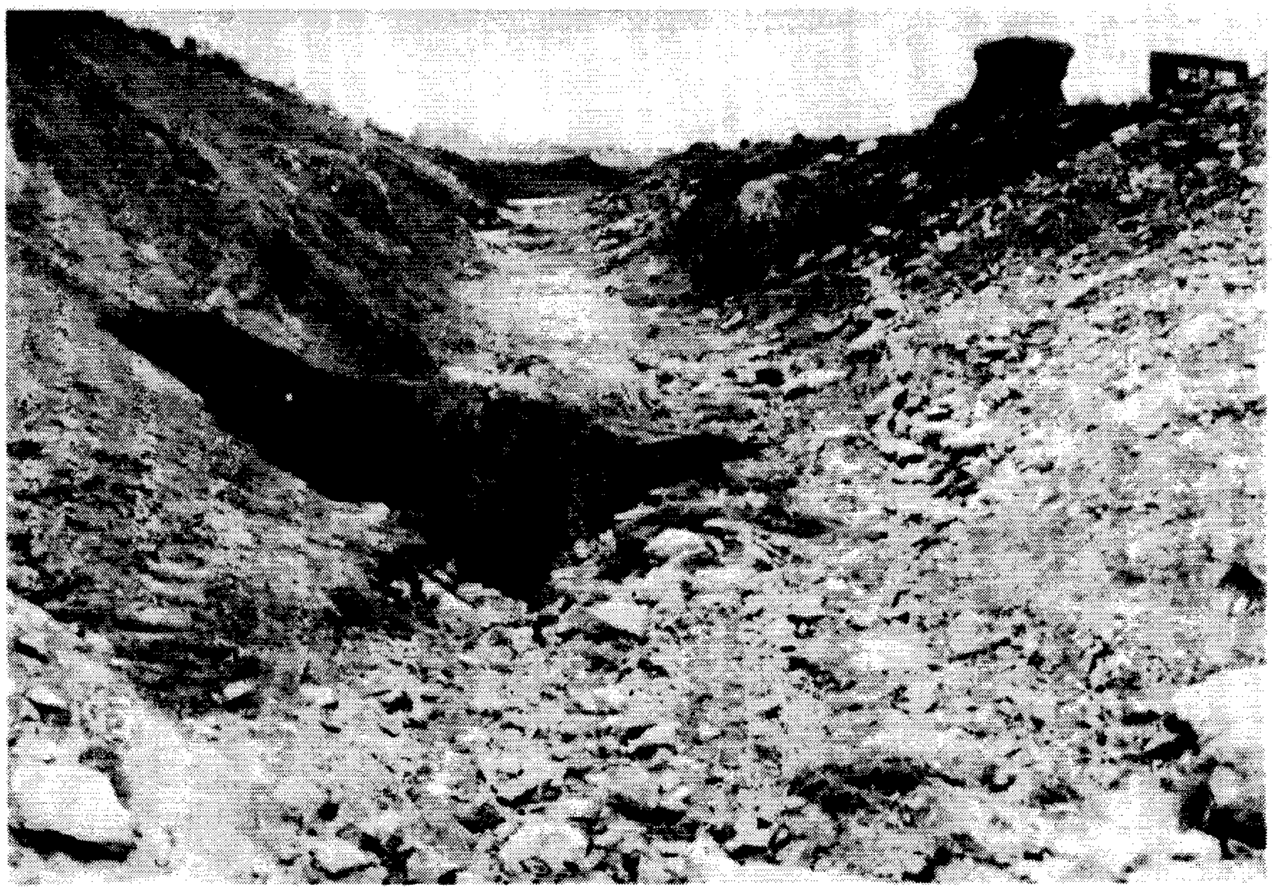


Figure 11. Excavation for the construction of the King of Prussia Plaza showing sinkhole. June, 1962 (after Chajkewsky, 1971).

THE ROUTE 202 SINKHOLE
A Case History

Edward J. Trojan

INTRODUCTION

U.S. Highway 202 is a heavily traveled, commercial roadway built on the carbonate terrain of the Chester Valley and the arkoses of the Triassic Lowlands in the field trip area (Fig. 1). The highway passes through rural countryside in a valley of low relief. These two factors would normally combine to help reduce construction costs. However, a portion of the roadway in the Chester Valley has suffered from sinkhole development and consequent collapse. As a result, the ultimate cost has been high.

A summary of developments from design through construction and maintenance is interesting to follow. In the design phase it was thought that the cost involved to remedy anticipated sinkholes during roadway construction would be excessive and it was therefore decided to pursue normal construction methods with carefully controlled surface drainage. After construction, any sinkhole development which threatened the road would be cared for by Highway Maintenance.

After construction a persistant sinkhole developed under Route 202 in January 1970 near the Bridgeport quarry (Upper Merion Reservoir of the Philadelphia Suburban Water Company). It affected not only the subject route, causing it to be closed to traffic, but also adversely affected design procedure for a 4-lane, limited access highway to be located adjacent to the collapse (Figs. 16 and 17). In order to repair Route 202 maintenance crews removed loose material from the sinkhole and poured a concrete plug in an effort to prevent further collapse. The highway was rebuilt over the sinkhole. After two months the repaired roadway collapsed again and was repaired in the same manner, only to collapse a third time within a week. Giving up in despair, PennDOT officials constructed a temporary roadway 100 feet to the west of the collapsed highway in June, 1970. The sinkhole beneath the original roadway collapsed six times from January, 1970 to October, 1970. All of the collapses occurred within a 100 foot diameter area, the biggest collapse being 35 feet in diameter by 30 feet deep. The "temporary" roadway has been in use for more than four years without failure, although some warping has occurred.

PennDOT's Soils Unit was asked to study the area near the sink, evaluate the alignment of the new 4-lane road, and make necessary design changes to stabilize the area.

GEOLOGY AND GEOPHYSICS

Bedding and joint planes control the extensive chemical and mechanical weathering of the Cambrian Ledger dolomite. Numerous deep, wide, near vertical seams and large solution channels are evident in the Bridgeport quarry. One hundred and eighty attitude measurements were taken on bedding and joint planes within the quarry to determine the predominant directions in which channels and sinkholes are most likely to occur. The data are presented in Figures 12 and 13 and are summarized below:

Planar Feature		Attitude
Bedding	(S_0)	N80W 45SW
Joints	(J_1)	N45E 70-90NW
	(J_2)	N22E 70-90NW
	(J_3)	N29W 78NE

Initially both seismic and earth-resistivity methods were considered for the geophysical investigations. However, the close proximity of the "temporary" roadway would cause too much interference for a seismic study so the earth-resistivity method was selected even though it is generally not recommended for rock containing vertical planar features.

Measurements were taken on 25-foot centers along two parallel lines; one located approximately along the center line of the proposed 4-lane road, the other offset 50 to 100 feet to the north. The equal electrode spacing method (Lee Modification of the Wenner Configuration) consists of a line of stations evenly spaced in three foot increments, symmetrically paired about a central station. The three foot spacing is termed the incremental A-spacing. Raw resistivity data were reduced by computer to obtain the apparent resistivity (Barnes Layer) for each A-spacing (or layer) to allow for the preparation of a subsurface contour diagram to a depth of 75 feet. A sample profile (Fig. 14) shows excellent correlation between the joint and earth resistivity studies. Nearly vertical clay filled, deeply weathered joints are evident in the profile, while bedding planes are somewhat masked by the difference in horizontal and vertical scales. A plot of apparent resistivities at 21, 42, 60, and 75 foot depths for each centerline station (Fig. 15) reveals anomalies where material with a high apparent resistivity overlies material with a lower apparent resistivity. For example, a ledge of dolomite overlies a clay seam. This type of problem area can be marked for stabilization during construction.

The information obtained from the earth-resistivity and joint studies was utilized to lay our 80 drillholes at possible sinkhole locations or above apparent clay seams. Most holes were drilled at least 15 feet into rock having an average Rock Quality Designation (R.Q.D.) of 70% over a continuous 15 foot length. R.Q.D. is defined as percentage of core recovery in pieces four inches or greater in length. Rock of this soundness should have sufficient strength to span any detrimental subsurface solution features. Figure 16 is based on the elevation at which bedrock was first encountered in the drill holes. Depth to bedrock in the project area varies from 20 feet to more than 188 feet, reflecting the uneven weathering of the dolomite surface. The "closed lows" on the map are interpreted as potentially unstable areas requiring remedial treatment.

ENGINEERING ANALYSIS

The projected traffic load on the new 4-lane route precludes closing the route for repair of sinkhole damage after its completion. Therefore, several large scale stabilization measures were considered.

1. Span the area on pile or caisson supported structures.

2. Pressure grout the underlying bedrock to solidify it to a given thickness.

3. Span the area with a mat foundation of reinforced concrete.

4. Span the area with a mat foundation of reinforced earth.

The uneven nature of the dolomite surface and the variable depth to 70% R.Q.D. exclude the use of piles or caissons as any differential movement between adjacent spans cannot be tolerated. Pressure grouting does not guarantee all cavities and channels will be sealed even though huge quantities of grout are used; therefore, it would be necessary to increase safety margins by using additional stabilization methods. The cost of using unsupported, thick, reinforced concrete slabs to span any considerable distance is prohibitive. Both engineering and economic considerations indicate that a reinforced earth slab, designed to span a 50 foot cavity without significant deflection, would prove the most satisfactory method of supporting the new roadway.

The construction sequence selected entails:

1. Excavating to 15 feet below ground surface.

2. Pressure injecting a cement-fly ash mixture into 10 foot deep holes in bedrock spaced on 10 foot centers.

3. Laying a roadbed foundation 3 feet thick consisting of alternating layers of steel bands and crushed stone. Strength is obtained through friction between the angular aggregate and the flat surfaces of the steel bands. The foundation must be under 10 to 15 feet of soil to obtain the necessary pressure for the development of frictional force within the foundation slab.

4. Backfilling with earth to the proposed roadway elevation.

5. Paving the road surface.

The reinforced earth concept is relatively new. This project is its first application as a mat foundation for a roadway in the United States.

CONCLUSIONS

1. The addition of geophysical and geological data has presented the designers with much more information than could be obtained by a core-drilling program alone.

2. The stabilization procedures used here cost approximately $2,000,000 for 1100 feet of roadway. Changing the right-of-way must be considered for regions where longer stretches of road must be stabilized under similar conditions to those described above.

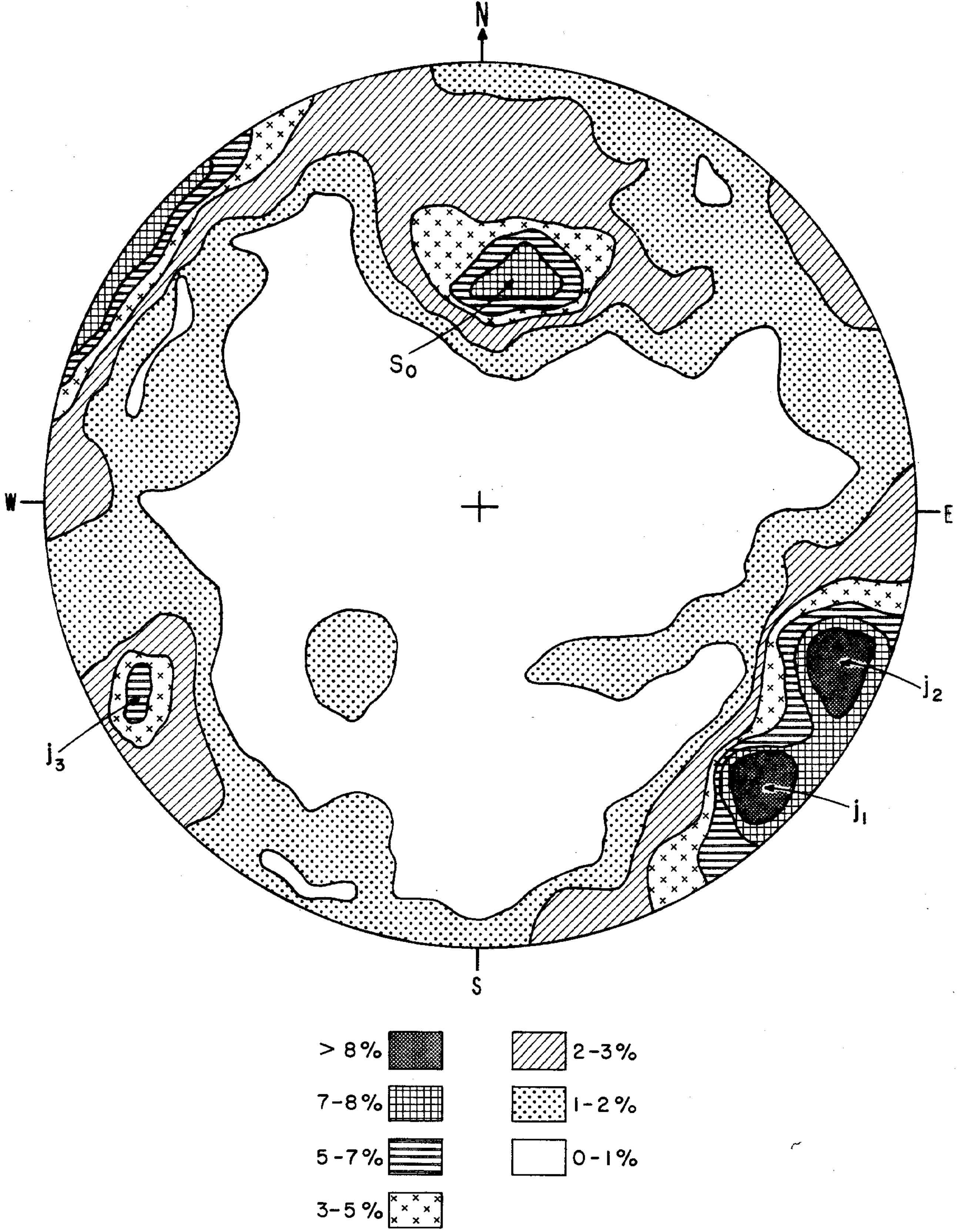


Figure 12. Contour diagram of poles to bedding and joint planes in Ledger Formation, Bridgeport Quarry (180 readings).

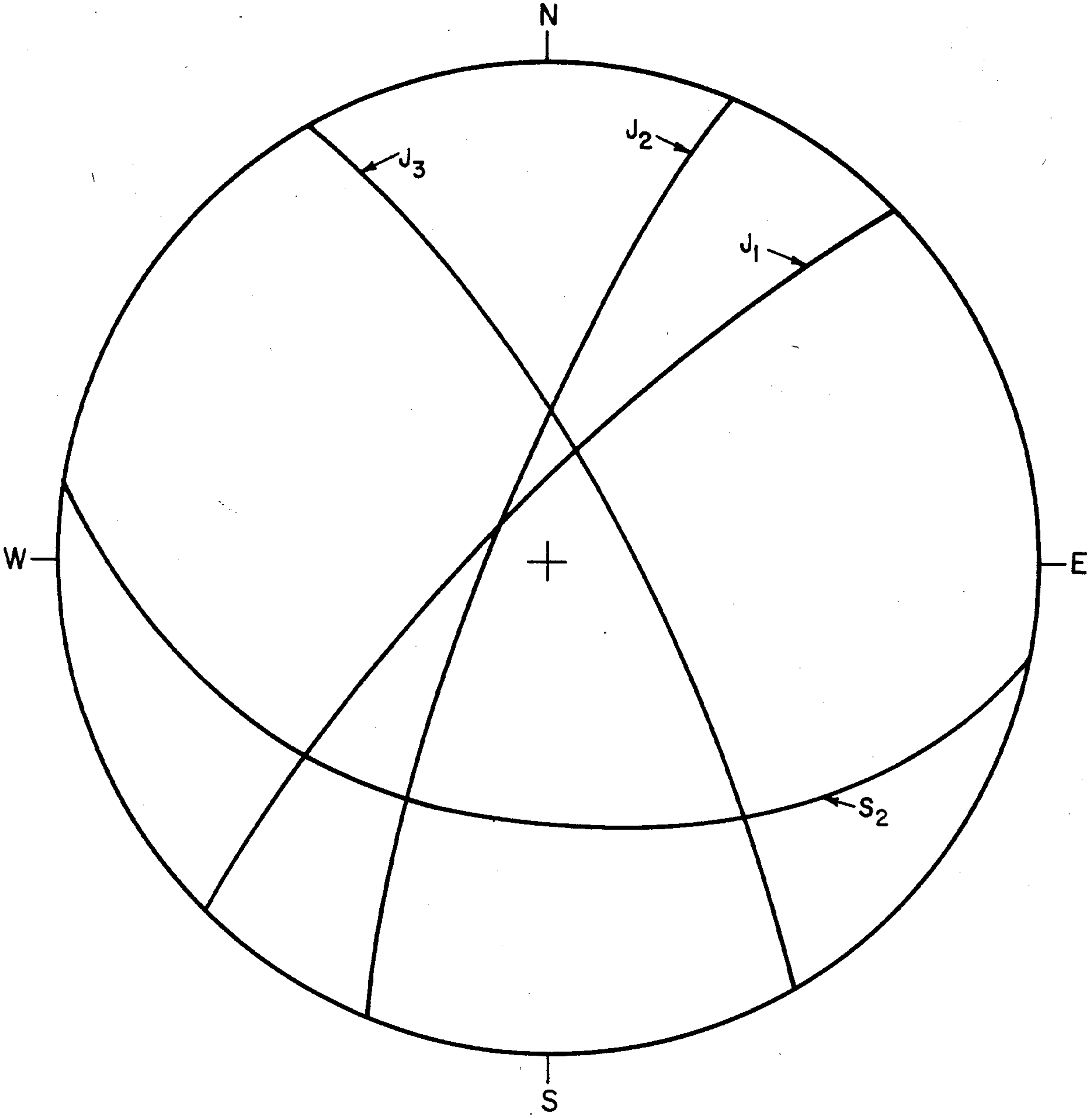


Figure 13. Stereonet plot of dominant bedding and joint planes in Ledger Formation, Bridgeport Quarry.

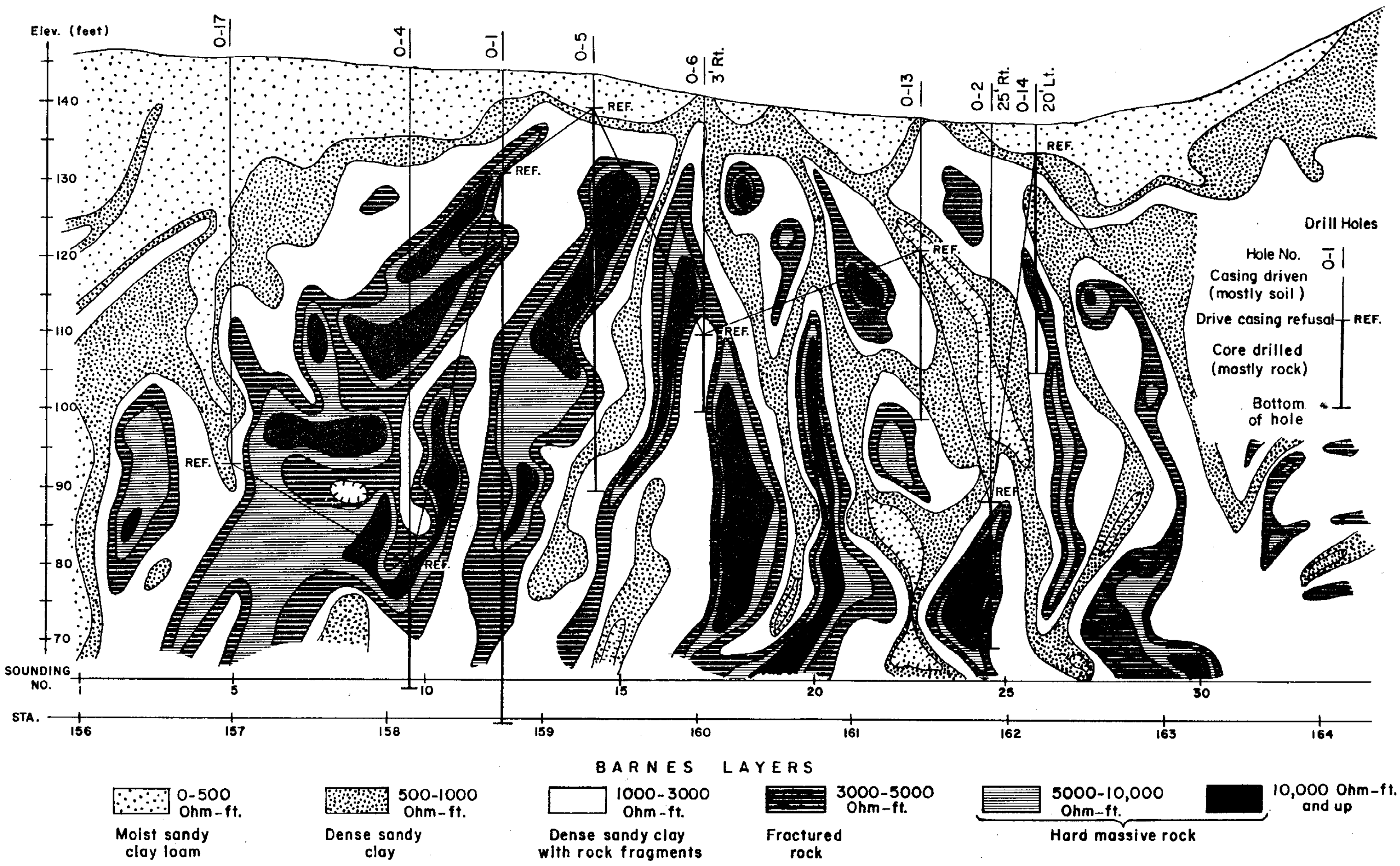


Figure 14. Barnes layer resistivity profile along center line of proposed new roadway.

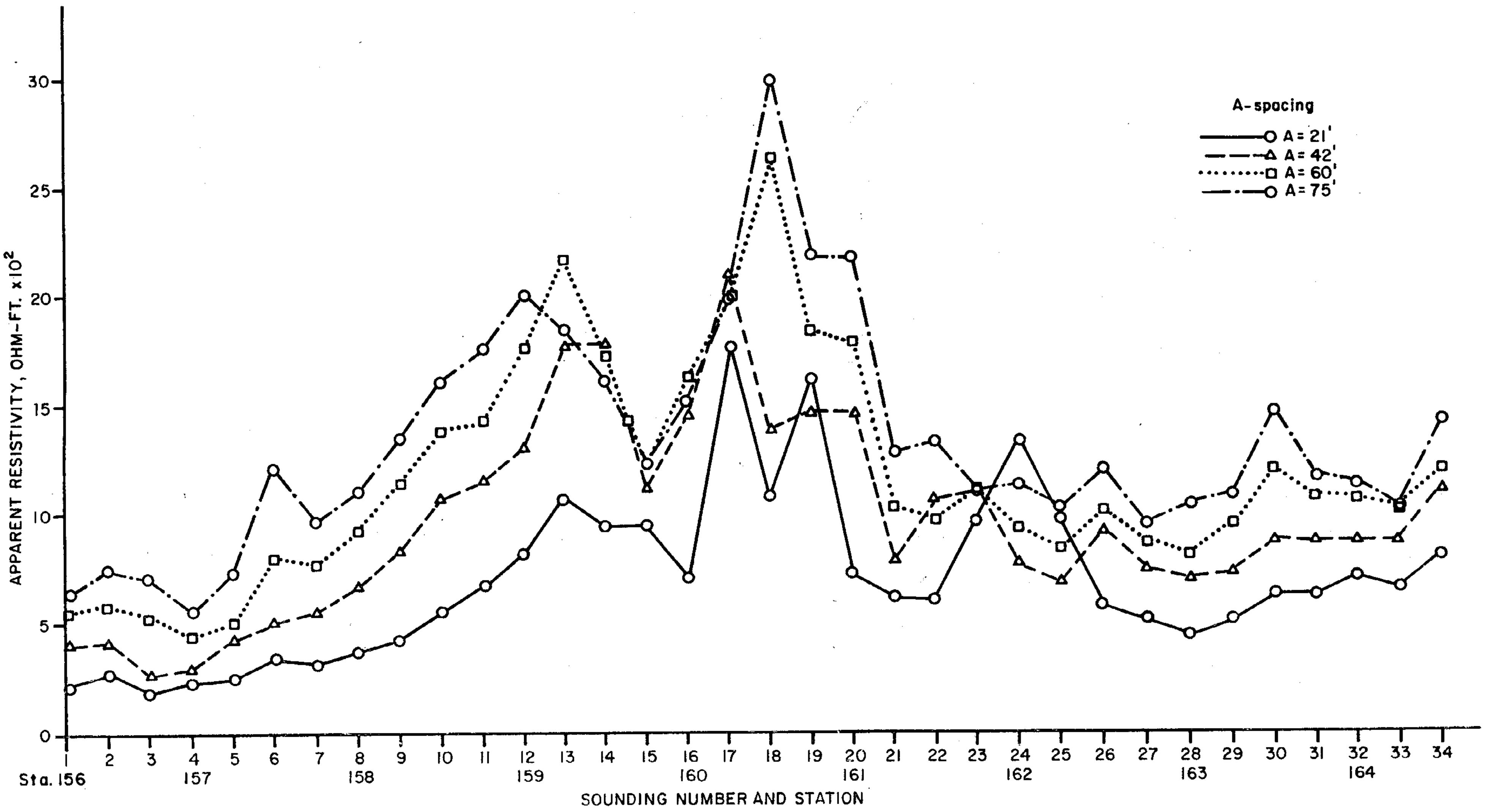


Figure 15. Horizontal resistivity traverse along center line of proposed new roadway.

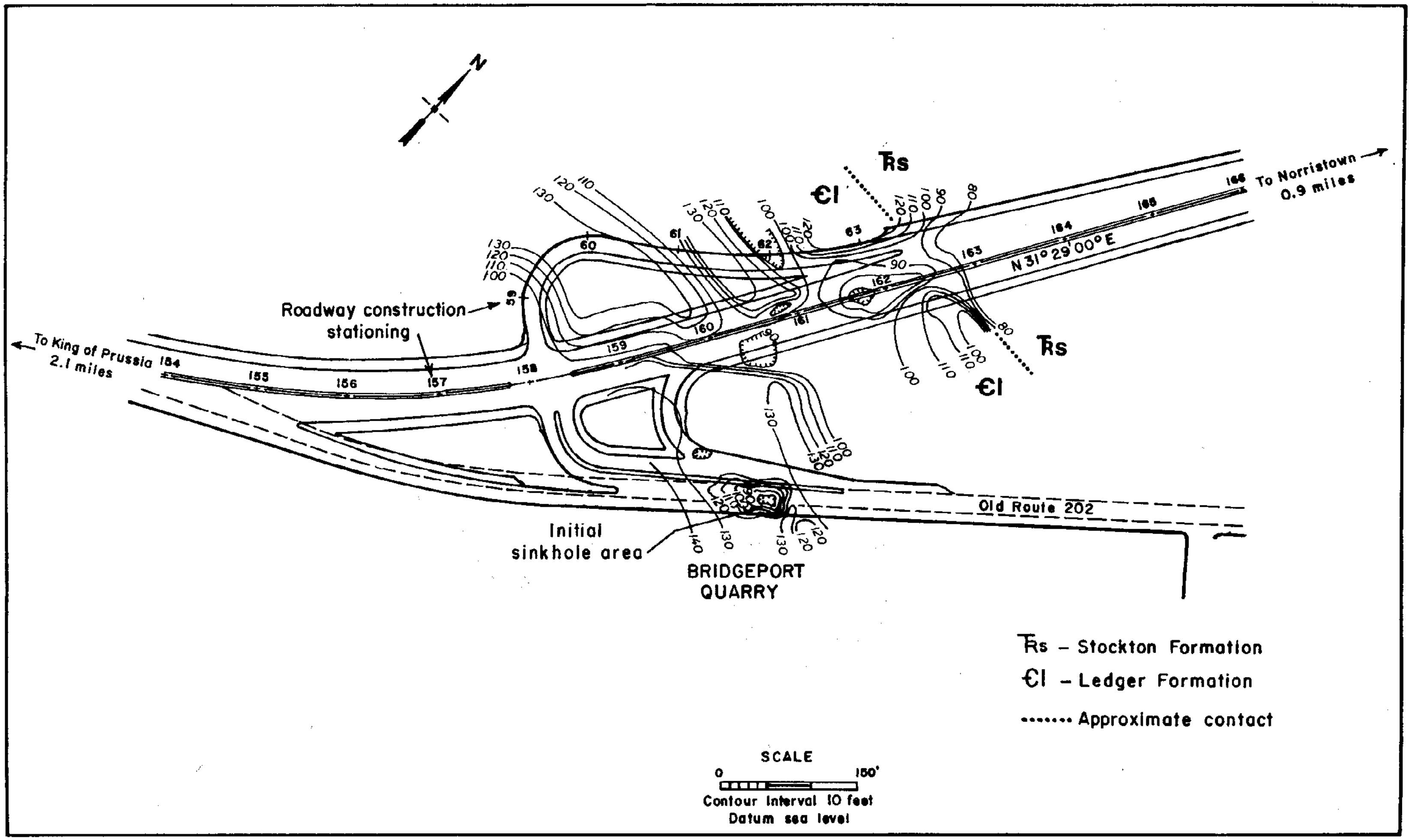
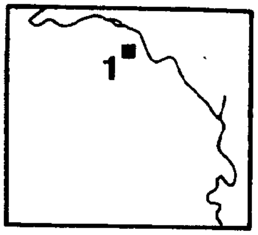


Figure 16. Structure contours on soil-bedrock interface in project area, showing numerous sinkholes and solution channels.

Mileage	MOTEL TO STOP 1
0.0	George Washington Motor Lodge. Leave by front entrance. Turn right onto Warner Road access ramp.
	The Motel lies in the Chester Valley which is underlain by the Cambrian Elbrook Formation containing limestone and dolomite.
	King of Prussia derives its name from the Old King of Prussia Inn whose first owner, a Prussian, named it for the Brandenburg Prince, who in 1701 transformed The Duchy of Prussia into a Kingdom, taking the title of King Frederic I. (French, 1957, p. 408)
0.3	Warner Road, turn left, cross over U.S. 202.
0.4	Turn right onto ramp to U.S. 202 North.
0.7	Exit right to I-76 (Schuylkill Expressway) to Philadelphia.
	Immediately southeast of the U.S. 202-Expressway intersection our route crosses the contact between the Cambrian Elbrook Formation and the Ordovician Conestoga Limestone Formation. We remain in the Conestoga Formation until after we leave STOP 1 except for a brief transecting of a septum of the Octoraro phyllite in the South Valley Hills just north of the Gulph Mills Exit.
3.7	Right lane for Gulph Mills Exit No. 36 (Pa. 320).
	An early grist mill on Gulph Creek lent its name to Gulph Mills. Gulph Road led from Lancaster Pike to Gulph Mills and beyond through Valley Forge as an alternate route to Lancaster. (Alderfer, 1951, p. 95)
4.1	Intersect South Gulph Road at bottom of ramp. Yield to all cross traffic. Turn left.
4.4	Turn right following Pa. 320 onto Holstein Road.
4.8	Turn right onto Jones Road.
5.2	Enter gate on left and park in field. This is the rear entrance to the Montgomery County Landfill #1 and is normally locked.
	STOP 1. ALLENTOWN PORTLAND CEMENT QUARRY #2 OR MONTGOMERY COUNTY SANITARY LANDFILL #1 by William B. Fergusson.



After the field conference visitors to the landfill should obtain permission from the Director of Solid Waste, Montgomery County Court House, Norristown, Pa. The front entrance is on Pa. 23 (River Road) immediately to the north of the bridge carrying the Mid-County Expressway over the Schuylkill River.

INTRODUCTION

During the fall of 1969 a geological and engineering study was performed to determine the feasibility of constructing and operating a sanitary landfill within Quarry #2 of the Allentown Portland Cement Company in West Conshohocken, Pennsylvania. (Fig. 17 and Fig. 1)

The study was performed with the tenets of the Clean Streams Act and Solid Waste Disposal Act of the Commonwealth of Pennsylvania firmly in mind. The fundamental purpose of the study was to ascertain if it was possible to economically keep the leachate (landfill effluent) separate from the groundwater regime.

LANDFILLS AND LEACHATE

Solid municipal wastes are generated in the United States at a rate of over 200 million tons per year. These wastes have an approximate composition of: paper products 60%, organic materials 20%, metals and glass 15%, "dirt" 2%, miscellaneous 3%.

One technique of disposing of municipal wastes is to store them in a sanitary landfill. The sanitary landfill is designed to prevent hazards to the public health and safety which may result from the decomposition of refuse. Refuse is spread in layers not more than eight feet in thickness, and a layer of soil is placed over the refuse. Also, at the end of each day a layer of soil is spread over the landfill.

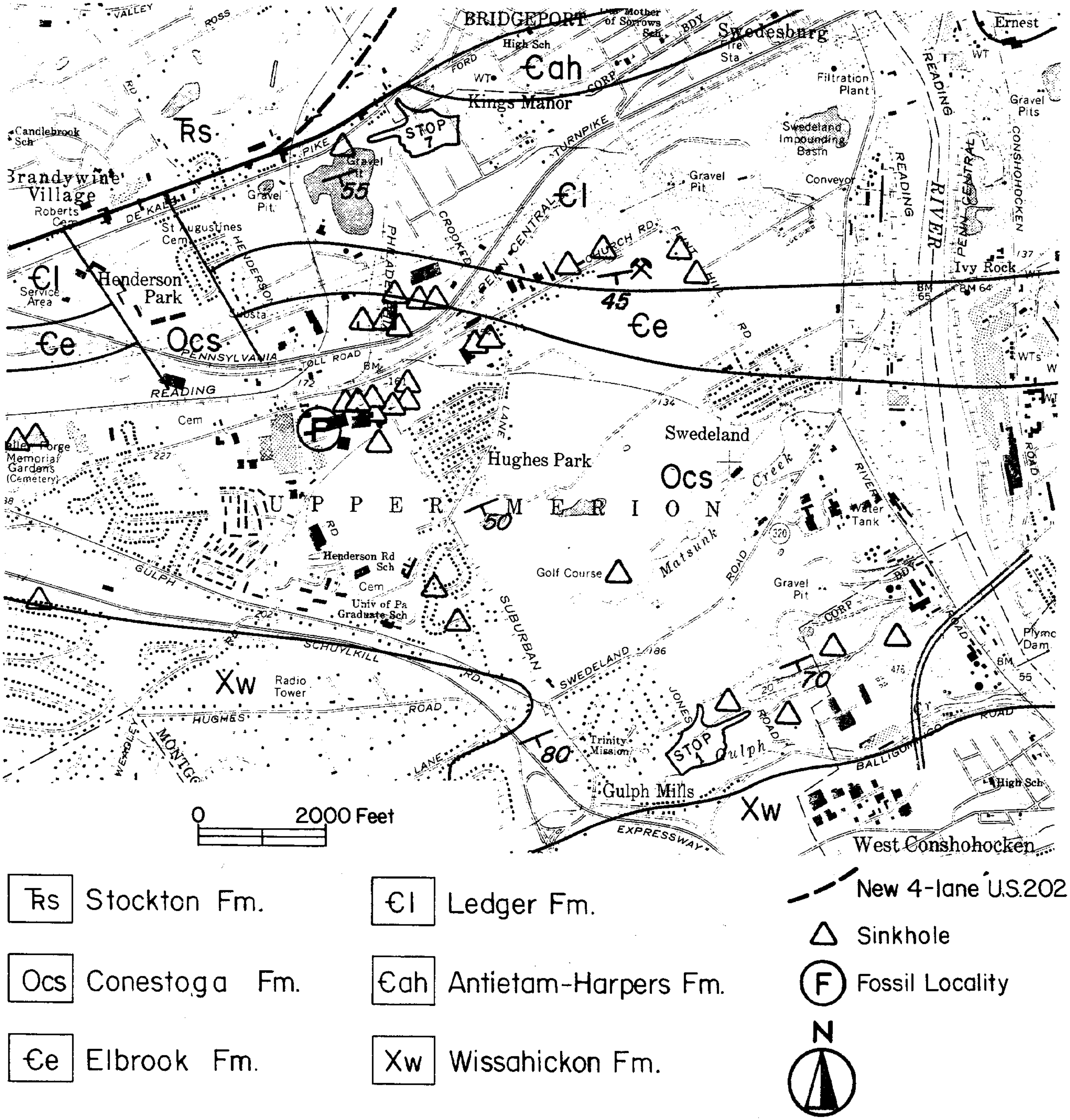
The action of the atmosphere, through precipitation, on the refuse pile results in decay and the generation of methane, carbon dioxide, hydrogen sulphide, and nitrogen. The methane and carbon dioxide are produced in large quantities, the methane is explosive when concentrated; and the carbon dioxide may combine with the groundwater to form excess carbonic acid and accelerate the weathering process.

The percolation and migration of meteoric and/or groundwater through the landfill reacts with the refuse to cause the formation of leachate. Leachate is a highly contaminated combination of various chemicals in water; and is a serious pollutant. Leachate commonly contains: iron, zinc, nickel, copper, sodium, nitrogen, chlorides, phosphates, sulphates, and carbonates, and has a total oxygen demand ranging from 100 to 51,000 milligrams per liter, at a pH of 4.0 to 8.5. Once this contaminant enters a body of water or percolates through the soil it is hazardous to the public health.

Leachate production is attributed to the following conditions at the time intervals indicated. During the early life of the landfill the leachate produced during the first one hundred days is a result of the compaction of the refuse; and the channeling of water through the refuse. After the landfill has been in operation about two hundred days leachate is produced by an advance wetting front

FIGURE 17.

GEOLOGIC SKETCH MAP
AREA of STOPS 1 & 7



which moves as a broad band through the refuse. After four hundred days of operation leachate production results from the main wetting front which indicates the landfill has reached field capacity (the minimum moisture content above which percolation may proceed). At this point, when the landfill has reached field capacity, the amount of leachate produced is roughly equivalent to the amount of water entering the landfill.

The production of leachate is dependent upon precipitation and evapotranspiration. In Southeastern Pennsylvania leachate production is negligible in the dry summer months and most leachate production occurs during the winter and spring. A representative landfill has a field capacity of 3.44 inches per foot of depth per unit surface area, and an initial moisture content of 0.46 inches. Therefore, 2.98 inches of moisture has to be added to the landfill per unit area to bring the field capacity of the landfill to unit capacity for each foot of depth. In Southeastern Pennsylvania the 2.98 inches of moisture necessary for field capacity (3.44 inches) can be delivered in January, February, and March. The moisture ordinarily delivered in this time period will bring the landfill to field capacity to a depth of at least four feet. As the wetting front proceeds through the landfill the entire fill will reach field capacity and leachate will percolate freely through the landfill, and if not properly managed, into the surface and subsurface environment. Many years after the landfill is completed leachate will still be produced and circulated.

The data given here are for Southeastern Pennsylvania but soil type and percolation rates are a function of climate, topography, and vegetation which are a direct function of geology and geography. Therefore, the desirability of a particular site for a landfill operation cannot be determined by design criteria, but has to be determined on the basis of the site's geologic features and geographic location.

LITHOLOGY AND STRUCTURE

The rocks exposed in and around the landfill site are thin interbedded micaceous limestones, dolomitic limestones, and marbles which are part of the upper section of the Conestoga Formation of Ordovician Age. The Ordovician Age was established by E. O. Ulrich from fossils found at the locality marked "F" on Fig. 17. This site has long since been covered by construction. The fossils identified were *Raphistoma, Maclurea,* and *Lituites cyrtoceras* (Bascom, *et al.*, 1909) and are reposited in the Department of Geology, Bryn Mawr College.

The bulk of the material removed from the quarry consisted of a gray to blue-gray, finely crystalline, micaceous limestone containing up to 2.5% magnesium oxide. The remaining minor thin beds were dolomitic limestone (10% magnesium oxide), and marble (50% calcium oxide). The calcium carbonate content of the rock increased with depth; probably, because of a surface leaching and redeposition at depth. Near the surface the calcium carbonate content averaged 76.6% and steadily increased to 82.6% at a depth of 80 feet (Miller, 1934).

The bedding and micaceous foliation are parallel to each other and strike N70-85E, and dip from 75° to 90° in a southeasterly direction. The bedding and foliation are tightly compressed into narrow isoclinal folds (Figs. 18, 19). The cores of the folds contain small drag folds that plunge gently in an easterly direction (Fig. 18).

Three sets of joints are present in the quarry. All of the sets strike N20E, and dip 76SE, 35SE, and 35NW. Some of the joints are filled with either quartz or calcite, but for the most part the joints are slightly open, very widely spaced, and appear to transmit very little groundwater.

SOLUTION FEATURES

Pinnacle weathering is prominent along both the north and south walls of the quarry. The pinnacles on the south side have been removed because they were hazardous to the present landfill operation. Most of the pinnacles ranged between four and ten feet in height and parallel the strike of the beds (Fig. 20).

Interpretation of old drill hole records indicated a deeply weathered zone behind the west wall of the quarry. The thickness of the weathered overburden varies from a few feet thick to 120 feet thick over a horizontal distance of 500 feet. The weathered zone consists of clay; and cross sections through the drill holes indicate a funnel shape to the clay deposits, with limestone pinnacles extending into the clay from the surrounding rock. These data imply a large inactive sinkhole behind the west wall of the landfill.

Information derived from drill hole logs when the quarry floor was at an elevation of 40 feet (the rim of the quarry is at an elevation of 160 feet and the bottom between sea level and 10 feet) indicate a zone of "broken rock" subparallel to the strike of the beds. The "broken rock" zone was graphically projected updip and along the strike and was found to correlate with the inactive sinkhole behind the west wall of the quarry.

Other test borings taken along strike and east of the quarry disclose the zone of "broken rock" continues eastward towards the Schuylkill River.

The presence of the large funnel shaped clay deposit within the limestone; cavities and "broken rock" zones noted in the drilling records; the presence of pinnacles and small sink holes along the north and south quarry walls; all attest to the widespread solution of the limestone in and around the quarry.

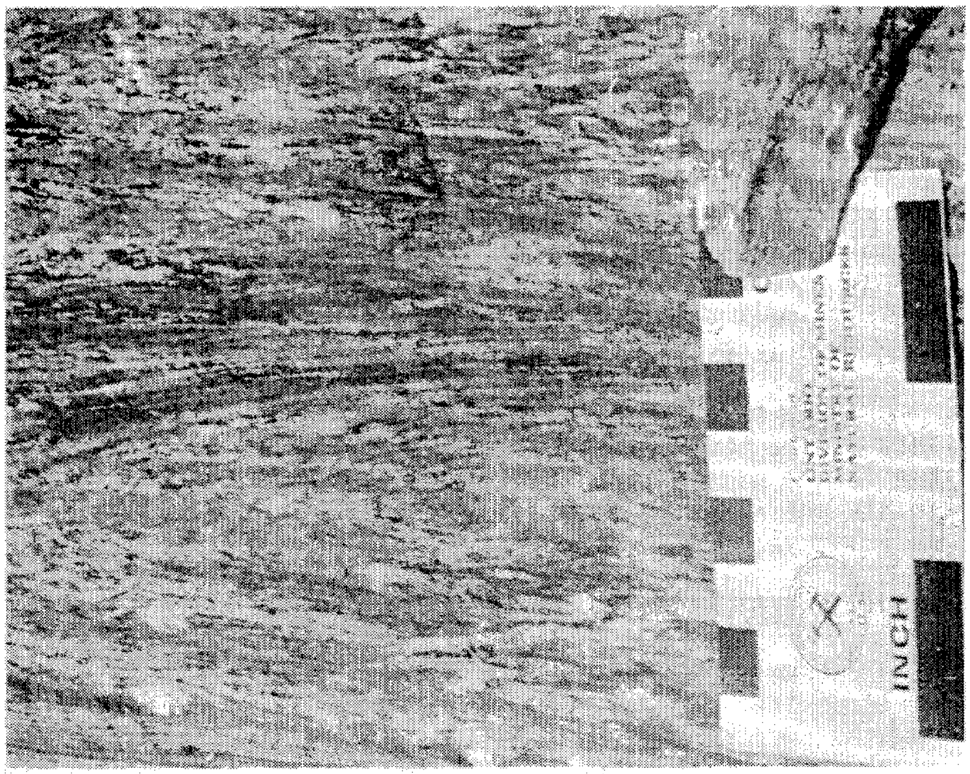


Figure 18. Isoclinal fold in micaceous limestone showing drag folds in core. View N85E.

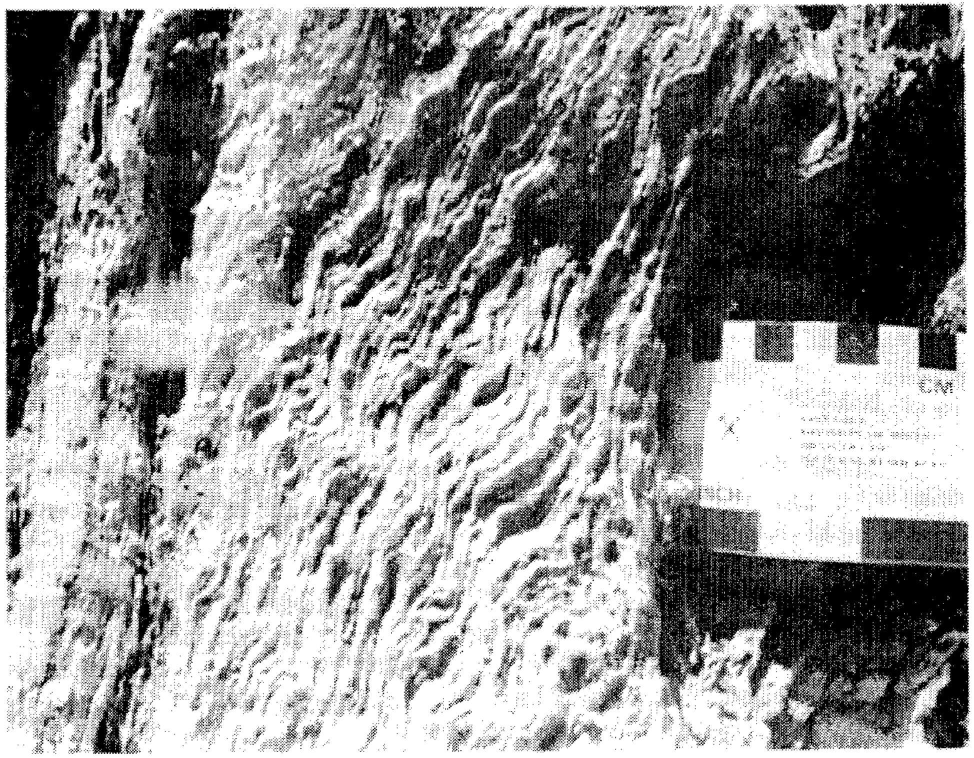


Figure 19. South limb of isoclinal fold. View S85W.

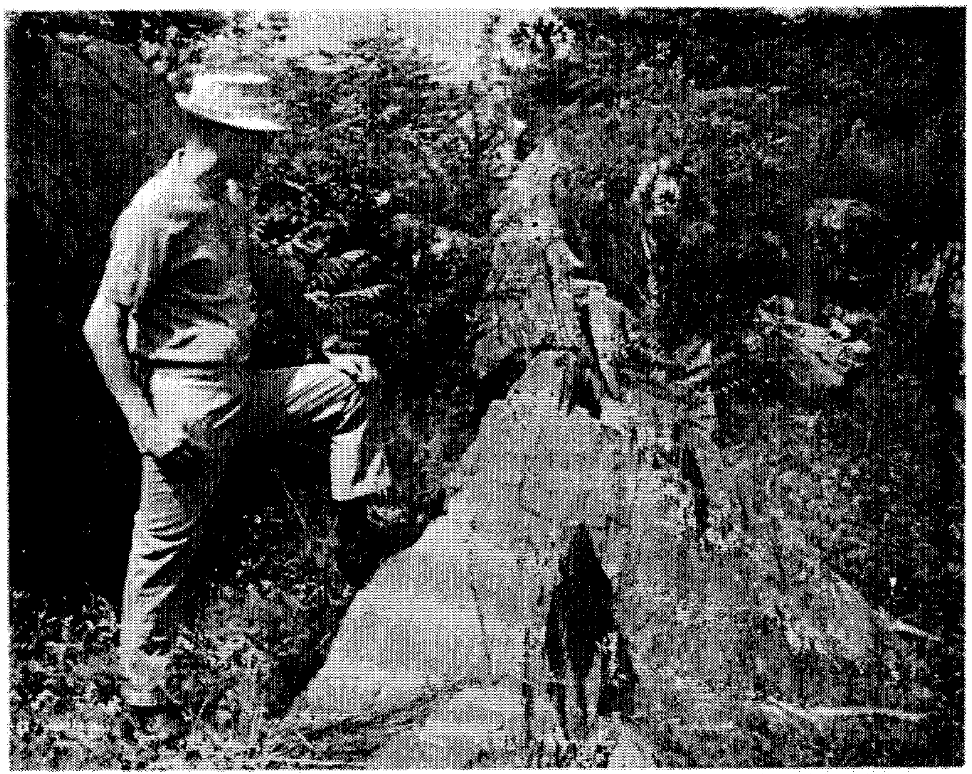


Figure 20. Limestone pinnacle trending S85W.

GROUNDWATER HYDROLOGY

In 1962 the water level of the quarry was at an elevation of 80 feet (70 to 80 feet deep). Pump down of the quarry commenced in 1964 and from 1966 to 1970, when present operations started, the elevation of the water in the quarry was maintained at an elevation of about 20 feet. This level was maintained by a constant pumping rate of 94 gallons per minute which denotes an infiltration rate into the quarry of slightly less than 94 gallons per minute after discounting precipitation and evaporation from the quarry surface.

South of the landfill along Gulph Creek the water table stands at an elevation of approximately 80 feet; and the Schuylkill River, 3000 feet east of the quarry, has a surface elevation of 50 feet. The groundwater level in the quarry should be 80 feet; but pumping in the quarry created a groundwater "sink" with concomittant flow into the quarry. Because of the presence of subsurface solution channels it is not possible to categorically state the direction of main groundwater flow into the quarry. Nevertheless, it is logical to assume that a groundwater gradient exists parallel to the strike of the beds, along and through the solution features, from the Schuylkill River (elevation 50 feet) to the quarry (elevation 20 feet).

Very little water enters the quarry through the joint system. Observations following heavy rainfall showed some water issuing from the steeply dipping (76SE) joints along the south wall of the quarry. This infiltration was from the south where a groundwater gradient exists from Gulph Creek, but the amount of infiltration was deemed negligible.

CONCLUSIONS (Fergusson and Loigman, 1970)

In order to construct and properly maintain and operate a sanitary landfill in the quarry the following recommendations were made on the basis of the geological and engineering information gathered during the study.

To prevent contamination of the subsurface environment by leachate flowing through the base of the landfill; and in order to keep the water table from rising up into the landfill, design of the landfill should incorporate the following suggestions.

Prior to construction the water in the quarry should be drawn down to expose the quarry bottom. A permeable gravel bed, of carefully selected and sized material, should be laid down over the quarry floor up to an elevation of 20 feet. The fill material should be placed and tamped so there will be no subsidence of the fill. Within the gravel bed a system of lateral drains should be provided to collect groundwater into a main sump for pump discharge out of the quarry. The discharge system should be capable of pumping more than 100 gallons per minute on a full time operational basis. The upper surface of the fill will have to be paved and sealed to prevent downward percolation of the leachate; and a leachate collection system installed above the seal. The collected leachate and groundwater should be pumped separately up the south wall of the quarry for treatment and disposal (Fig. 21). The open joints in the quarry walls should be sealed with cement grout or asphalt cement, and a clay buffer placed between the quarry walls and service road to prevent leachate from entering the subsurface through the joint system.

The sanitary landfill was deemed feasible and the recommendations were incorporated in the design. The result is a sanitary landfill capable of accepting 500,000 tons of municipal waste without polluting the surrounding hydrological environment, and restoring the quarry up to grade (160 foot elevation) to provide usable land.

QUARRY HISTORY

After an extensive drilling program and chemical evaluation the quarries #1 and #2 were opened to supply raw material for the manufacture of Portland Cement in 1927. During the exploratory phase, from 1924 to 1927, it was found that the bulk chemical composition of the Conestoga Formation was quite similar to that of the Jacksonburg Formation "cement rock" found in the vicinity of Allentown. There had been a few small quarries operated on the property before the turn of the century and into this century for the purpose of obtaining building stone.

During 1934 the first froth flotation plant used in the cement industry was erected on the site to beneficiate the calcium content of the quarry output. The finely ground quarry product was mixed with a froth that lifted the calcium carbonate on bubbles to the top of the cell where the calcium carbonate was skimmed off. The rejected material was mica and quartz which was floated in another cell to obtain an aluminum magnesium rich product. This product was sold as a filler for roofing materials and paving materials. The mica would also have been marketable except for a high iron content in the form of pyrite and pyrrhotite inclusions.

In 1953 it was considered more economical to close the flotation plant and import high calcium limestone from other sources to operate the cement plant. By 1965 the shipping of limestone became impractical and since that time clinker has been shipped to the plant for grinding and processing to manufacture Portland Cement. During the period from 1965 to 1971 some aggregate was produced from the property, but the aggregate did not quite meet specifications and aggregate production was stopped in 1971.

During late 1969 Quarry #2 was assessed for potential use as a sanitary landfill site for Montgomery County. The landfill operation was considered to be feasible and the application to the Pennsylvania Department of Natural Resources was approved. Construction of the landfill began in the fall of 1970 and on October 21, 1971 the Montgomery County Sanitary Landfill #1 was opened to receive refuse.

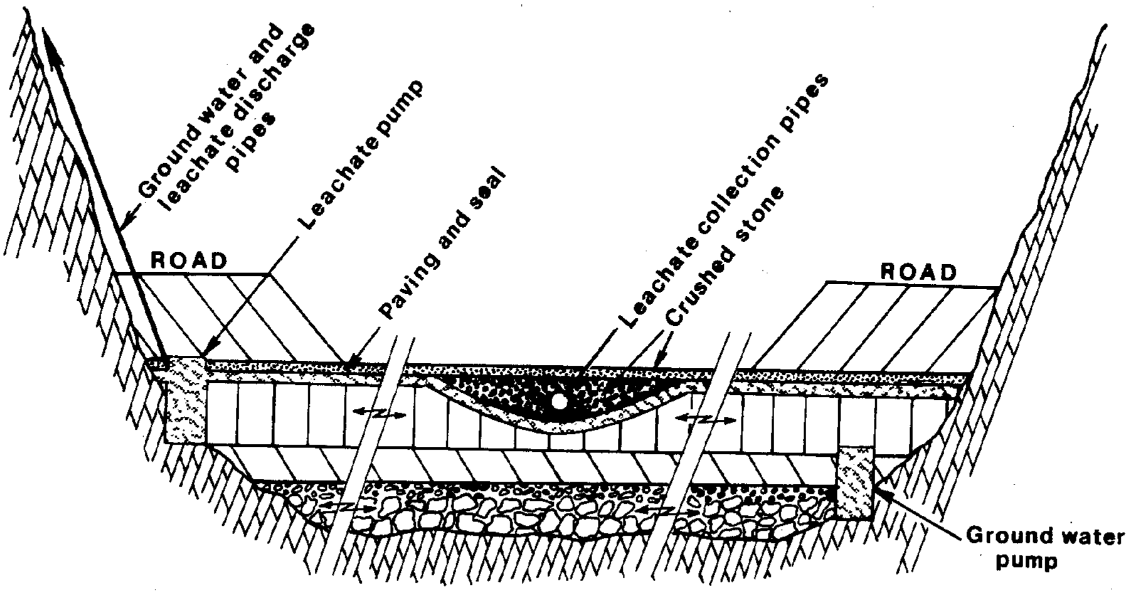


Figure 21. Generalized cross-section, Montgomery County landfill prior to operation.

STOP 1 TO STOP 2

5.6 Retrace route from landfill to the intersection of Jones Road and Swedeland Road (Pa. 320). Turn left onto Swedeland-Holstein Road.

6.0 Turn left onto South Gulph Road.

6.3 Leave the Chester Valley limestones and enter Gulph Creek Gap through the South Valley Hills comprised of phyllite of the greenschist facies of the Wissahickon Formation. Once through the gap we are back into an arm of the Chester Valley underlain by the Conestoga Limestone Formation. Gulph Creek flows northeast along the valley formed by this septum of Conestoga limestone, turns northwest cutting through the phyllite hill to reach the main Conestoga limestone valley and returns to its northeasterly course to the Schuylkill River. The reasons why this stream cut through the phyllite ridge instead of flowing northeast along the limestone septum to the Schuylkill River are not understood.

6.4 Wasington's army passed through this defile in December of 1777 before going into Winter Quarters at Valley Forge. The boulder of phyllite jutting out over the road here is sacred to the historical societies who fight every attempt to have it removed. (Faris, 1917, p. 153)

6.7 Turn left onto Old Gulph Road. On the right is an outcropping of a diabase dike that may be traced from New Jersey to Virginia. It forms a falls in Gulph Creek.

Lt. Aaron Burr commanded a guard post here at what is now the Pickett Post Restaurant in the winter of 1777. (Faris, 1917, p. 152)

6.9 Cross the contact between the Ordovician Conestoga Limestone Formation in the valley and the Precambrian basement gneiss forming the upland. This contact is the Cream Valley fault.

8.3 Light at intersection with Spring Mill Road. Turn left onto Spring Mill Road.

9.1 Morris Avenue, turn right.

9.8 Cross contact between Precambrian basement gneiss and ultramafic body C-3 of Fig. 7. This contact is the Rosemont fault.

10.1 Cross contact between ultramafic body and Wissahickon Formation (amphibolite facies).

10.4 Williamson Road, turn left.

10.9 Cross contact between Wissahickon Formation and ultramafic body D-3 of Fig. 1.

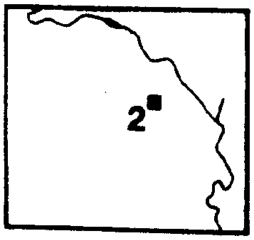
11.0 Black Rock Road, turn right.

11.1 Dove Lake Road (one way), turn left.

11.3 Cross contact between ultramafic body and Wissahickon Formation (amphibolite facies).

Mill Creek was an industrial center in the mid-19th century. In 1858 sixteen industries manufactured paper, flour, brass, copper utinsels, gun powder, and cotton goods along the creek. (Alderfer, 1951, p. 202)

11.5 Park on right shoulder of road beyond large road cut.



STOP 2. DOVE LAKE ROAD by R. V. Amenta

Station A. Location: This stop in the Wissahickon formation consists of two stations, A and B. A is a road cut; B lies 100 feet northeast of Dove Lake Road on private property. See Fig. 1 and Fig. 22.

LITHOLOGY

A. The rhythmic alternation of pelitic schists and psammitic, slightly calcareous gneisses in this road cut suggests an origin due to cyclic deposition of sediments as in a turbidite. However, I think it is hazardous to interpret internal phenomena as primary in view of the complex metamorphic and deformational fabrics present.

B. The layers (S_0) consist of muscovite-biotite-garnet-staurolite schist and quartz-plagioclase-hornblende-garnet gneiss. Veins of coarse grained quartz are concordant with S_0 and are believed to be of metamorphic origin rather than recrystallized chert.

C. See Fig. 2 and Fig. 3 for the relationship of the metamorphic grade of these rocks to those of the other stops.

STRUCTURE

A. Bedding (S_0) and the regional schistosity (S_1) are parallel and dip northwest to vertical.

B. The tight folds with axial planes dipping steeply northwest are F_2.

1. They deform the S_1 schistosity into an axial plane crenulation cleavage (S_2). This cleavage is tightly appressed in the fold cores making it difficult to see mesoscopically.

2. Generally the F_2 folds are the dominant minor folds south of the Rosemont fault zone. They are overturned to the southeast, in contrast to most folds in the Appalachians which are overturned to the northwest.

C. Subhorizontal, S_3, fracture cleavage and crenulation cleavage (in schists) is superimposed on the F_2 folds.

1. Thin sections showing S_3 in the schists reveal recumbent crenulations outlined by unstrained, polygonized (recrystallized) micas.

2. S_3 is parallel to axial planes of barely visable, broad, open folds (F_3) in S_0 and S_1.

3. The dominant lineations in the schists are L_3 crenulation axes which are produced by the intersection of S_3 and S_1. In this exposure L_3 and F_2 axes are parallel.

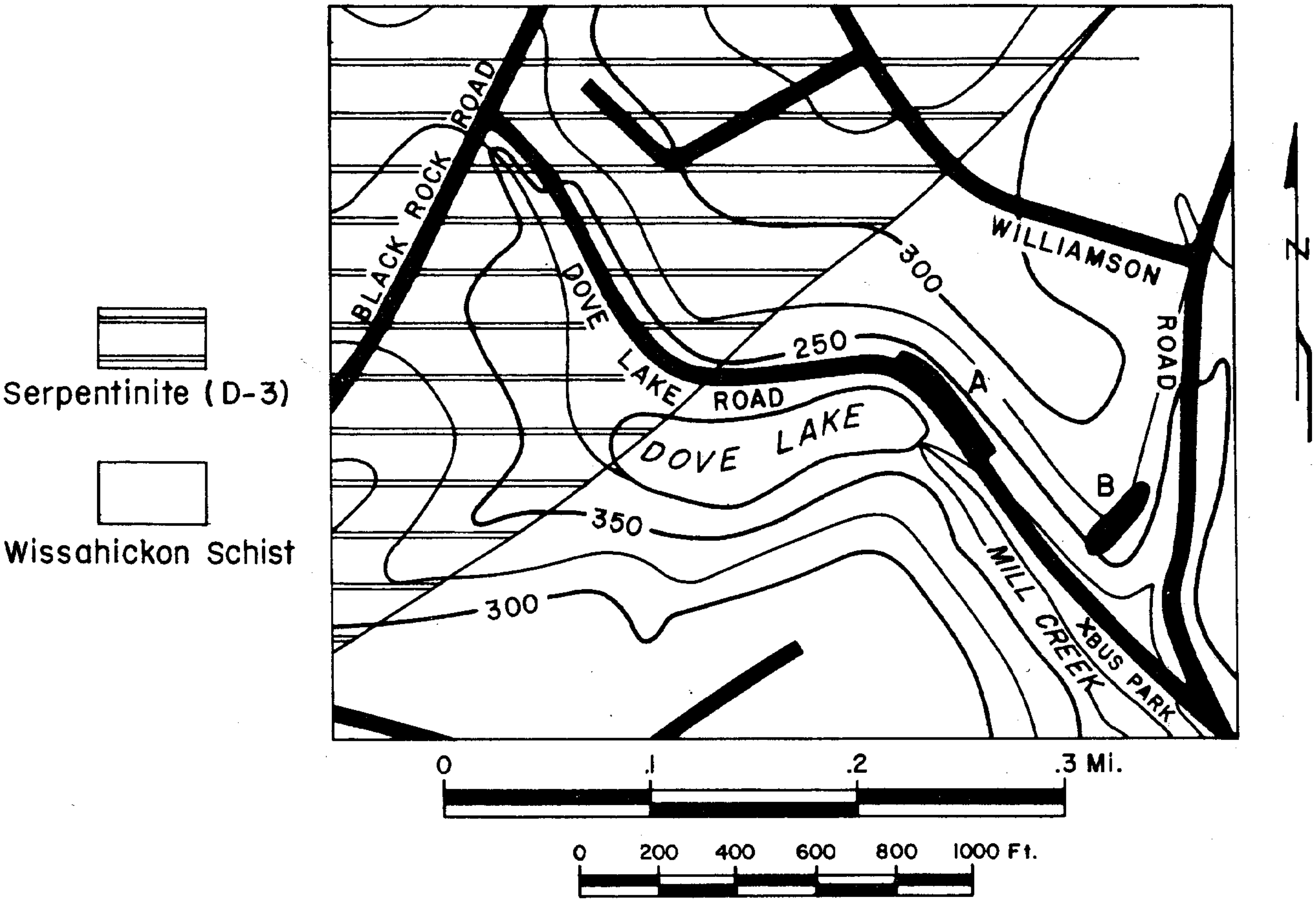


Figure 22. Detailed map of Stop 2, Dove Lake.

Station B.

STRUCTURE

A. Prominent S_4 crenulation cleavage deforming S_1 schistosity. S_4 dips southeast and is parallel to axial planes of small open folds (F_4).

B. Criteria for distinguishing between S_3 and S_4 and for determining their relative ages.

1. Distinctive orientations.

   a) S_3 generally strikes N45E and dips approximately 10NW, whereas S_4 strikes N45E and dips 45SE.

2. Relationship to metamorphism (M_2).

   a) S_3 developed near the peak of metamorphism, and micas which were deformed by S_3 movement were recrystallized by M_2. S_4 developed after the peak of metamorphism and micas deformed in the northern part of the area show little recrystallization and are strained.

3. Structural superposition.

   a) S_4 overprints F_3 folds and S_3 axial plane cleavage. This phenomenon cannot be seen here.

STOP 2 TO STOP 3

11.5 Leave parking area.

11.6 End of Dove Lake Road, bear right onto Williamson Road.

We remain in the Wissahickon Formation (amphibolite facies) all the way to STOP 3. The remnants of several old mills and their dams may be seen as our route parallels Mill Creek.

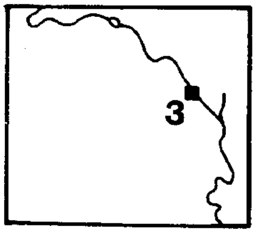
11.7 Williamson Road becomes Old Gulph Road. Continue straight on Old Gulph Road.

12.0 Light at intersection of Mill Creek Road with Old Gulph Road. Continue straight on Mill Creek-Old Gulph Road.

12.2 Bear left at "V", following Mill Creek Road.

13.7 Turn left onto Hollow Road following signs to I-76 (Schuylkill Expressway).

14.5 Park by curb on right side of Hollow Road before reaching the intersection with Sprague Road. Walk along curb to Expressway entrance. WATCH HIGH SPEED TRAFFIC ON RAMP.



STOP 3. GLADWYNE INTERCHANGE OF SCHUYLKILL EXPRESSWAY by R. V. Amenta.

LOCATION: This stop in the Wissahickon Formation at the Gladwyne Interchange of the Schuylkill Expressway consists of Station A and B located along the exit, and Station C and D located along the entrance. See Fig. 1 and Fig. 23.

Station A: EXIT

LITHOLOGY

A. Predominantly mica schists with some gneisses.

B. Pegmatites and veins are numerous, but they terminate or pinch out abruptly. This together with the fact that their mineralogy is similar to that in the host rock, namely quartz, plagioclase, muscovite, biotite and garnet; suggests that they were derived locally by partial melting of the country rock.

C. See Fig. 2 and Fig. 3 for the relationship of the metamorphic grade of these rocks to those of the other stops.

STRUCTURE

A. Bedding and schistocity (S_0-S_1) dip northwest.

B. Crenulation cleavage (S_4) is strongly developed and dips southeast.

  1. In contrast to Dove Lake, micas deformed by S_4 here are recrystallized.

  2. Fabric studies (Amenta, 1974, in press) indicate that this recrystallization is restricted to S_4 in schists located within 1½ to 2 miles from the granitized zone which suggests that the granitized zone was still "warm" during D_4.

C. F_4 fold deforms small F_2 fold in layer of gneiss. Note that S_4 is superimposed across the axial plane (S_2) of the F_2 fold.

D. Folds in pegmatites which are concordant with S_0 (above and to the right) are probably F_2. Tight folds with anomalous orientations in larger pegmatite (below) are also probably F_2, but pegmatite was initially discordant with S_0.

  1. Some of the concordant veins may not be folded at all, but may be younger than and mimetic to the F_2 folds. The mineralogy of the veins and pegmatites, however, does not suggest that there are two generations.

Station B. EXIT

LITHOLOGY

A. Predominantly quartz-feldspar gneisses with minor schists.

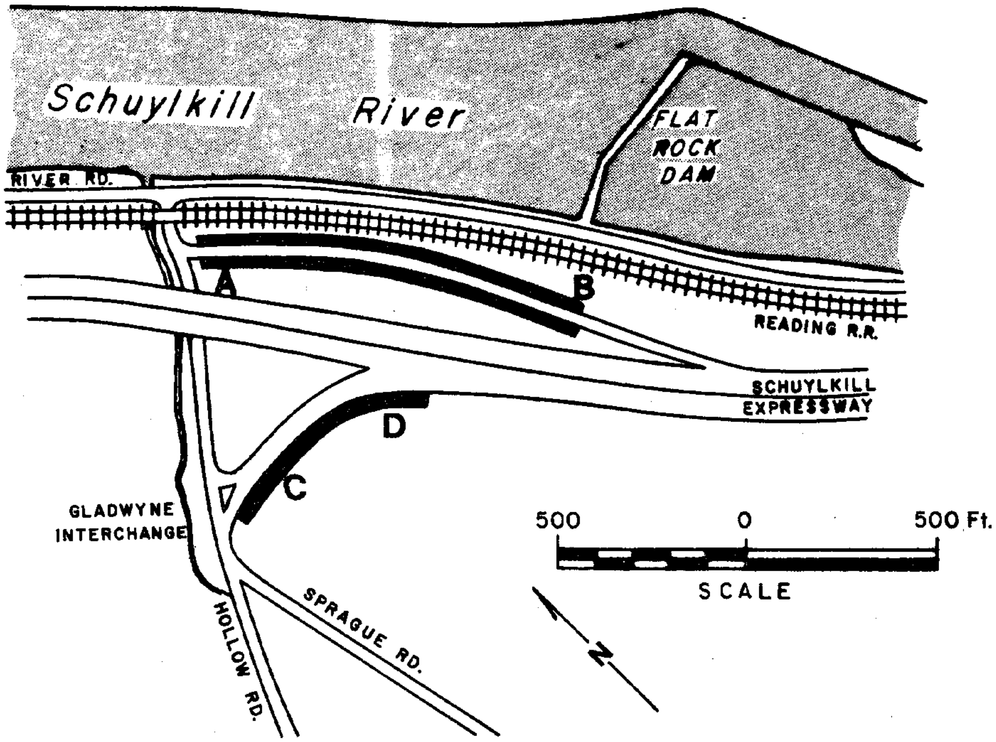


Figure 23. Detailed map of Stop 3, Gladwyne Interchange, Schuylkill Expressway.

STRUCTURE

A. F_2 folds with axes plunging northeast and with axial planes dipping northwest are strongly developed in the gneisses. Note that F_2 folds deform the S_1 schistosity.

B. F_2 fold axes are the dominant linear structures and they plunge northeast. Superimposed on some F_2 hinges, however, are two sets of subhorizontal crenulation lineations (L_3) and (L_4). Their relative ages cannot be demonstrated here, but these lineations are related to the subhorizontal cleavage (S_3) and the southeast dipping cleavage (S_4) respectively. S_3 is poorly developed here, but is visable in the rocks on the expressway nearby. L_5 crenulation lineations rake steeply on S_1 and may be observed locally.

C. Fig. 24 shows stereographic projections of F_2, L_2, L_4 and poles to S_2 and S_4 measured from station A to station B.

STOP 3. GLADWYNE ENTRANCE TO SCHUYLKILL EXPRESSWAY

Station C: ENTRANCE

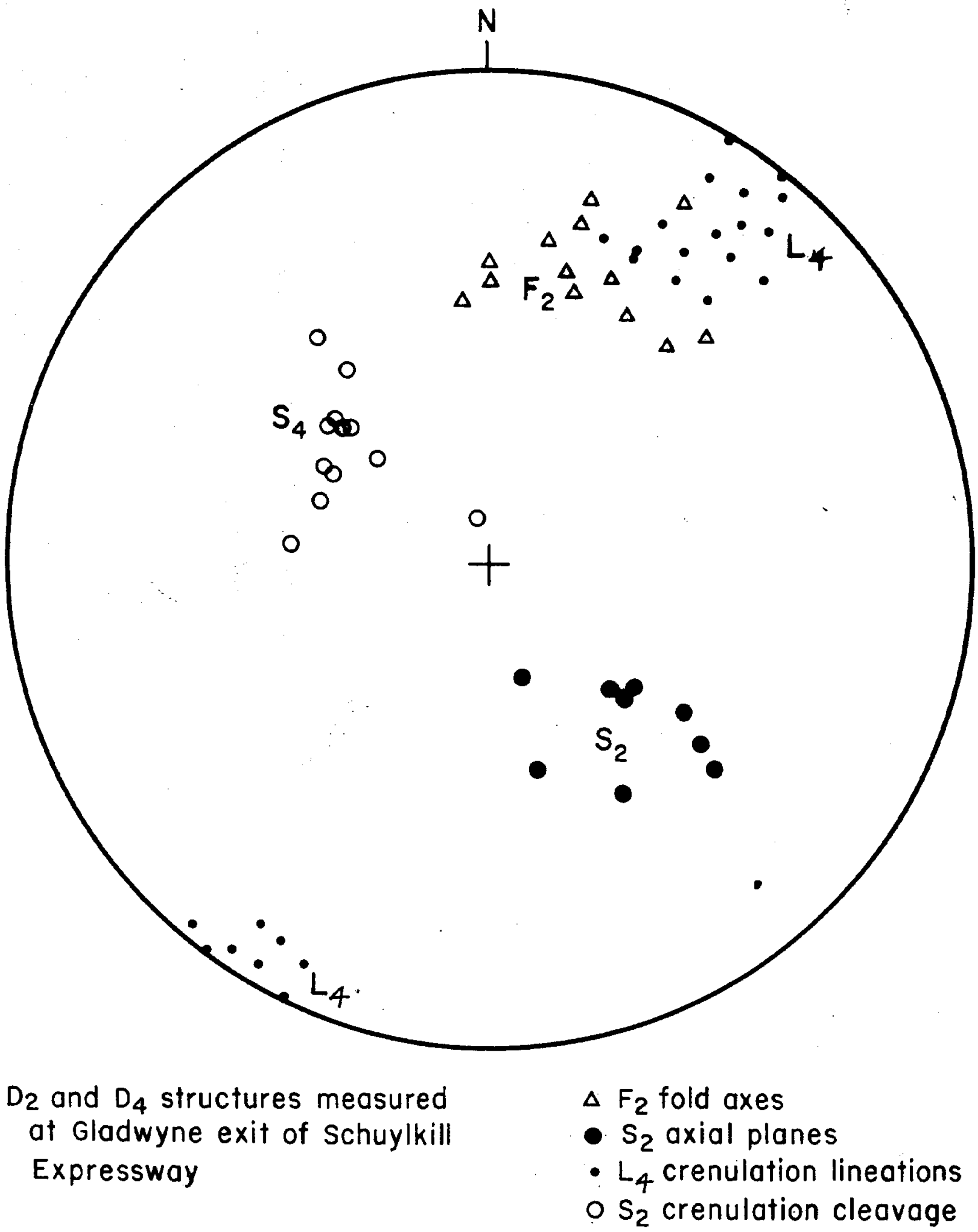


Figure 24. D_2 and D_4 structures measured at Gladwyne exit of Schuylkill Expressway.

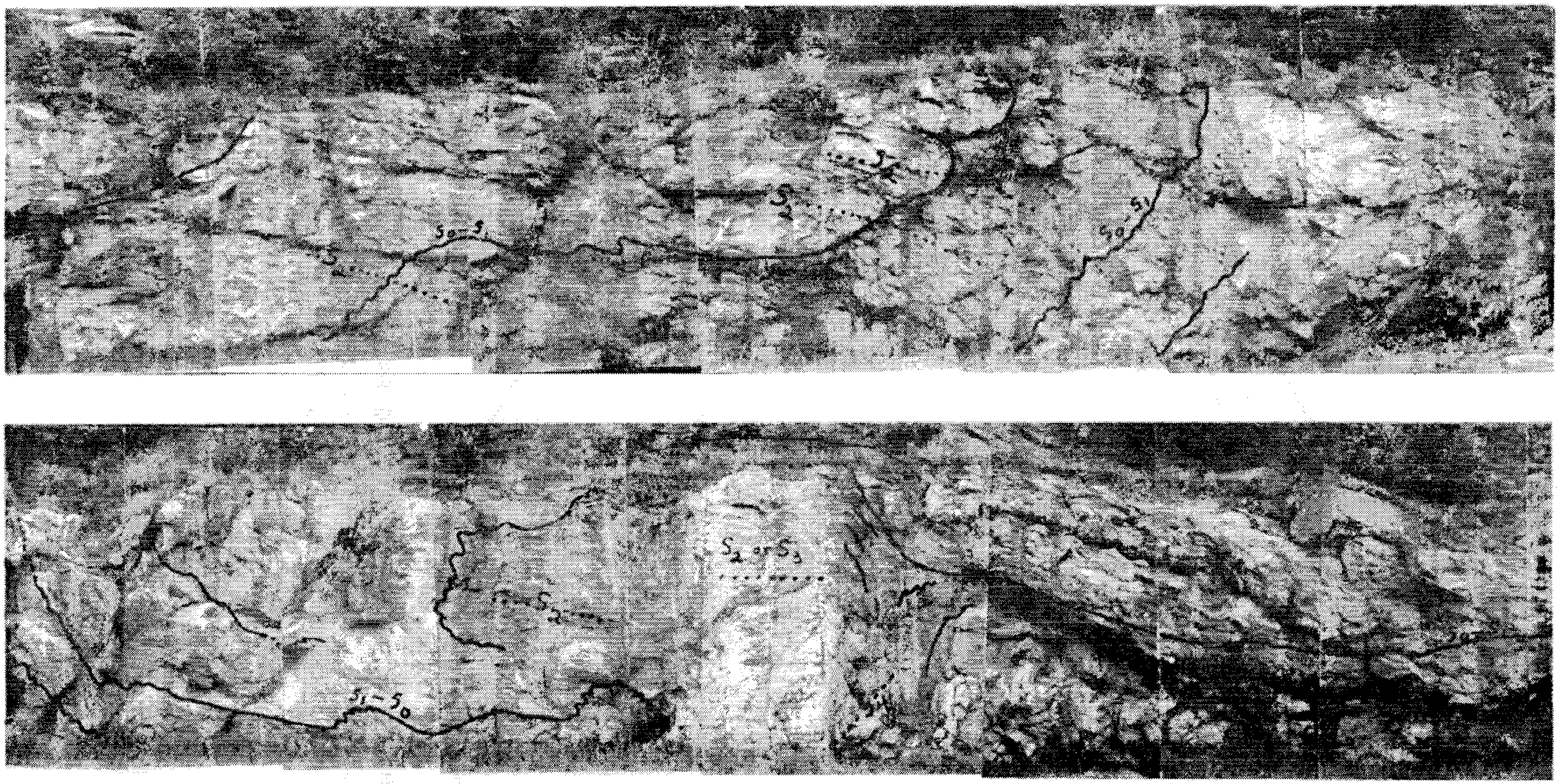


Figure 25. Panoramic view of the roadcut at Gladwyne entrance to Schuylkill Expressway.

LITHOLOGY

A. Mica gneisses and mica schists with numerous discordant pegmatites and veins.

STRUCTURE

A. Bedding and schistosity (S_0-S_1) dip southeast to northwest and outline large F_2 folds (Fig. 25). Bedding, however, is obscured by numerous discordant pegmatites, by joints and by S_2 cleavage which dips northwest.

B. The small parasitic F_2 folds are tight to isoclinal, but here it may be debatable whether the large folds have the same geometry.

C. This road cut demonstrates that major F_2 folds probably exert a strong influence on "map patterns" in the Philadelphia area.

Station D: ENTRANCE

LITHOLOGY

A. Large vertical pegmatite terminates abruptly at the level of the first terrace.

STRUCTURE

A. Pegmatite does not appear folded by F_2 (compare with thin, intensely folded pegmatite to the right), but yet it is penetrated by a subhorizontal planar fabric resembling a cleavage. Two interpretations regarding the structural relationships of the pegmatite and the folds in the host rock follow:

1. The pegmatite is pre-D_2. During D_2 it was deformed by homogeneous strain (rather than by folding). The cleavage within the pegmatite is S_2 and represents a plane of flattening which contains the maximum and intermediate axes of the strain ellipsoid.
2. The pegmatite was intruded during D_3 and M_2, and the cleavage in the pegmatite is S_3 rather than S_2. I prefer this interpretation.

STOP 3 TO STOP 4

14.5 Leave parking area.

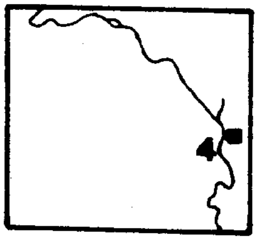
14.6 Take Expressway (I-76) on-ramp to Philadelphia.

We remain in the Wissahickon Formation (amphibolite facies) all the way to STOP 4.

17.5 Left lane for Exit 40, Wissahickon Drive, leave Expressway.

18.0 Bear left to East River Drive.

20.0 Park in the refreshment stand parking lot on the right just south of the Strawberry Bridge.



STOP 4. EAST RIVER DRIVE SOUTH OF STRAWBERRY MANSION BRIDGE by R. V. Amenta.

STOP 4 is in Fairmont Park and STOPS 5 and 6 are in Wissahickon Creek Park, both administered by the Fairmont Park Commission. A 5 acre tract acquired by Philadelphia in 1812 for a water works site and reservoir along the Schuylkill River has grown to the largest municipal park in the world - over 7,700 acres.

Judge Lewis built the present Strawberry Mansion (then called Somerton) about 1799. In 1846 the property was sold to the Steward of the Philadelphia Club who opened a restaurant specializing in strawberries and cream resulting in the new name of Strawberry Mansion. It became park property in 1867, a beer garden with bandstand in 1876, and an Italian style resort in 1890. In 1900 another change took place - sailors on leave had a rendezvous with cooperating ladies on the second floor, a police court and recreation area for the park guards used the first floor, while rumor had it that a speakeasy operated in the cellar. Finally the sailors and police and possible bartenders were evacuated and the Womens Committee for the Susqui-Centennial Exposition took over in 1929 (Rivinus, 1967, p. 19-22).

LOCATION: This stop of three stations in the Wissahickon Formation is on the east side of East River Drive across the street from the refreshment stand near Strawberry Mansion Bridge (Fig. 1 and Fig. 26). Caution, fast, heavy traffic adjacent to the outcrop on East River Drive.

LITHOLOGY

A. Mica-garnet-sillimanite schist and quartz-feldspar gneiss in beds of approximately equal thickness.

B. See Fig. 2 and Fig. 3 for the relationship of the metamorphic grade of these rocks to those of other stops.

STRUCTURE

Bedding (S_0) and schistosity (S_1) appear to be parallel and dip approximately 30NW in a homocline, but this simplicity is deceiving.

A. Station A: Close inspection reveals that bedding is isoclinally folded and that near fold hinges the schistosity is not parallel to bedding but is parallel to fold axial planes. These folds are F_1, i.e. the oldest

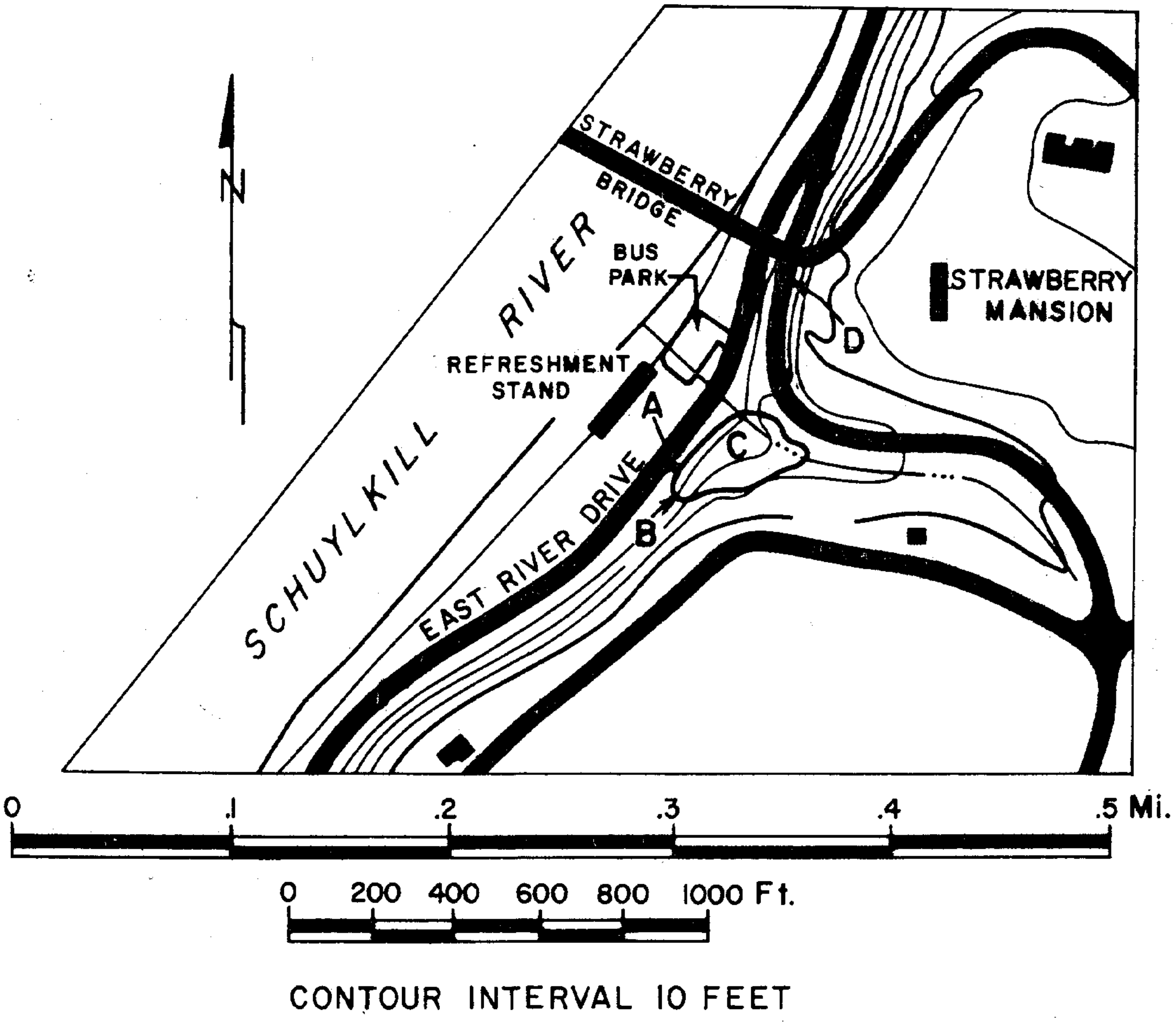


Figure 26. Detailed map of Stop 4, Strawberry Mansion Bridge.

set of folds found in the Wissahickon Formation in this area. The regional schistosity is S_1.

B. Station B: One of the F_1 folds is refolded by a small open fold (station B) with axial plane dipping 45NW (S_2?). The open fold is the only one of its kind observed in this outcrop, but its orientation is similar to F_2 folds in the region.

C. Station C: 1. L_1 lineations.

   a. Quartz-plagioclase-fibrolite (sillimanite) augen are "flattened" in the plane of the S_1 schistosity and elongated parallel to F_1 axes. At station C the augen appear to be "flattened"

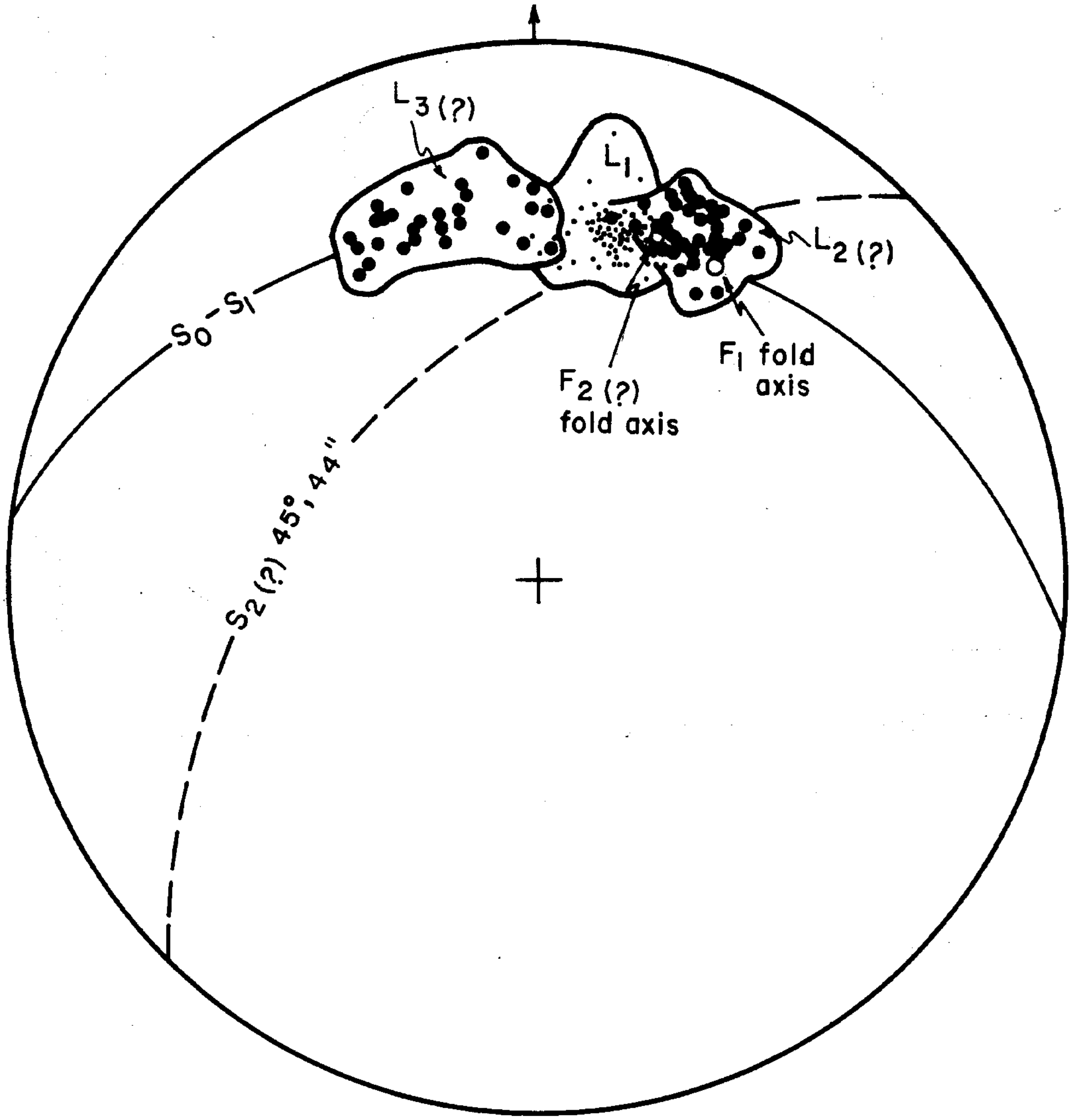


Figure 27. Crenulation lineations weakly developed on S_1.

at an angle to schistosity, but this may be an erosional effect.

   b. Muscovite and biotite show a slight elongation in L_1.

   c. Ribbing structure (L_1) is found in some gneisses.

   d. Amphibolites near Strawberry Mansion Bridge (Site D) to the north contain hornblende needles aligned along L_1.

2. The mineral evidence indicates that the F_1 folding was contemporaneous with Amphibolite facies metamorphism (M_1).

3. Two sets of crenulation lineations (L_2(?) and L_3(?)) are weakly developed on S_1. (Fig. 27). Their relative ages are uncertain although they are both undoubtedly younger than L_1.

   a. The set of lineations raking east of L_1 may be L_2 because they plot near the intersection of S_2 fold axial plane with S_1.

   b. The set of lineations raking west of L_1 may be L_3, by process of elimination, but S_3 is not developed.

STOP 4 TO STOP 5

20.0 Turn left from parking lot onto East River Drive heading north.

We remain in the Wissahickon Formation (amphibolite facies) all the way to STOP 5.

21.1 At light turn right onto Midvale Street.

21.2 At light turn left onto Ridge Avenue.

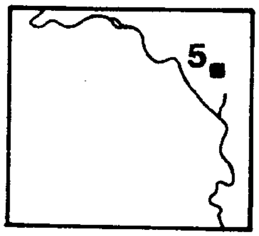
22.3 Stay in right lane. At light bear right on Hermit Street.

23.1 At light turn left onto Henry Avenue.

25.8 At light turn right onto Wise's Mill Road.

26.6 Park in lot at Valley Green area of Wissahickon Creek Park.

STOP 5. EAST BANK OF WISSAHICKON CREEK, NORTH OF VALLEY GREEN ROAD by R. V. Amenta.



Wissahickon Creek Park became part of Fairmont Park in 1867. The Valley Green Inn was a favorite resting place in the Wissahickon Valley in the 19th Century. The old inn now houses a restaurant. (Weygandt, 1930, p. 271).

LOCATION: This stop of two stations in the Wissahickon Formation is on a trail above the east bank of Wissahickon Creek on the north side of Wise's Mill Road (Fig. 1 and Fig. 28).

Station A.

LITHOLOGY

A. Interbedded quartz-feldspar gneiss and muscovite-biotite-garnet-staurolite-kyanite schist.

B. See Fig. 2 and Fig. 3 for the relationship of the metamorphic grade of these rocks to those of the other stops.

STRUCTURE

A. Bedding (S_0) and schistosity (S_1) folded into F_3 recumbent folds.

B. S_3 crenulation cleavage is well developed parallel to fold axial planes.

C. Enveloping surface (S_0) to folds dips approximately 45NW. This is the surface that is tangential to the folds and approximates the average dip of the layers. Because the enveloping surface dips parallel to the regional dip and to S_2 axial planes, I believe it was oriented during deformation D_2.

FABRIC ANALYSIS - relationship between S-surfaces and porphyroblasts.

A. Mica, deformed by S_3 crenulation cleavage, is recrystallized.

B. Porphyroblasts of kyanite and muscovite lie across and do not deflect S_1 and S_3.

C. Porphyroblasts of staurolite and garnet deflect S_3 but appear to lie across S_1. Inclusion trains within porphyroblasts suggest that:

1. some garnets grew over undeformed S_1 and were overgrown in turn by staurolite, and

2. some staurolite grew over S_1 which was mildly deformed by a crenulation cleavage. This cleavage, preserved within the staurolite, is parallel to intensely developed S_3 surrounding the staurolite.

D. Minor strain produced in micas and kyanite by S_4 crenulations (not apparent mesoscopically).

CONCLUSIONS IN REGARD TO SEQUENCE OF EVENTS:

A. Growth of micas in S_1 schistosity followed by,

B. tilting of S_1 to the northwest during D_2 followed by,

C. growth of garnet and staurolite over S_1 followed by,

D. initial phase of development of S_3 and synkinematic growth of staurolite followed by,

E. final phase of development of S_3 around previously formed garnet and staurolite followed by,

F. growth of kyanite and muscovite over S_3 followed by

G. S_4 which produced minor strain in minerals.

Station B

LITHOLOGY

A. Muscovite-biotite-garnet-kyanite-staurolite schist

B. This is a good locality for collecting large crystals of staurolite. Twinned crystals have not been reported from the Philadelphia region. As in all parks defacing outcrops with hammers is discouraged.

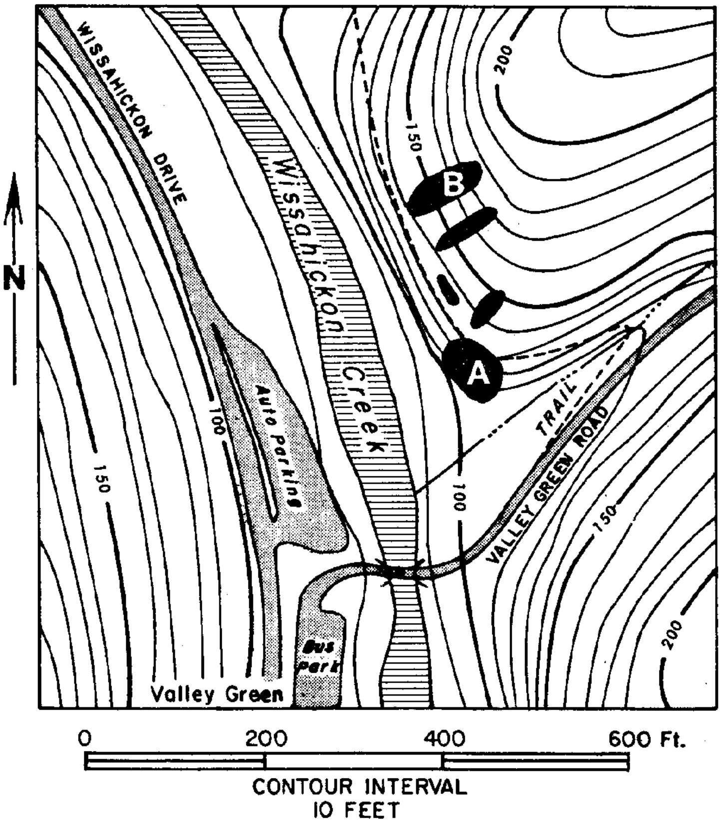


Figure 28. Detailed map of Stop 5, Valley Green, Wissahickon Creek Park.

STOP 5 TO STOP 6

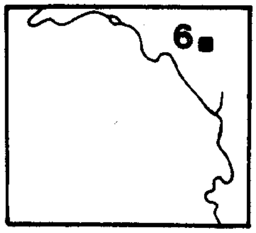
26.6 Leave lot and retrace route on Wise's Mill Road.

27.5 At light turn right onto Henry Avenue.

28.8 At light turn right onto Bell's Mill Road.

29.8 Enter large dirt pull-off area on right side of road and park. Walk 0.1 mile east along Bell's Mill Road to Wissahickon Creek. After the conference visitors with one or two cars can park in the lot by the Creek.

STOP 6. ROSEMONT FAULT ZONE NEAR BELL'S MILL ROAD by R. V. Amenta and F. H. Roberts.



LOCATION: We will visit 3 stations in the Wissahickon Formation, 2 in ultramafic pod D-1 of Fig. 7, and one in a small granite body; all are located along Wissahickon Drive near Bell's Mill Road. (Fig. 1 and Fig. 29)

General Statement: Here we will examine structural relations between the Rosemont fault zone, lenses of ultramafic rock and F$_2$ folds. The Rosemont fault forming the boundary between the Wissahickon Formation and the basement gneisses is not exposed, but it is located approximately 1400 feet north of Bell's Mill Road as indicated by the development of mylonite in rocks in the creek (Fig. 29). The zone in the Wissahickon Formation affected by the fault is approximately 2000 feet wide and is further characterized by vertically dipping beds (S$_0$) and isoclinal folds (F$_2$) produced by intense shearing. Ultramafic rocks occur near and within this fault zone from Wissahickon Creek to Lima, Pennsylvania, 17 miles southeast (Fig. 7). This fact, that the ultramafic rocks are intimately associated with the fault zone, points to the conclusion that they were emplaced diapirically during horst-like uplift (D$_2$) of the basement gneiss complex. See Fig. 2 and Fig. 3 for the relationship of the metamorphic grade of these rocks to those of the other stops.

Station A

LOCATION

A. We are approximately on the southern boundary of the zone in the Wissahickon Formation affected by the Rosemont fault (see Fig. 29).

LITHOLOGY

A. The small, lichen-covered outcrop of the Wissahickon Formation

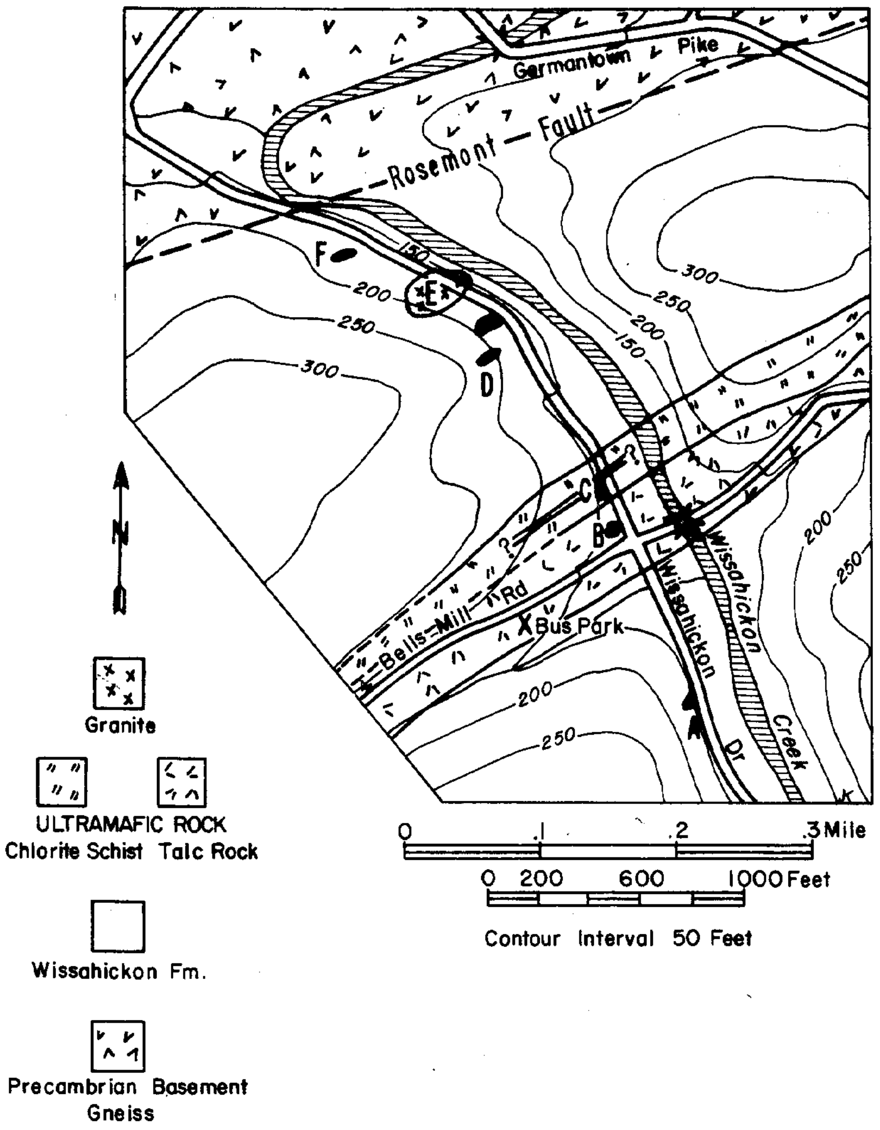


Figure 29. Detailed map of Stop 6, Bells Mill Road, Wissahickon Creek Park.

consists of muscovite-biotite-garnet-(staurolite)-schist and quartz-feldspar gneiss.

STRUCTURE

A. Bedding (S_0) and schistosity (S_1) are nearly vertical.

B. The folds in the gneiss layers are isoclinal with horizontal axes and nearly vertical axial planes (S_2). They belong to the F_2 generation because:

1. They are gradational in style and orientation in F_2 folds south of here.

2. They are overprinted by S_3.

C. Horizontal, S_3, crenulation cleavage (visable microscopically) overprints the isoclinal folds. L_3 lineations in schist are parallel to F_2 fold axes.

D. L_4 crenulation lineations are weakly developed. They are subhorizontal and at a small angle to L_3.

FABRIC (relationship between porphyroblasts and S-surfaces)

A. In schists on the east bank of the creek staurolite porphyroblasts appear to have grown under static conditions over vertical S_2 cleavage. Further north staurolite has grown over transposition schistosity (S_2).

B. None of the observed garnets appear to have grown over S_2; in fact both S_1 and S_2 appear to swirl around them. Garnets with both linear and pin wheel trains of inclusion are found, but generally the trains are at an angle to and discontinuous with the surrounding S-surfaces.

ULTRAMAFIC ROCKS

LOCATION: This body is ultramafic pod D-1 of Fig. 7.

REASON FOR STOPPING HERE:

A. To see two varieties of ultramafic rocks characteristic of folded Appalachian eugeosynclinal rocks: a talc-olivine rock and a chlorite schist with magnetite.

B. To contrast these rocks with those to be seen at STOP 9.

TABLE 6. CONTRAST OF ULTRAMAFIC ROCKS AT STOPS 6 AND 9

LOCALITY:	BELL'S MILL ROAD (6)	LAFAYETTE ROAD (9)
Rock types present:	Talc rock with olivine Chlorite schist	Pyroxenite Anthophyllite rock Chlorite schist
Original rocks:	Dunite and pyroxenite	Pyroxenite
Retrograde Metamorphism:	Only olivine of the original rocks remains	Core of pyroxenite remains. Outer portion changed to chlorite schist.

PETROLOGY:

The metamorphic schemes illustrated here are:

A. (Pyroxene)⟶ (anthophyllite)⟶ chlorite-talc

B. Olivine ⟶ serpentine

Station B: Talc-olivine rock

The large boulders and outcrop of talc-olivine rock located on the western corner of the intersection of Wissahickon Drive and Bell's Mill Road contain dark inclusions of olivine now partly altered to serpentine. The original rock appears to have been peridotite. The pyroxene has changed to talc while the olivine is partly changed to serpentine. Accessory carbonate minerals are not uncommon in such rocks. Here small crystals of siderite up to 0.5 mm. across may be found while at ultramafic locality D-2 dolomite occurs and at D-4 magnesite is present.

Station C: Chlorite schist

LITHOLOGY

This outcrop is located 174 feet northwest of the intersection between Wissahickon Drive and Bell's Mill Road, along the former. Chrome-rich magnetite octahedrons up to 0.5 cm across overgrow the schistosity and cause a good hand magnet to cling to the outcrop. This highly sheared and foliated chlorite schist appears to have originally been pyroxenite.

STRUCTURE

A. The vertical schistosity in the talc-chlorite schist is probably correlative with S_2 in the adjacent rocks of the fault zone, and it may have formed as the ultramafic body moved upward from a deeper source (Amenta).

B. The horizontal lineations on the schistosity are probably L_4. Some fold axes have been found in these ultramafic rocks, but it is unclear what generation they belong to.

Station D

The Wissahickon Formation exposure of interest is located approximately 100 feet up the bank which may be muddy and slippery. The exposure is small and probably not more than 25 people can inspect it at one time. Other exposures located closer to the road where it turns northwest exhibit some of the same phenomena but not as well.

LITHOLOGY

A. Resistant rock ledge composed predominantly of quartz feldspar gneisses and some mica schist. The compositional layering is vertical; and although the gneisses have a dense flinty aspect produced by shearing and cataclasis, the layering probably originated from bedding (S_0).

STRUCTURE

A. The upright similar folds in the layers (S_0) are F_2 (although they may resemble the F_1 folds observed at station 4). Thin sections show that the schistosity which is parallel to the axial planes of these folds is S_2, a transposition schistosity; i.e. the micas in S_1 have been reoriented into the S_2 direction.

B. The side of this exposure reveals a horizontal compositional banding developed on the surface (S_0). This banding is due to the intersection with S_0 of quartz veins and micas parallel to S_2. The banding is parallel to F_2 fold axes.

Station E: Small granite quarry.

LITHOLOGY

A. The granite in this quarry contains quartz, oligoclase, microcline, muscovite, biotite and epidote. It is a small body restricted to the west bank of the creek.

STRUCTURE

A. The contacts are exposed and the body is concordant with S_2 schistosity in the adjacent schists. Contact metamorphic affects have not been found.

B. The foliation in the granite is vertical and defined by oriented strained micas and by thin separated lenses of granulated quartz and feldspar. The correlation of this foliation with S-surfaces in the country rock would provide a relative minimum age for the intrusion. Although the foliation in the granite is essentially cataclastic in nature and oriented parallel to S_2 in the schists, the cataclasis is noticeably less pronounced than in nearby gneisses and there has been little postkinematic recrystallization. These facts suggest that the foliation in the granite is not correlative with S_2 but rather with S_4. This is consistent with observations that post-metamorphic deformation of micas in the fault zone becomes progressively more pronounced northwest suggesting renewed movement of the Rosemont fault during D_4.

Station F

LITHOLOGY

A. This outcrop of mica schist and fine grained quartz feldspar gneisses is located approximately 225 feet south of the Rosemont fault.

STRUCTURE

A. The isoclinal folds within the gneiss layers are F_2. Quartz veins which were originally discordant with S_0 are also folded.

B. Folds with axial planes dipping southeast in the schists are F_4. These folds deform the transposition schistosity (S_2) and hence are younger than the shearing in the fault zone. The micas they deform are strained.

Structural and metamorphic history from rocks at STOP 6.

A. Development of S_1 schistosity and growth of garnet during metamorphism (M_1) followed by,

B. development of F_2 folds and S_2 transposition schistosity synchronous with faulting, basement uplift and dirapiric emplacement of ultramafic rocks followed by,

C. early episode of metamorphism (M_2) with growth of staurolite over S_2 and recrystallization of cataclastic rocks in fault zone followed by,

D. development of S_3 crenulation cleavage during later episode of metamorphism (M_2) followed by,

E. intrusion of granite followed by,

F. post-metamorphic development of F_4 folds, S_4 cleavage, and cataclastic foliation in granite perhaps related to renewed movement on Rosemont fault.

STOP 6 TO MOTEL

29.8	Turn around and retrace route on Bell's Mill Road.
30.8	At light, turn left onto Ridge Pike.
31.3	Cross contact between the Wissahickon Formation and the Precambrian basement gneiss. This is the Rosemont fault.
31.5	Turn left on Barren Hill Road. The crest of a small hill hides this intersection.

The old Barren Hill Inn was noted for a colony of purple martins that lived under the eaves (Weygandt, 1930, p. 46).

33.2 Intersection of River Road with Barren Hill Road. Follow Barren Hill Road to the right.

Cross contact between the Precambrian basement gneiss and the Cambrian Chickies Quartzite Formation. This is the Cream Valley fault.

33.25 Cross contact between Chickies Formation and the Ordovician Conestoga Limestone Formation.

33.3 Turn left onto Hector Street.

34.6 Cross contact between Conestoga Formation and Wissahickon Formation (Greenschist facies).

34.7 At light turn left onto Fayette Street in downtown Conshohocken.

Conshohocken means "pleasant valley" in the original Indian tongue. This borough, incorporated in 1850, had its origins in colonial days at the site of Matson's Ford across the Schuylkill River. Early iron works here evolved into the present Alan Wood Iron and Steel Company (Alderfer, 1951, p. 168, 202).

35.1 Southwest end of bridge over Schuylkill River. At light turn left onto Front Street.

35.2 Turn right at "T" intersection to Moorehead Avenue.

35.7 Moorehead Avenue has become an entrance ramp to I-76, the Schuylkill Expressway. Proceed northwest on I-76.

36.9 Cross contact between Wissahickon Formation and Ordovician Conestoga Limestone Formation.

40.1 Get in right lane to leave Expressway at Exit 35-S, U.S. 202S-Paoli. Stay in right lane of ramp and in right lane on bridge over Expressway to Warner Road Exit from U.S. 202.

40.4 Turn right into motel. END OF FIRST DAY.

DAY 2 MOTEL TO STOP 7

0.0 Leave motel front entrance by turning right onto Warner Road access ramp.

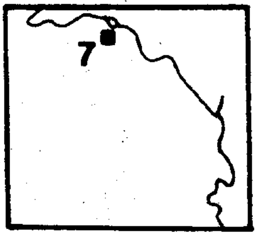
0.3 Turn left onto Warner Road bridge over U.S. 202.

0.4 Turn right onto U.S. 202 North.

1.2 Pass King of Prussia Inn on left.

3.2 Turn right into entrance of Bridgeport Quarry and Park.

STOP 7. THE BRIDGEPORT QUARRY or UPPER MERION RESERVOIR by William B. Fergusson.



Bridgeport got its start from Swedes Ford on the Schuylkill River and the tavern located there. The Schuylkill Canal was on the south side of the river and was paralleled by the Philadelphia and Reading Railroad in 1838. These superior transportation facilities gave Bridgeport an advantageous position over Norristown in the coming industrialization of the region (Alderfer, 1951, p. 169).

LITHOLOGY AND STRUCTURE

The Bridgeport Quarry is situated in the Ledger Formation of Cambrian Age (Fig. 17). The formation consists of massive dolomite beds that strike N85E and dip from 40° to 50° in a southerly direction The dolomite is fine to medium grained, crystalline, siliceous in part, and the color ranges from white to light gray. Some of the beds contain an almost chemically pure dolomite which in some cases attain an aggregate thickness of from 300 to 500 feet (Miller, 1934). The massive, almost pure, dolomite zones are interbedded with thinner beds of siliceous dolomite. An average of five chemical analyses considered typical of the high quality dolomite is as follows.

CaO	30.44%
MgO	20.44%
Fe_2O_3	0.56%
Al_2O_3	0.68%
SiO_2	2.03%
ignition loss	46.36%

Joints are wide spaced, steeply dipping (70° to 80°), a major joint set strikes N85E parallel to the bedding, and a minor joint set strikes N10E. Watson and Wyckoff (1951) indicate a shear zone, which may represent a fault, that strikes N40E and dips 80NW through the center of the quarry.

SOLUTION FEATURES

Pinnacle weathering is well developed along the east wall of the quarry; and excellent examples of pinnacles may be seen in the northeast sector of the quarry (Fig. 30). Many solution features are observable along the east wall including a cross section of a large sinkhole near the center of the wall (Fig. 31). A red clayey soil rests on the weathered dolomite surface and fills the voids between the pinnacles. The clay has been washed down solution channels and solution enlarged joints deep into the subsurface. During quarry operations boulders

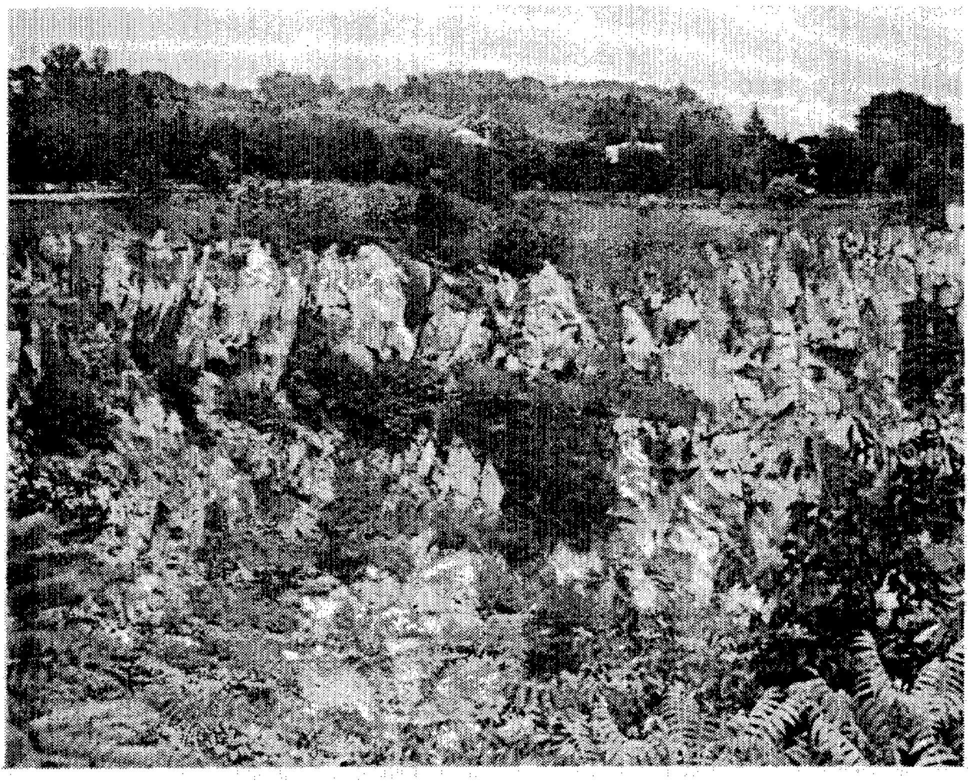


Figure 30. Pinnacle weathering of northeast sector, Bridgeport Quarry.

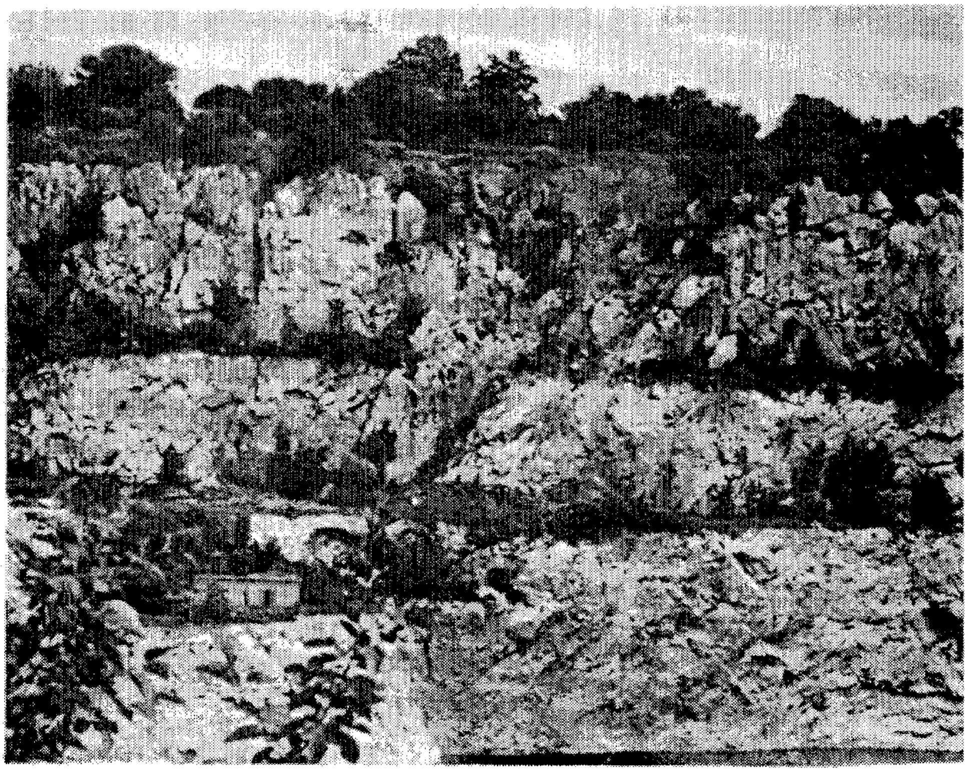


Figure 31. Sinkhole cross-section, center of east wall, Bridgeport Quarry.

and cobbles of the Triassic Stockton Formation have been found at considerable depth in the solution channels and solution enlarged joints (Miller, 1934).

QUARRY HISTORY

The Bridgeport Quarry was operated from 1925 to 1967 by Bethlehem Mines Corporation a subsidiary of Bethlehem Steel Company. The dolomite was removed to a depth of about 400 feet from a surface elevation of 160 feet to a bottom elevation of -240 feet. Approximately 40 million tons of rock was taken from the quarry, of which 60% was utilized by Bethlehem Steel for flux and refractories; 35% was sold as construction materials for concrete and road aggregate; and about 5% was marketed as agricultural stone.

The following test results are representative of the physical characteristics of the Ledger Formation in the Bridgeport area.

Specific Gravity	2.84
Absorption	0.2 %

Soundness and Strength Tests

Sodium Sulfate (5 cycles)	0.0% loss
Deval Abrasion	3.8% loss
Los Angeles Rattler	30.61% loss
Compressive Strength	
X axis	18,000 psi
Y axis	19,000 psi
Z axis	18,500 psi

After quarrying space was depleted Bethlehem Mines Corporation transferred the quarry to the Philadelphia Suburban Water Company for use as a reservoir. The water company has been operating the reservoir since 1969. In general, the water level in the reservoir is maintained at an elevation of -75 feet, a water depth of 165 feet. At this level the storage capacity of the reservoir is approximately 750 million gallons. Groundwater infiltrates into the reservoir during the winter at a rate of from 7 to 9 million gallons a day; and in the summer water is pumped from the reservoir at about the same rate. On rare occasions the pumping rate may be as high as 20 million gallons a day for short periods.

STOP 7 TO STOP 8

3.2 Turn left out of parking area onto U.S. 202 South (DeKalb Pike).

3.4 At light turn left onto Henderson Road.

4.9 At light turn left off Henderson Road onto South Gulph Road.

Though we remain on the Ordovician Conestoga Limestone Formation the ridge to the right (southwest) is underlain by the Wissahickon Formation (greenschist facies).

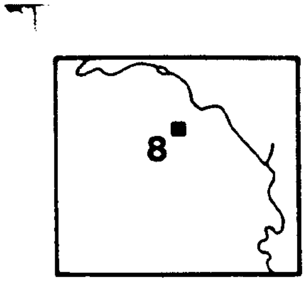
6.4 After following South Gulph Road past the Schuylkill Expressway ramps to the first light, turn left on Old Gulph Road.

We have just passed through a gap in the Wissahickon Formation ridge and are back onto a septum of the Conestoga Limestone Valley.

6.6 Cross the contact between the Conestoga limestone and the Precambrian basement gneisses (Cream Valley fault).

7.0 Park at bridge over Mid-County Expressway.

STOP 8. BASEMENT GNEISS by M. L. CRAWFORD.



LOCATION: A major road cut along the Mid-County Expressway immediately northeast of the Old Gulph Road overpass (Fig. 1 and Fig. 32).

RESTRICTIONS: Those who wish to visit this outcrop after the field conference should obtain permission from the District Engineer, Pennsylvania Department of Transportation, 200 Radnor-Chester Road, St. Davids, Pennsylvania 19087.

GENERAL SETTING:

A. The outcrop lies approximately 460 meters south of the Cream Valley Fault zone which separates Conestoga limestone (Lower Ordovician) from the Precambrian rocks (Fig. 32). North of this stop (not seen on trip) a 120 meter wide septum of Wissahickon schist (staurolite-garnet) lies within the fault zone between the limestone and the gneiss.

B. The outcrops at this stop consist of cataclastic gneisses presumably formed during the emplacement of the block of basement gneisses up into the overlying Wissahickon schist and younger sediments.

REASON FOR STOPPING:

A. To show cataclastic textures ranging from mylonite gneiss and blastomylonite to mylonite (nomenclature of cataclastic rocks from Higgins, 1971, see Table 7 below). (Fluxion structure * cataclastic foliation.)

Table 7

CLASSIFICATION OF CATACLASTIC ROCKS

[Porphyroclastic, protoclastic, diaphthoritic, pseudotachylitic, polymetamorphic, polycataclastic, phyllitic, and other terms are used as modifiers. See text and glossary]

<table>
<tr><th rowspan="3">Approximate volume percent porphyroclasts in rocks <i>with</i> fluxion structure.
or
Approximate volume percent fragments in rocks <i>without</i> fluxion structure.</th><th rowspan="3">Rocks <i>without</i> primary cohesion</th><th colspan="4">Rocks <i>with</i> primary cohesion</th><th rowspan="3">Approximate size of <i>most</i> porphyroclasts in rocks <i>with</i> fluxion structure.
or
Approximate size of <i>most</i> fragments in rocks <i>without</i> fluxion structure.</th></tr>
<tr><th colspan="3">Cataclasis dominant over neomineralization-recrystallization</th><th>Neomineralization-recrystallization dominant over cataclasis</th></tr>
<tr><th>Rocks <i>without</i> fluxion structure</th><th colspan="2">Rocks <i>with</i> fluxion structure</th><th>Rocks <i>with</i> fluxion structure</th></tr>
<tr><td>>50</td><td rowspan="2">Fault breccia</td><td rowspan="2">Microbreccia</td><td colspan="2">Protomylonite</td><td rowspan="2">Mylonite gneiss (mylonite schist)</td><td rowspan="2">Visible to naked eye</td></tr>
<tr><td><50
30</td><td rowspan="2">Mylonite</td><td rowspan="3">Phyllonite (variety)</td></tr>
<tr><td>>10</td><td rowspan="2">Fault gouge</td><td rowspan="2">Cataclasite</td><td rowspan="2">Blastomylonite</td><td>>0.2mm</td></tr>
<tr><td><10</td><td>Ultramylonite</td><td><0.2mm</td></tr>
</table>

All rocks are gradational

B. To discuss the development of open to isoclinal folds with curved hinges. These folds formed during the faulting and emplacement of the gneisses.

C. To compare these structures with those seen at STOP 6.

D. To compare the lithologies in the gneisses with those of STOPS 10 and 11.

LITHOLOGY AND TEXTURE:

A. Three principal rock types alternate along the roadcut:

1. Biotite-quartz-plagioclase blastomylonite and mylonite with varying proportions of epidote and sphene.

2. Granitic mylonite gneiss and blastomylonite. The K-feldspar is microcline, minor muscovite occasionally is present.

3. Cataclastic amphibolites or amphibolite-biotite-plagioclase rocks.

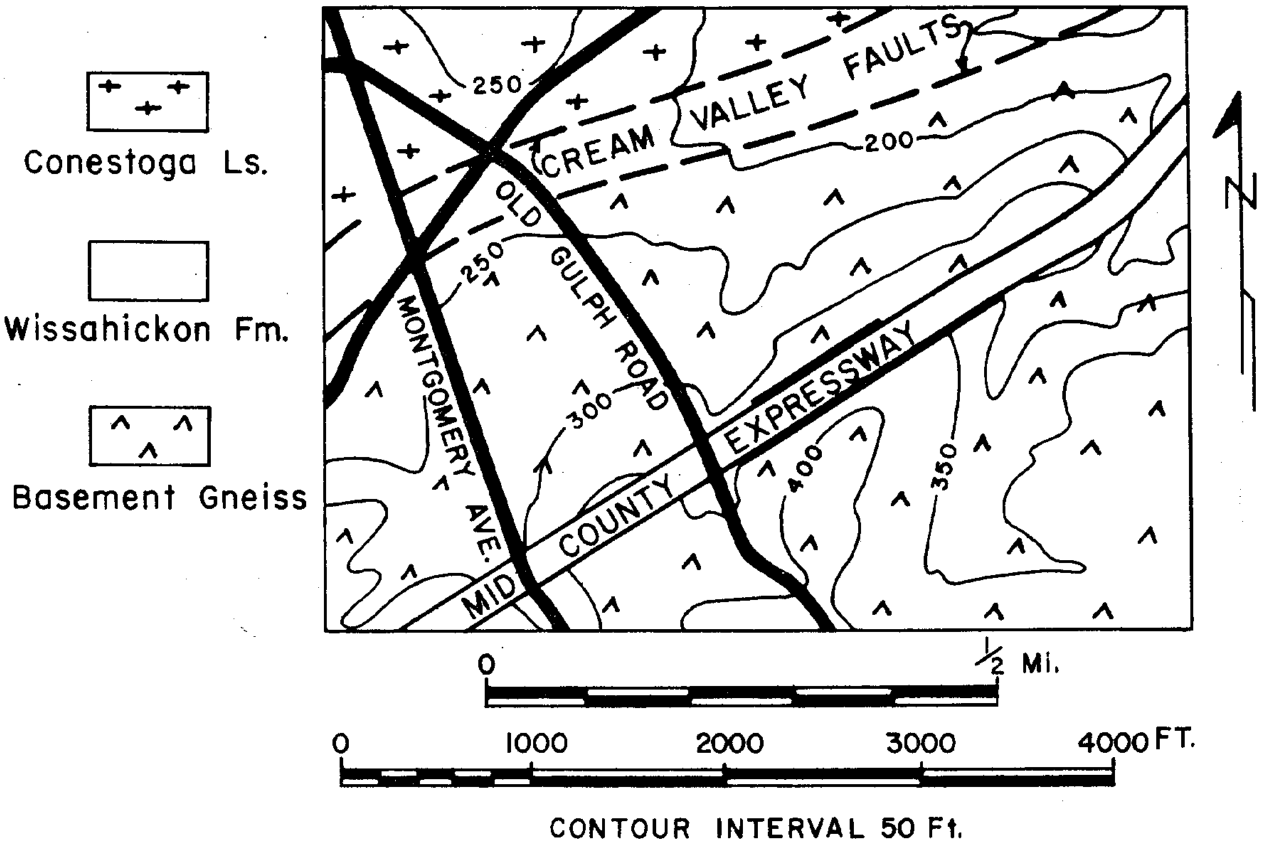


Figure 32. Detailed map of Stop 8, Mid-County Expressway.

B. Other minerals:

1. Secondary minerals include chlorite in the more mafic rocks and calcite which occurs in all samples.

2. Later quartz veins cut across the foliation and banding.

C. Cataclasis:

1. The amount of cataclasis is controlled to a large extent by lithology: mica-rich rocks show the finest grain size, fewest porphyroclasts, best developed fluxion structure.

2. The amount of cataclasis increases northward toward the fault; the grain size decreases and the width of mylonite zones increases.

3. Biotite and quartz are most susceptible to crushing; they form the bulk of the fine matrix. In thin section plagioclase (oligoclase), microcline and hornblende show varying degrees of comminution from slight fragmentation along grain margins to the formation of well rounded oval grains surrounded by a fine "paste" of the same material.

D. Recrystallization:

1. All samples show some degree of recrystallization, it is more extensive in the granitic blastomylonites and mylonite gneisses.

2. The following mineralogical changes are noted resulting from recrystallization. Epidote invariably shows a secondary rim enriched in iron, forming euhedral grain outlines. Quartz becomes coarser develops straight grain boundaries and is unstrained. Plagioclase is rimmed by a narrow more sodic margin and microcline is replaced by myrmekite. Recrystallization and cataclasis were apparently simultaneous.

E. Metamorphic Grade:

See Fig. 2 and Fig. 3 for the relationship of the metamorphic grade of these rocks to those of the other stops.

STRUCTURE

A. Foliation is well developed in all rocks dipping steeply (70-90°) at an azimuth of 315°. It is axial plane to the folds and is defined by fluxion structure, compositional banding, and vertical joints in the rocks.

B. Folding varies from moderately open folds in the mylonite gneisses and blastomylonites to isoclinal folds in the more highly crushed rocks. The true mylonites show no evidence of folding.

1. Most of the folds plunge moderately to steeply (40-70°) to the northeast parallel to folds in migmatitic rocks within the more massive Precambrian rocks.

2. Some fold hinges are curvilinear and lie in the foliation with plunges which vary from 35SW through horizontal to 40NE. Individual fold hinges curve over distances ranging from a few centimeters to several meters.

3. The lack of folds in the mylonite is interpreted as being due to the more extensive deformation in those zones. Isoclinal folds with sheared off limbs are not uncommon.

SUMMARY

A. The primary pattern of deformation involves cataclasis which produces foliation in all rock types and folds in the less sheared rocks by differential movement. The parallelism of these folds with those in the less deformed migmatites of the Precambrian block suggest they formed simultaneously.

B. Evidence of a second episode of deformation in the fault zone includes:

   1. Intersecting lineations on some joint surfaces - one plunging northeastward, the other southwest. Armstrong (1941) suggested the southwest plunging folds and lineations corresponded to a second deformation.

   2. Two periods of deformation in the Wissahickon schist north of the fault (Amenta, personal communication). The second, which almost obliterates the first, produced tight isoclinal folds with subhorizontal axes but without recrystallization of mica, staurolite, and garnet.

C. However, the presence of curved fold hinges with plunges parallel to the northeast and southwest plunging lineations permits the interpretation of one movement episode, with motion upward on the northside and a direction of transport which plunged steeply to the southwest.

STOP 8 TO STOP 9

7.0	Continue southeast on Old Gulph Road.
8.0	At light turn left onto Spring Mill Road.
8.8	Turn right onto Morris Avenue.
9.5	Cross contact between Precambrian basement gneiss and ultramafic body C-3 of Fig. 7. This contact is the Rosemont Fault.
9.8	Cross contact between ultramafic body and Wissahickon Formation (amphibolite facies).
10.0	Turn left onto Waverly Road.
11.4	Turn left onto Young's Ford Road.
12.6	Park on right in dump area; just past small bridge.

STOP 9. ULTRAMAFIC ROCKS NEAR THE SCHUYLKILL RIVER by Frank Roberts.

LOCATION AND GENERAL SETTING

A. This is mass C-1 of Fig. 7 located near the intersection of Young's Ford Road and Lafayette Road (see Fig. 33) in an undeveloped Lower Merion Township Park, Gladwyne.

B. The Rosemont fault marking the boundary between the Precambrian gneiss and the Wissahickon schist lies 500 feet northwest of the parking area (see Fig. 33).

C. A parallel band of ultramafic rocks lies 0.5 miles to the southeast (Fig. 7).

D. The ultramafic rocks tend to resist erosion more than the surrounding schist; thus they form a ridge with streams flowing along the contacts with the schist.

REASON FOR STOPPING HERE

A. To look at the diverse petrology of the ultramafic rocks.

B. To illustrate the scheme of metamorphism which characterizes the ultramafic rocks.

STRUCTURAL GEOLOGY

A. Strike of the predominant foliation: N45E±5°
Dip of the predominant foliation: SE 70° ± 20°

B. The folds correspond to those termed F_2 by Amenta in the Wissahickon schist.

PETROLOGY

A. The metamorphism scheme illustrated here is:

Pyroxenite ⟶ Anthophyllite ⟶ Chlorite-talc, Serpentine

B. See Fig. 2 and Fig. 3 for the relationship of the metamorphic grade of those rocks to those of the other stops.

DESCRIPTION OF STOP 9

Introduction: In order to see the diversity of the ultramafic rocks, STOP 9 has been divided into seven "sublocalities." We shall follow a trail up the hill, then over and down the other side of the hill, following red flags (no trail), crossing the

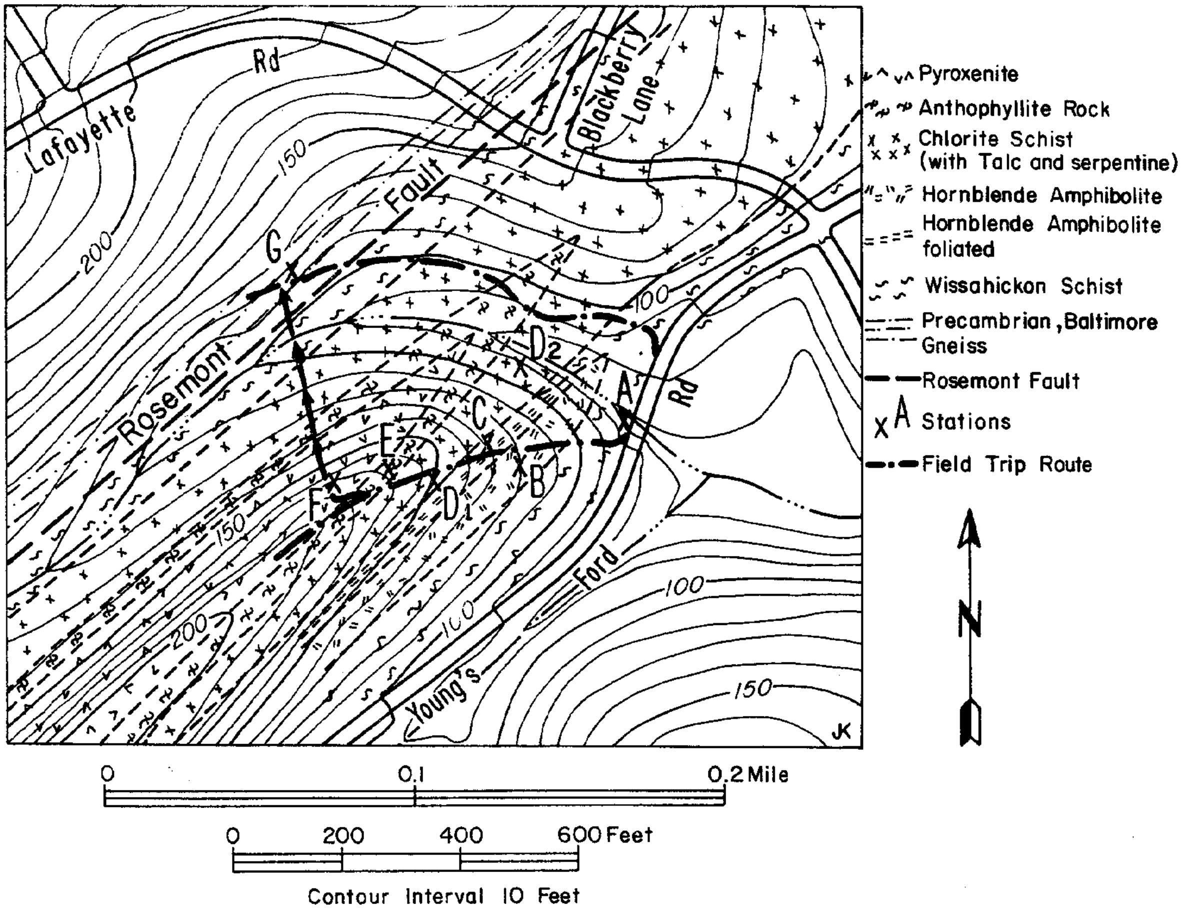


Figure 33. Detailed map of Stop 9, Lafayette Road.

stream, and returning to the busses on another trail. (See fig. 33). Two of the outcrop areas are large (Stations E and F); the others are entirely too small for a large group, but may be considered typical of the area. Guides posted at each outcrop will direct you to the points of interest. Approximate locations of contacts are noted by signs posted along the trail, and correspond to the drawn contacts on the map.

A. Station A: Wissahickon schist (quartz, muscovite, garnet; staurolite subfacies of the almandine amphibolite facies); outcrops in and beside the stream.

B. Station B: Hornblende amphibolite. (Hornblende, plagioclase, quartz). Occurs adjacent to the ultramafic rocks at other localities to the SW. See small "quarry" to the left of the trail.

C. Station C: Foliated hornblende amphibolite. This appears to be a shear zone on the NW side of the amphibolite. (The rock resembles the chlorite schist of Station D, but is not part of the ultramafic series.)

D. Station D_1: Chlorite schist, with talc and serpentine. This is the first ultramafic rock seen at this stop. It is the end-stage of the retrograde metamorphism of pyroxenite. Some is rather massive, other is more foliated. There is a large outcrop of this rock at the stream level, which may be conveniently seen after Station F. Closer to Station E, anthophyllite occurs in the chlorite schist.

E. Station E: Anthophyllite rock. This is the intermediate stage in the retrograde metamorphism of pyroxenite. Some contains chlorite and talc. There is no precise contact with the chlorite schist. One grades into the other.

F. Station F: Pyroxenite, showing alteration to anthophyllite. (On the crest of the hill: several outcrops.) Hand specimens show typical pyroxene cleavage and the fibrous cleavage of anthophyllite. Pyroxenite also occurs on the central cores of the larger pods of ultramafic rocks to the southwest (C-4, actually norite; D-4 south of Newtown Square, and D-5 east of Lima).

On the way down the hill look for chlorite-talc schist, which may be found as float, giving the "ringed" effect of retrograde metamorphism about a less metamorphosed center. One may also find pieces of a highly sheared Wissahickon schist in the float. This has been referred to as the "spangled schist" in the past. The stream is approximately on the Rosemont fault. A guide will show you the way. Look for the flag people at the stream. They will point out a convenient place to cross. As you cross the stream you are going to the upthrown side of the fault.

G. Station G: The Precambrian gneiss (often called the Baltimore gneiss). There are several small outcrops. Note the milonite texture of the rock. The Rosemont fault is probably a fault zone, rather than a single fault. If you wish to see Station D_2, the large outcrop of chlorite schist, you should cross the stream at the point designated by a guide before returning to the bus.

STOP 9 TO STOP 10

12.6 Turn right out of dump area onto Young's Ford Road.

12.7 At stop sign turn left onto Lafayette Road.

Cross contact between Wissahickon Formation (amphibolite facies) and ultramafic body (C-1 of Fig. 7).

12.8 Cross contact between ultramafic body and Precambrian basement gneiss. This is the Rosemont Fault.

14.2 Intersection with Conshohocken State Road. Stay on Lafayette Road.

14.4 Turn right on Mt. Pleasant Road.

14.8 Turn left on Spring Mill Road.

16.0 Intersection of Spring Mill Road with Old Gulph Road. Stay on Spring Mill Road (now Pa. 320).

17.1 Villanova University on left. Named for St. Thomas of Villanova, Bishop of Valencia (1544-55) was founded by the Augustinian Fathers of the Roman Catholic Church in 1842 (French, 1957, p. 439).

17.35 Cross U.S. 30 Lancaster Pike.

17.6 Veer right on Pa. 320 which now becomes Sproul Road.

20.4 At light turn right onto Bryn Mawr Avenue.

Cross contact between Precambrian basement gneiss and Wissahickon Formation (amphibolite facies). This is the Rosemont Fault. Immediately leave Wissahickon Formation and enter ultramafic body C-D-4 of Fig. 7.

21.9 Cross contact between ultramafic body and Wissahickon Formation (amphibolite facies).

22.6 At light turn right onto West Chester Pike (Pa. 3).

22.65 Cross contact between Wissahickon Formation and Precambrian basement gneisses. This contact is the Rosemont Fault.

West Chester Pike was laid out in 1793 as a part of a state road from Philadelphia to York. By 1800, when stages were rolling over the road, it took most of the day to go the 24 miles from Philadelphia to West Chester. On one irksome journey, when Judge Darlington and Olof Stromburg were among the passengers, the Judge made the interjectional remark, "What a long road from Philadelphia to West Chester." Olof concurred in the opinion, but added, "It's a good thing for us that it is so." "Why so?" asked the Judge. "Because," replied Olof, "if it was not so long it would not reach!" (Faris, 1917, p. 96, 97).

23.0 Get in left lane to turn left at third light onto Newtown Street Road (Pa. 252).

The village of Newtown Square had its origins in the early 1800's with the construction of the Friends Newtown Meeting House

23.6 Cross contact between Precambrian basement gneiss and ultramafic body C-D-4 of Fig. 7.

24.1 Turn right on Gradyville Road. Spruce Street Baptist Church is on the right.

24.5 Cross contact between ultramafic body and Precambrian basement gneiss. This is the Rosemont Fault.

25.7 Cross arm of Springfield Reservoir.

26.2 Cross Providence Road. Enter Ridley Creek State Park.

26.6 At "T" intersection turn left toward the park office.

27.3 At "V" intersection bear left toward the park office.

27.6 Turn right toward park office.

27.65 Turn left into bus parking area.

LUNCH. Ridley Creek State Park.

Ridley Creek State Park encompasses 2,489 acres of woodland and meadows. Within the Park boundaries is a small 18th century village which grew up around the site of a mill known at present as Sycamore Mills. The miller's house, the office and library, and several small millworkers' dwellings are still in existence.

28.0 Return to "V" intersection and turn left.

29.3 Cross Middletown Road. Stay on Gradyville Road.

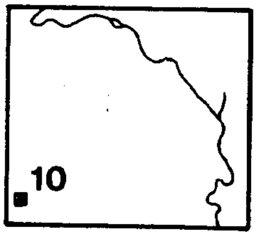
29.9 Turn left off Valley Road.

31.3 At "T" intersection turn right on Forge Road.

32.3 Turn right into Glen Mills Quarry.

The Glen Mills paper mill was founded in the late 1700's and is still in business. John Taylor built the first nail factory and first rolling and slitting mill in the province at Glen Mills in 1746 (French, 1957, p. 72, 73).

STOP 10. GLEN MILLS QUARRY by
W. R. Parrott, Jr.



LOCATION: Glen Mills Quarry is located on the east side of Chester Creek at the village of Glen Mills, Pennsylvania, approximately 30 km. (18 mi.) west-southwest of Philadelphia (Fig. 1, Fig. 34 and Fig. 35).

RESTRICTIONS: Release forms must be completed and signed at the office adjacent to the main gate; hard hats are required.

REASON FOR STOPPING: The Glen Mills Quarry is the best locality to examine the amphibolite facies rocks of the basement gneisses in detail. In particular one should note:

A. variation in rock type.

B. metamorphic and structural relations (and styles of deformation).

C. possible sequence of events.

Station A: Intermediate to mafic gneiss; folding

LOCATION: Top of quarry, south end. From this vantage point the gross structure of the quarry can be seen, as can the operation itself; there are 6 levels below this rim, at 50 foot intervals.

ROCK TYPE: Intermediate to mafic gneiss, with fine banding, fairly typical of most of the quarry, particularly where migmatization has been minimal.

STRUCTURE: Isoclinal folds; coaxial folds (fold axes parallel, axial planes not); open folding; pinching out of units; cross-cutting vein.

Station B: Intermediate gneiss; calcsilicate; serpentine; boudinage

LOCATION: Ramp from 150' level to 100' level, south end of quarry.

ROCK TYPE: To the left, intermediate gneiss, slightly migmatized; ahead, calcsilicate (see Station C for description); above, weathered zone with serpentine; to right, intermediate to mafic gneiss.

STRUCTURE: Here calcsilicate rock can be seen bounded on both sides by intermediate and intermediate to mafic gneiss; a more competent mafic band within has been boudinaged; the serpentine included in the weathered zone above bears an uncertain relation structurally to the other rocks, although it appears to be related to the carbonate--how did it get there?

Station C: Calcsilicate Rock

LOCATION: 100' level, southeast side.

ROCK TYPE: Calcsilicate rock: up to 50% calcite locally; the following minerals are present:

Calcite (rel. pure)
Ferroan calcite
Hornblende
Quartz
Microcline
Epidote
Sphene
Apatite
Zircon
Plagioclase
Garnet

Fractures are filled with almost pure calcite containing hornblende.

STRUCTURE: This unit is approximately 50' thick, and dips off to the east; it overlies a distinctive green and reddish banded gneiss.

Station D: Thrust fault in intermediate to mafic gneiss.

LOCATION: 100' level, south end.

ROCK TYPE: A mafic banded gneiss; contains considerable garnet locally, and diabasic texture of some bands is preserved.

STRUCTURE: The isoclinally folded gneiss here has been thrust upward to the west; this is the clearest fault in the quarry, but by no means the only one.

Station E: Felsic to intermediate banded gneisses, isoclinally folded

LOCATION: 100' level, west side, just southwest of crusher building.

ROCK TYPE: A felsic banded gneiss, with considerable garnet locally.

STRUCTURE: Isoclinal folds may be observed, along with gentle warping and open folding; prominent groove lineations, crenulations and pods of feldspar porphyroblasts.

Station F: Felsic to intermediate gneiss, prophyroblastic

LOCATION: 100' level, northwest corner, northwest of crusher plant and next to small pond.

ROCK TYPE: A felsic to intermediate banded gneiss, with prominent pink microcline porphyroblasts; locally quite garnetiferous.

STRUCTURE: Prominent banding foliation, axes of porphyroblasts aligned parallel to mineral lineations and mullion.

Station G: Boudinage

LOCATION: 100' level, north wall, nearly to eastern end.

ROCK TYPE: Intermediate to mafic banded gneiss; locally garnetiferous. Mafic bands preserve diabasic texture.

STRUCTURE: Impressive boudinage; here mafic units have been drawn out, indicative of the stretching that is pervasive throughout the quarry, and appears to have occurred later than much of the migmatization; careful scrutiny reveals isoclinal folding as well.

Station H: Small fold illustrating bending of lineation around it.

LOCATION: East end, north side of ramp from 100' to 50' level.

ROCK TYPE: Intermediate banded gneiss.

STRUCTURE: Here can be seen a small fold, axial plane N40W, 40E, fold axis trending N55W, plunging 12S; wrapped around it is a lineation: on the east side of the fold, where the foliation is N10W, 90°, the lineation plunges 78S.

Station I: Local folding on east side of quarry

LOCATION: 50' level, approximately 1/5 of the way south along the eastern wall, or 200'-300' south of the extreme NE corner.

ROCK TYPE: Intermediate to mafic rock type, tending toward the latter; locally a dark greenish-red rock, due to garnet and hornblende.

STRUCTURE: In this corner of the quarry, on both the 50' and 0' levels, local folding into anticlines and synclines complicates the structure, and bends the boudinaged rocks; fold axes plunge 25S at S27E.

Station J: Local folding into a "mushroom" shape; very fine scale banding

LOCATION: West end of ramp leading from 50' level to lower levels; small turn around space.

ROCK TYPE: Intermediate to felsic banded gneiss, revealing very fine banding along north wall. Pink and green microcline is present in bands and prophyroblasts; garnet is present, though not in quantity.

STRUCTURE: Folding under fairly plastic conditions has produced a "mushroom" along the western wall:

A. The banding foliation on the north side, N45W, 50E, with prominent grooves plunging 25S at N70W; smaller grooves and crenulations, both folded about the structure here plunge at 65S where the foliation is nearly vertical.

B. Above, in the middle of the structure, the foliation N10E, 27E, while the axis and lineations on the foliation plunge 25-35S toward S60E.

C. On the south side the foliation steepens and overturns.

Station K: Synclinal structure at depth in quarry

LOCATION: North end of the -50' level.

ROCK TYPE: Intermediate banded gneiss.

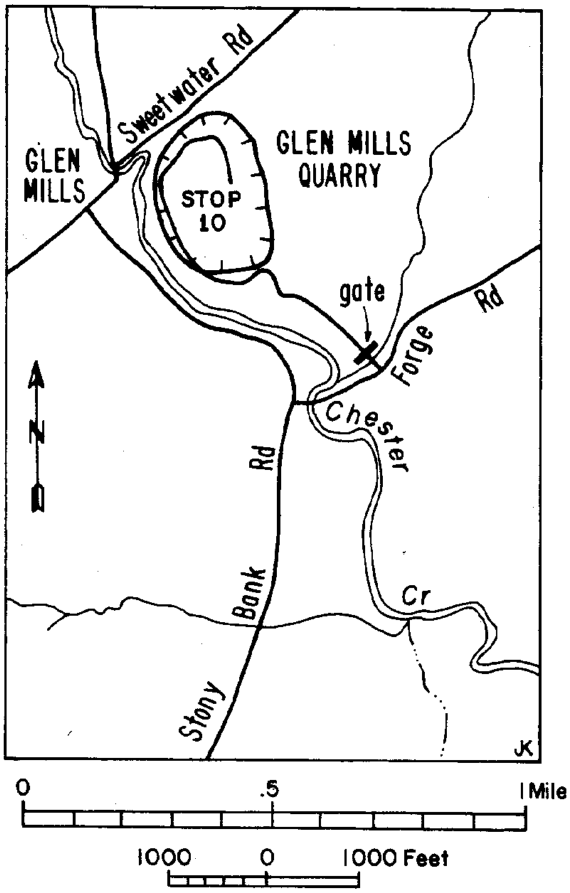


Figure 34. Location map of Stop 10, Glen Mills Quarry.

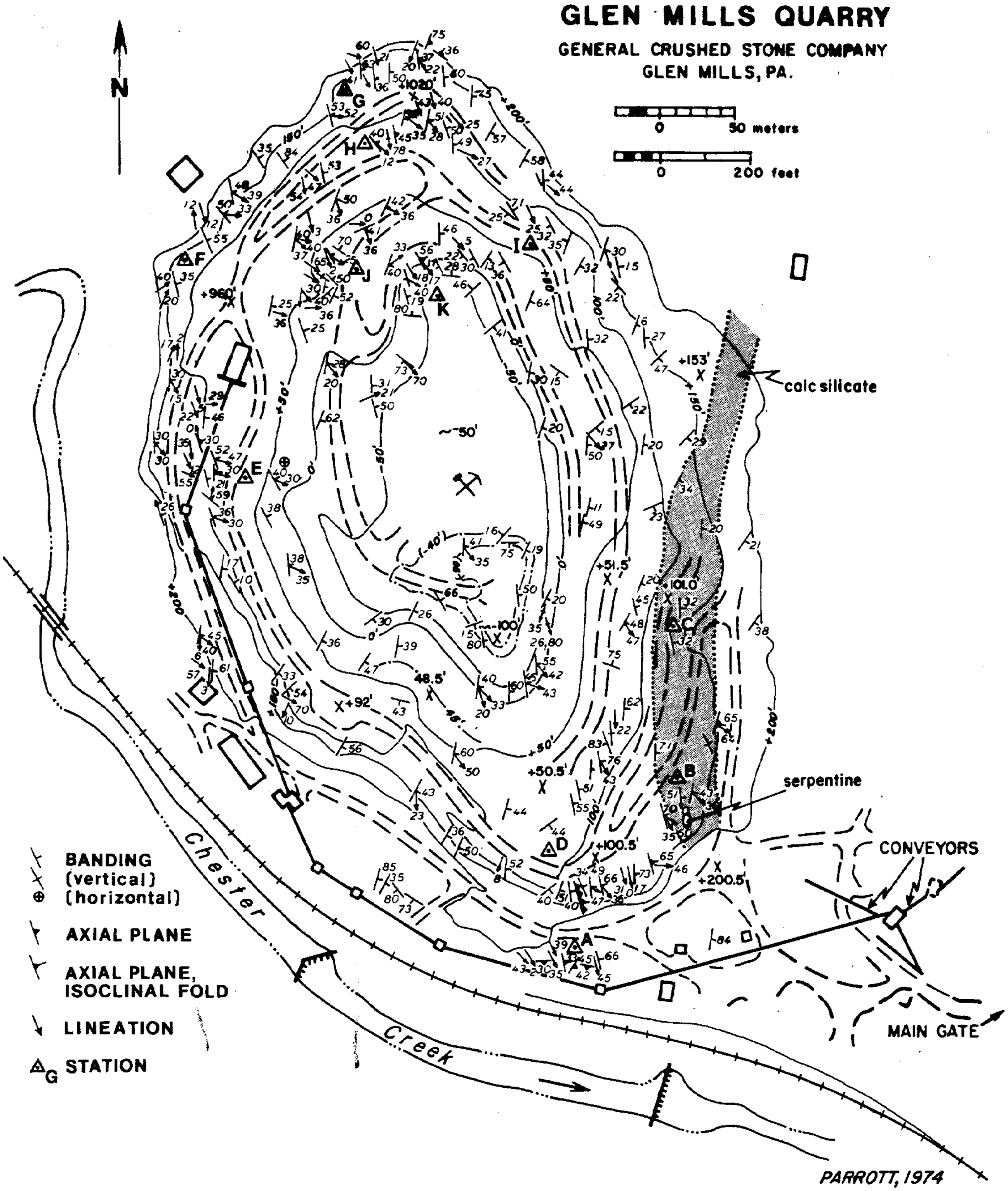


Figure 35. Detailed map of Glen Mills Quarry.

STRUCTURE: This is the best place where the synclinal structure affecting the eastern side of the quarry is evident; here a clear synclinal form of large dimension is present; smaller scale folding can be seen; fold axes plunge at 17° and 18° to the southeast.

STOP 10 TO STOP 11

32.3 Turn left from quarry entrance onto Forge Road.

We remain in the Precambrian basement gneisses during our drive to STOP 11.

33.2 Turn left onto Valley Road.

34.7 At stop sign turn right onto Gradyville Road.

35.3 Cross Pa. 352 (stop sign).

35.5 At the "V" intersection take Delchester Road, the left branch.

37.3 Cross Pa. 3 (stop sign).

38.7 At the stop sign turn right onto Goshen Road.

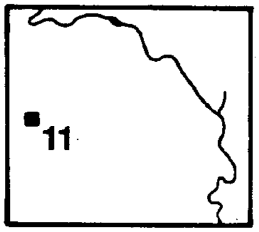
40.2 Turn left onto Grubbs Mill Road.

41.6 At the "V" intersection take White Horse Road, the left branch.

41.8 Turn left onto Rabbit Run Road.

41.9 Park at the curb by the outcrop on the right.

STOP 11. BASEMENT GNEISS by M. E. Wagner.



LOCATION: A small road cut on the west side of Rabbit Run Road, 0.1 miles south of the intersection of this road with Grubb Road (Fig. 1 and Fig. 36).

GENERAL SETTING: Precambrian rock metamorphosed to the granulite facies during Grenville time approximately 1000 m.y. ago (Grauert, *et al.*, 1973). At this locality the rocks are quartzofeldspathic gneisses, of approximately quartz monzonite composition, intruded by a diabase dike.

REASON FOR STOPPING:

A. To see the lithology of some of the demonstrably oldest gneisses in the area.

B. To discuss the metamorphic history of these gneisses and their relation to the metamorphism in the Wissahickon schist as well as the basement gneisses seen at STOPS 8 and 10.

LITHOLOGY AND STRUCTURE

A. The minerals in the gneiss are calcic oligoclase to sodic andesine, orthoclase, quartz, hypersthene, hornblende, and garnet with minor biotite, clinopyroxene, magnetite, and apatite. On fresh surfaces the gneiss is dark bluish gray because of the dark color of the quartz and feldspar.

B. Secondary garnet coronas surround the hypersthene, hornblende, and magnetite.

C. The gneiss has a strong lineation due to the arrangement of mafic minerals in streaks which show on weathered surfaces.

D. A fine-grained undeformed diabase dike 75 cm wide, with its original ophitic texture preserved, cuts the gneiss.

E. Secondary minerals in the diabase include small garnets growing in plagioclase and replacement of most of the igneous pyroxene by fine-grained pale brown hornblende.

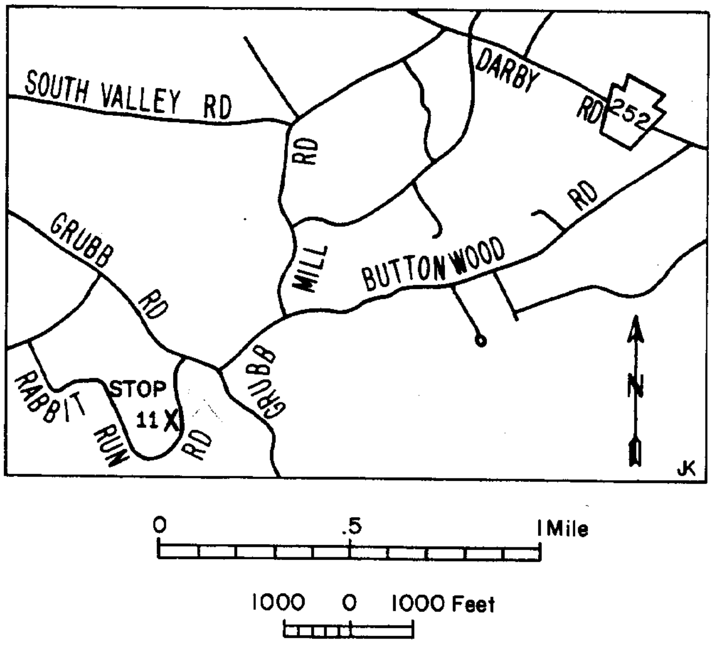


Figure 36. Location map of Stop 11, Rabbit Run Road.

DISCUSSION

A. The cross-cutting relation and undeformed nature of the diabase show it intruded following the granulite facies metamorphism of the gneiss.

B. The development of secondary garnets in the gneiss and the diabase suggest they were both subject to a later fairly high-grade metamorphism.

C. Mineral assemblages in rocks of basaltic composition and in quartz-aluminosilicate rocks nearby suggest the first metamorphism occurred at approximately 775-850°C, 8-9 kbars whereas the second was at 650-700°C, 7-8 kbars (Fig. 3).

D. The intrusion of the diabase may have occurred when the rocks were at much lower temperatures to account for the fine grain size of the dike.

E. The time of the second metamorphism is thought to be Taconic on the basis of discordant ages on zircons from the gneiss, which fall on a chord whose upper intersection with the concordia curve is approximately 1000 m.y. and whose lower intersection is about 450 m.y. (Grauert, *et al.*, 1973).

STOP 11 TO STOP 12

41.9 Continue straight ahead on Rabbit Run Road.

42.1 Turn right on Fox Chase Road.

43.0 At stop sign turn right onto White Horse Road.

43.4 Turn left onto Grubbs Mill Road.

43.6 Turn right onto Buttonwood Road.

44.9 At stop sign turn left onto Darby-Paoli Road (Pa. 252).

46.3 Cross contact between Precambrian basement gneiss and Wissahickon Formation (amphibolite facies). This is the Cream Valley Fault.

47.2 Cross contact between Wissahickon Formation (amphibolite facies) and Wissahickon Formation (greenschist facies).

47.7 At light cross U.S. 30 (Lancaster Pike). This crossroads is Paoli.

Lancaster Pike had its beginnings in 1687 and at last was opened all the way to Lancaster by 1741. The Lancaster Turnpike (a toll road) was completed and had stages running on it in 1797. This improved highway did not follow the exact route of the old road. For the accommodation of the constant travel on the turnpike there were sixty-one taverns in sixty-six miles. (Faris, 1917, p. 110-146)

Paoli received its name from the old General Paoli Tavern destroyed by fire in 1906. General Pasquale Paoli was a Corsican patriot. (French, 1957, p. 440)

Near here on the night of September 20, 1777 an American force under General Anthony Wayne was surprised and defeated with large loss of life as the British gave no quarter and freely used the bayonet on sick and wounded men. (Faris, 1917, p. 139)

48.5 Cross contact between Wissahickon Formation and Ordovician Conestoga Limestone Formation of the Chester Valley.

49.8 Turn left onto U.S. 202 North.

50.7 Get in the right lane and take the Devon Exit.

51.0 At the base of the ramp turn left on Valley Forge Road (Pa. 252).

52.2 Entrance to Valley Forge Park.

Valley Forge State Park is a 1500 acre memorial to the ragged Continentals who wintered here in 1777-8. The natural military advantages of the site include the Schuylkill River and high ground. Washington's army mustered 11,000 soldiers, one third of whom were rendered unfit by illness or lack of necessities. (French, 1957, p. 408)

52.4 Pa. 252 turns left, continue straight ahead on Baptist Road.

As we drive along Baptist Road the hill on the left, Mt. Joy, is underlain by the Cambrian Chickies Quartzite Formation and the valley to the right is underlain by the Cambrian Ledger Dolomite Formation.

53.0 At stop sign cross Gulph Road.

53.1 Leave the Chickies quartzite and drive on the ridge underlain by the Triassic Stockton Arkose Formation.

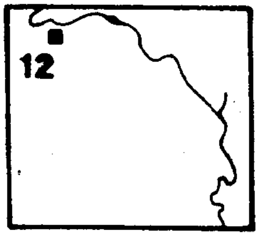
53.6 At stop sign turn right on Valley Forge Road (Pa. 23).

53.7 Leave the Chickies quartzite and drive on the ridge underlain by the Triassic Stockton Arkose Formation. The valley to the right is formed in the Ledger dolomite.

55.1 Port Kennedy. Park at the intersection of Pa. 23 and Port Kennedy Road. (Special permission must be obtained from the Park Commission through the Superintendent of Valley Forge Park to park here.) Walk a few hundred feet southwest on Port Kennedy Road to quarry on right.

The parking area and Port Kennedy Road are on the Cambrian Ledger Dolomite Formation.

STOP 12: PORT KENNEDY QUARRY by William A. Crawford.



LOCATION: An abandoned quarry in the Cambrian Ledger dolomite 700 feet southwest of the intersection of Valley Forge Road (Pa. 23) and Port Kennedy Road (see Fig. 1 and Fig. 37).

RESTRICTIONS: Those wishing to bring groups of students to this quarry should contact the Superintendent, Valley Forge State Park, by letter well in advance so he may obtain permission for your visit from the Park Commission. As in all State Parks defacing outcrops with hammers is discouraged.

WHAT TO SEE HERE

A. An excellent exposure of the angular unconformity between Triassic and Cambrian rocks crops out on the north wall (Fig. 39).

B. Cambrian Ledger dolomite is the lower unit.

  1. Bedding: strike N80E, dip 44 ± 5 S. Bedding may be observed near the western terminus of this quarry.

  2. Joints: strike N80E, dip vertical. This is the dominant surface seen here and may be confused for bedding. Other quarries to the south illustrate the relationship between joints and bedding more clearly.

C. Triassic Stockton arkose is the upper unit.

  1. Bedding: strike N85E, dip 11 ± 2 N.

  2. The irregular nature of the contact probably represents pre-Triassic weathering into pinnacles.

D. The quarry floor has been raised several feet by the dumping of a gooey, white impure $CaCO_3$ residue from the nearby magnesia plant. A faint horizontal line a few feet above the present floor marks the uncompacted fill level.

HISTORICAL NOTE: In 1871, C. M. Wheatley reported the results of the exploration of a cave uncovered during the quarrying of the dolomite. After clearing arkosic rubble to a depth of 40 feet a black clay layer containing leaves, stems, and seedpods of Pleistocene plants was uncovered (Fig. 38). It was in this clutter of vegetable matter and the red clay beneath that remains of mammals and birds were found. In total, 27 species of vertebrates, 10 of insects, and 10 of plants were reported by E. D. Cope and G. H. Horn. This cave was filled-in a number of years ago to prevent curiosity seekers

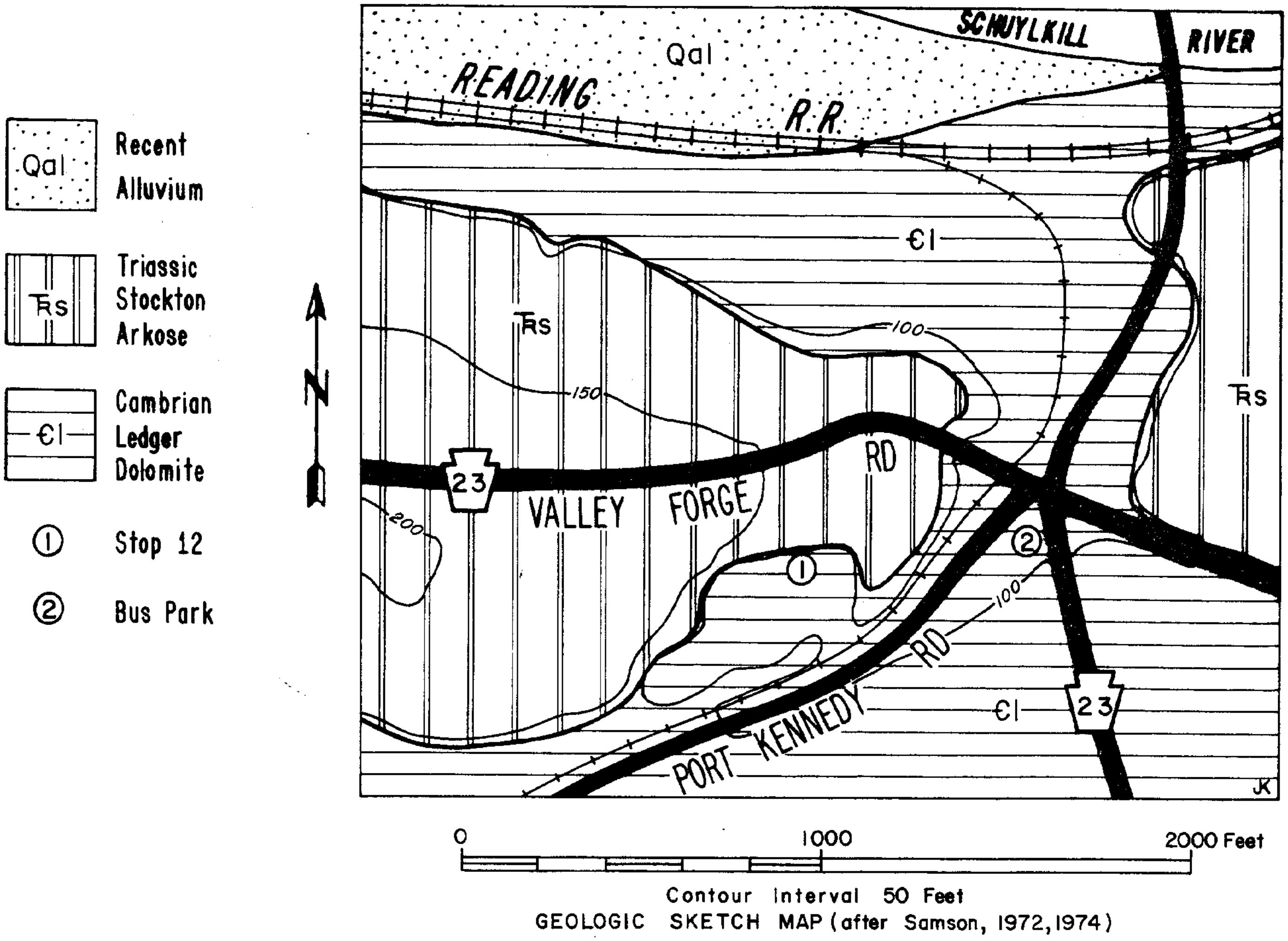


Figure 37. Detailed map of Stop 12, Port Kennedy Quarry.

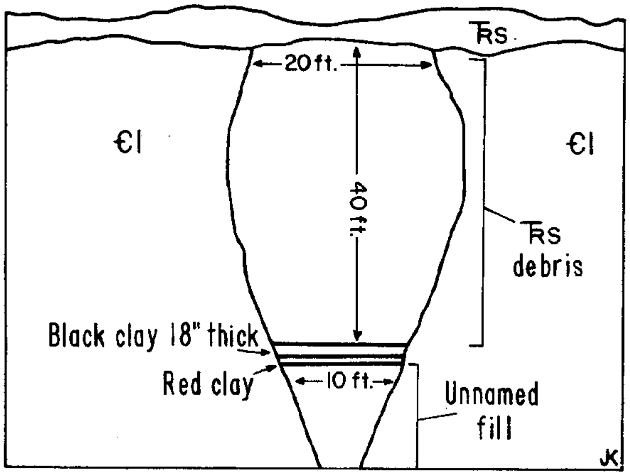


Figure 38. Vertical Section of Port Kennedy Bone Cave, after Wheatley, 1871

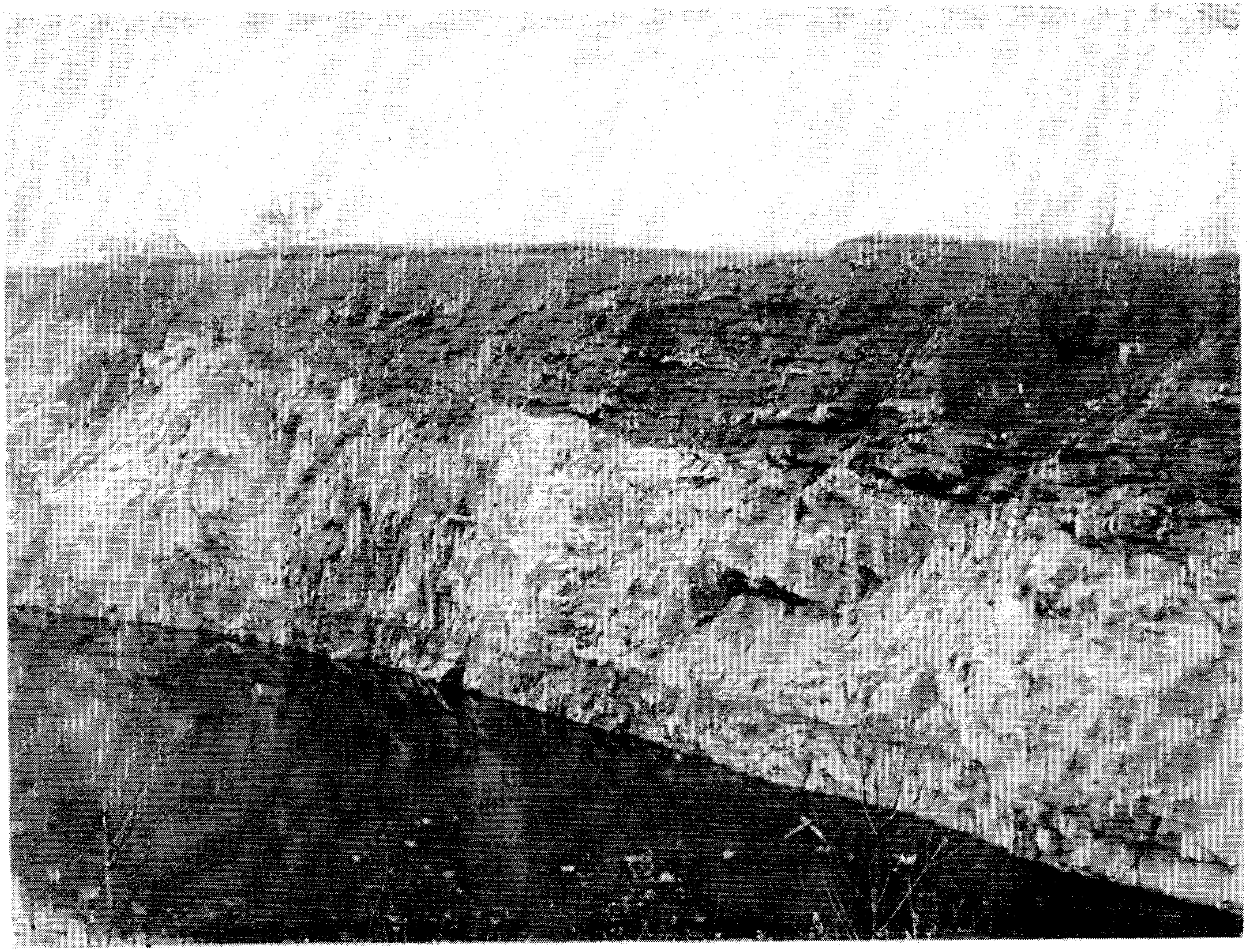


Figure 39. Photograph of Port Kennedy Quarry at the turn of the century.

from injuring themselves. Now the exact site is lost. A display of selected specimens is on exhibit in the Geology Department, Bryn Mawr College. The remainder of the collection is housed at the Academy of Natural Sciences, Philadelphia, Pennsylvania.

STOP 12 TO MOTEL

55.1 Turn right onto Pa. 23

55.4 Pa. 23 turns to the left. Continue straight ahead on Pa. 363 South which becomes North Gulph Road further on.

57.0 Turn left onto I-76 (Schuylkill Expressway) to Philadelphia.

57.3 Exit right at Exit 35 South (U.S. 202 South).

57.6 Follow signs to Warner Road. Keep right. Enter motel.

APPENDIX

Stop Locations

For the convenience of future users of this Guidebook, the following list of Field Trip Stops is presented with their county, 7½' quadrangle and 15' quadrangle locations.

STOP	7½' QUADRANGLE	15' QUADRANGLE	COUNTY
1. Landfill	Norristown	Norristown	Montgomery
2. Dove Lake	Norristown	Norristown	Montgomery
3. Gladwyne Interchange	Norristown	Norristown	Montgomery
4. Strawberry Bridge	Philadelphia	Philadelphia	Philadelphia
5. Wise's Mill Road	Germantown	Germantown	Philadelphia
6. Bell's Mill Road	Germantown	Germantown	Philadelphia
7. Sinkholes	Norristown	Norristown	Montgomery
8. Mid-County Expressway	Norristown	Norristown	Montgomery
9. Young's Ford Road	Norristown	Norristown	Montgomery
10. Glen Mills Quarry	Media	Chester	Delaware
11. Malvern	Valley Forge	Norristown	Chester
12. Valley Forge	Valley Forge	Norristown	Montgomery

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