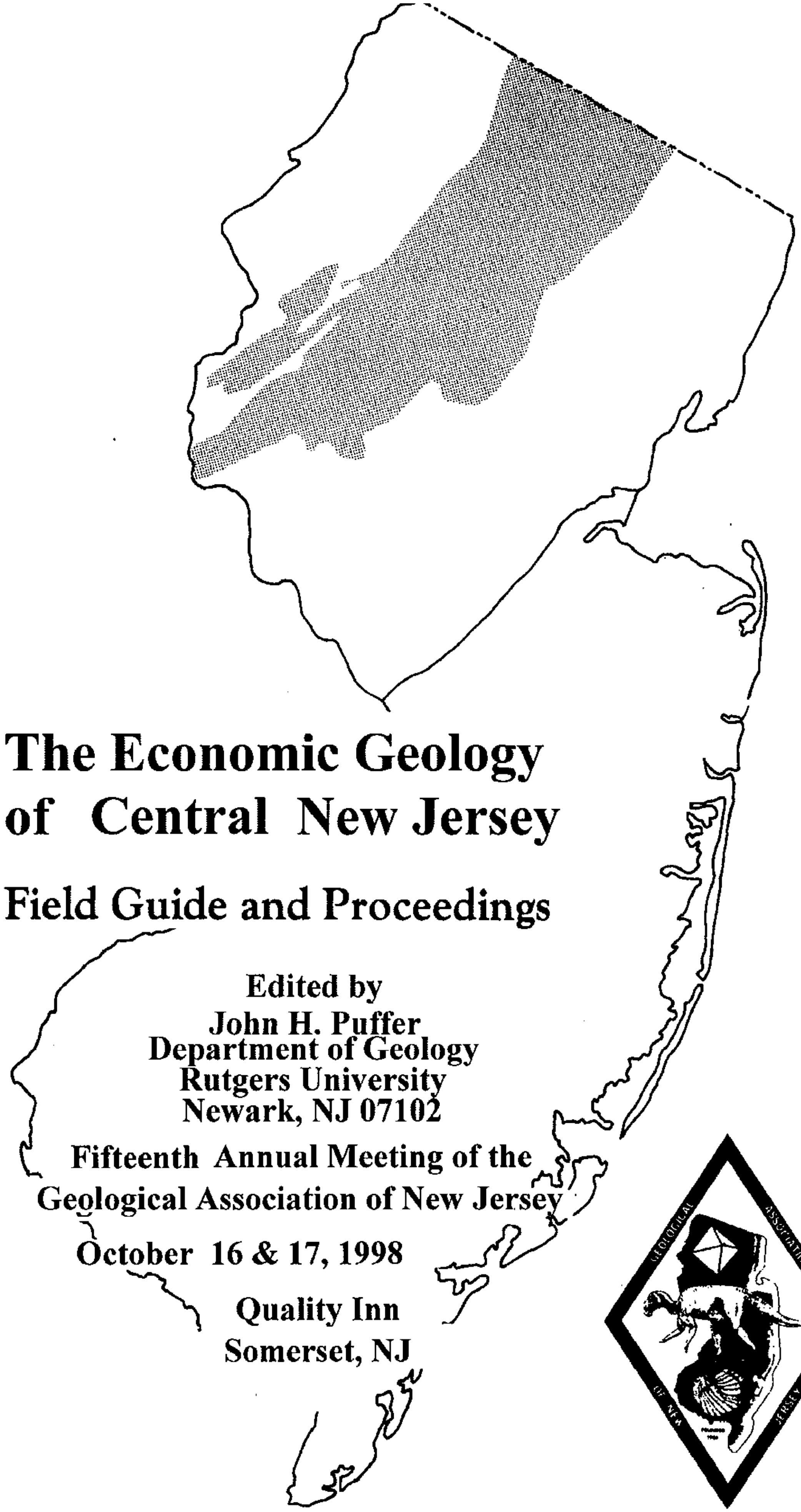

The Economic Geology of Central New Jersey

Field Guide and Proceedings

Edited by
John H. Puffer
Department of Geology
Rutgers University
Newark, NJ 07102

Fifteenth Annual Meeting of the
Geological Association of New Jersey
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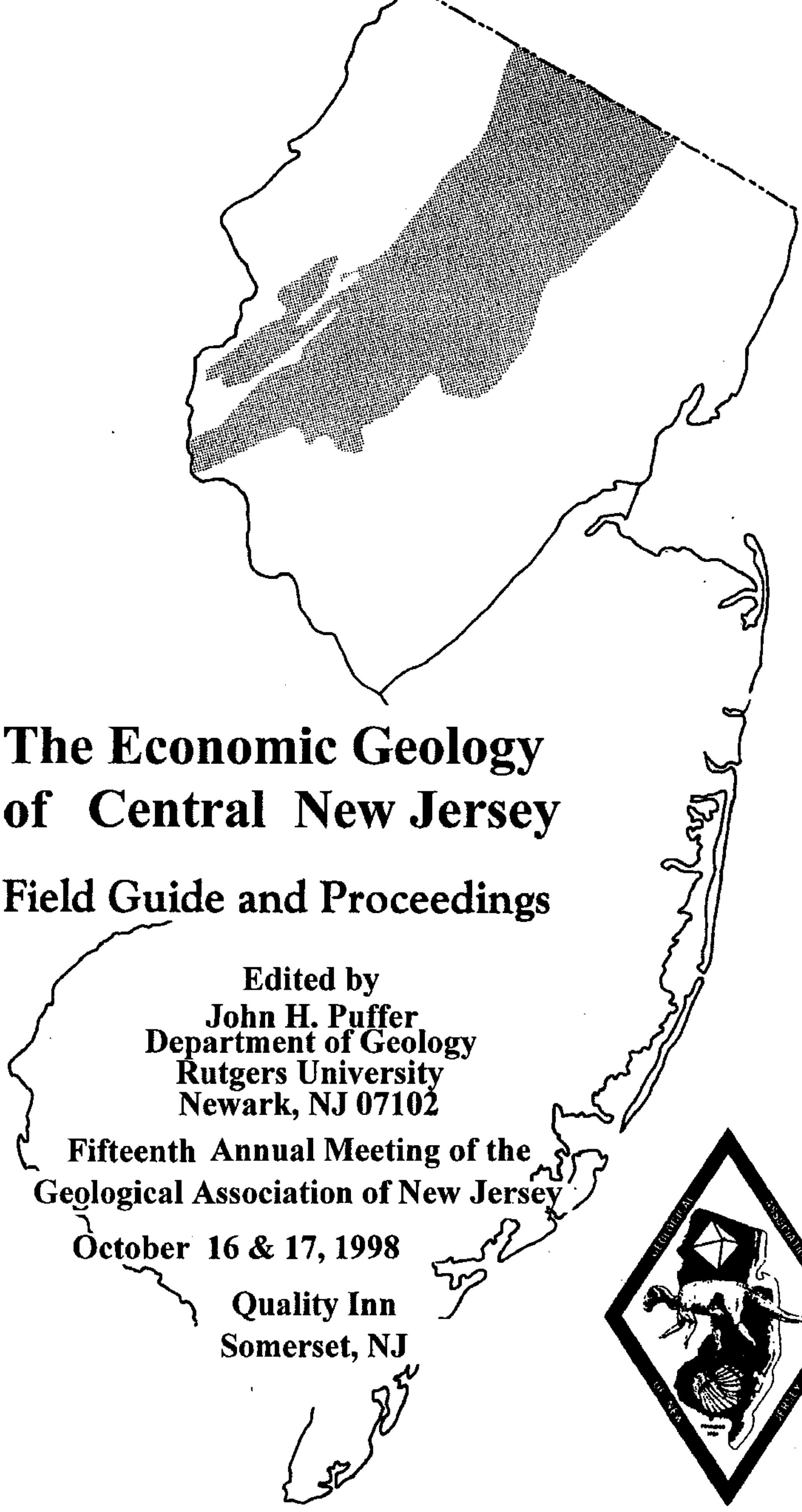

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Fourteenth Annual Meeting - 1997
Benimoff, Alan I. and Puffer, John H., 1997, *The Economic Geology of Northern New Jersey.*

FOREWORD

The 1998 Geological Association of New Jersey (GANJ) meeting will focus on the Economic Geology of Central New Jersey as a follow-up to last years theme the "Economic Geology of Northern New Jersey". The mining activity of central New Jersey includes a variety of resources of historic and current importance including trap-rock, clay, titanium, copper, and iron. The New Jersey Geological Survey has played a role in the development of each of these ores. We are, therefore, fortunate to have Richard Dalton as the speaker at the Conference Dinner Banquet this year. He will describe some of the more important ore deposits that have been mined in New Jersey and the way that he and the New Jersey Geological Survey was involved.

This year's Friday evening speakers will include:

John Puffer who will offer some new ideas pertaining to the origin of the historic copper mines in the Mesozoic rocks of the Newark Basin. John Puffer will also speculate about the origin of the titanium deposits of the Lakehurst area of New Jersey.

Warren Cummings will review the trap rock mines in the Mesozoic basalts and diabase and will talk about a copper occurrence at the Chimney Rock quarry;

Victoria Hover will review the clay industry of central New Jersey, particularly the clays of the Raritan Formation exposed near Sayreville.

Steven Laney will talk about a diabase quarry near Belle Mead and will focus on the structural aspects of the intrusion.

This year's Saturday field trip stops will include:

1. An active trap-rock quarry in a Mesozoic diabase intrusion exposed near Belle Mead.
2. Historic bog iron deposits exposed in the Sayreville area
3. Historic clay pits exposed in the Sayreville area
4. An active trap-rock quarry in the Hook Mountain Basalt Formation near Millington.

These four stops will fill our day with economic geology, although we are disappointed that we were not granted an opportunity to visit any of the more interesting titanium or copper mines in the state. We sincerely thank each of the property owners that let us visit their sites.

Next year's (1999 GANJ) meeting will be a major event. We plan to take on a topic that involves considerable controversy and current interest. We plan to examine the **New Jersey Beach Protection and Restoration** issue from a geologic prospective. Each of the leading experts that are researching New Jersey beaches will be invited to participate and volunteer contributions are also encouraged. If any of you would like to participate or know of an appropriate contributor please let me know.

Dr. John H. Puffer
Dept. of Geological Sciences
Rutgers University
Newark, N.J. 07102

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TEACHERS WORKSHOP

DEDICATION
THE CONTRIBUTIONS OF DR. CHARLES B. SCLAR AND HIS GRADUATE STUDENTS

Alan I. Benimoff
The College of Staten Island
Department of Applied Sciences
Staten Island, NY 10314

This Volume is dedicated to Dr. Charles B. Sclar of Lehigh University and his graduate students who in the period 1973-1990 carried out modern geochemical, electron optical, and phase-equilibrium studies on mineral deposits in New Jersey including the ores of Sussex County(Sterling Hill) , titanium -rich black sands near Lackhurst, NJ and iron ores of the Oxford, NJ area. The principal tools they used were analytical electron microscopy and quantitative electron microprobe analysis. The use rate costs for the instrumentation were supported in part by grants from the New Jersey Geological survey through the office of Kemble Widmer. Copies of all the student theses based on this work were deposited in the files of the New Jersey Geological Survey. The work on the Iron Ores of the Oxford area was strongly supported in terms of field mapping by the U.S. Geological Survey through the office of the then Eastern regional Geologist Avery A. Drake. The graduate students who carried out their thesis research on mineral deposits in New Jersey included the following:Anthony Carvallo III, Robert Kastellic, Joanne Meglio-Mathis, Frank Sine,Samuel Squiller,Albert Valentino.

Dr. Charles B. Sclar was born in Newark, N. J., and, until he was ten years old, lived in Bayonne, N. J. at which point his family moved to Long Island. He received the B.S. degree in geology from CCNY, where he was a Ward Medalist, and the M.S. and Ph.D. degrees in geology from Yale University where he was a James Dwight Dana Fellow and a William E. Ford Scholar. His graduate work was focussed on igneous and metamorphic petrology and genetic aspects of ore deposits. Following two years as an instructor in the Department of Geology at The Ohio State University, he joined the staff of the Battelle Memorial Institute in Columbus, Ohio as Research Mineralogist in the Minerals Processing Division where he worked on applied mineral-development problems (now known as process mineralogy) and traveled widely on projects for the mineral industry. In 1959 he joined the newly formed high-pressure laboratory in the Physics Department at Battelle where he worked on the synthesis of pressure-dependent phases and on pressure dependent phase transformations in systems of geological and geophysical significance. When he left Battelle in 1968 he was an Associate Division Chief and Director of the High-pressure Laboratory. In 1968 he was appointed Professor in the Department of Geological Sciences at Lehigh University where he established a high-pressure laboratory dedicated to geological and geophysical research. He served as Department Chairman from 1976 to 1985. From 1969-1978 he was a Principal Investigator for NASA on all the Apollo Missions to the Moon (11,12,14-17) for which he studied the returned lunar rocks for evidence of shock-wave damage r-elated to meteoritic impacts on the lunar surface and carried out related shock-wave experiments on candidate minerals. During 22 years on the faculty at Lehigh University, he was the principal advisor for the dissertations of 10 doctoral candidates and the principal advisor for the theses of 21 M. S. candidates. He became Professor Emeritus in 1990, but, in "retirement", he continues to carry out mineralogical and petrological research and publish the results of his research.

MINERAL PRODUCTION IN THE NEWARK BASIN AND COASTAL PLAIN

David P. Harper
New Jersey Department of Environmental Protection
Bureau of Underground Storage Tanks
P.O. Box 433, Trenton, NJ 08534

The Newark Basin and Coastal Plain have long histories of mineral production. The Newark Basin saw some of the earliest Colonial copper mining. The Coastal Plain produced some of the earliest bog iron and glass sand. The bog iron was smelted using local charcoal and calcium carbonate from shells from seafood houses and Indian middens. The industry had developed before the Revolutionary War and was a significant asset to the Continental army. New Jersey schoolchildren are routinely told of the cannonballs produced at Batsto in southern New Jersey. Cannonballs were produced, but were minor in number and importance, if not in drama, in comparison with horseshoes, nails, cooking kettles, shovels, chain, and other Batsto products needed by the army.

The first profitable glass works in the English colonies opened in 1735 on Alloway Creek. Glass making has continued its importance in southern New Jersey to the present. In addition to glass, the silica sand of southern New Jersey, over 99 percent quartz, is used for metal casting and is ground to a powder used for making silica gel, cosmetics, and polish.

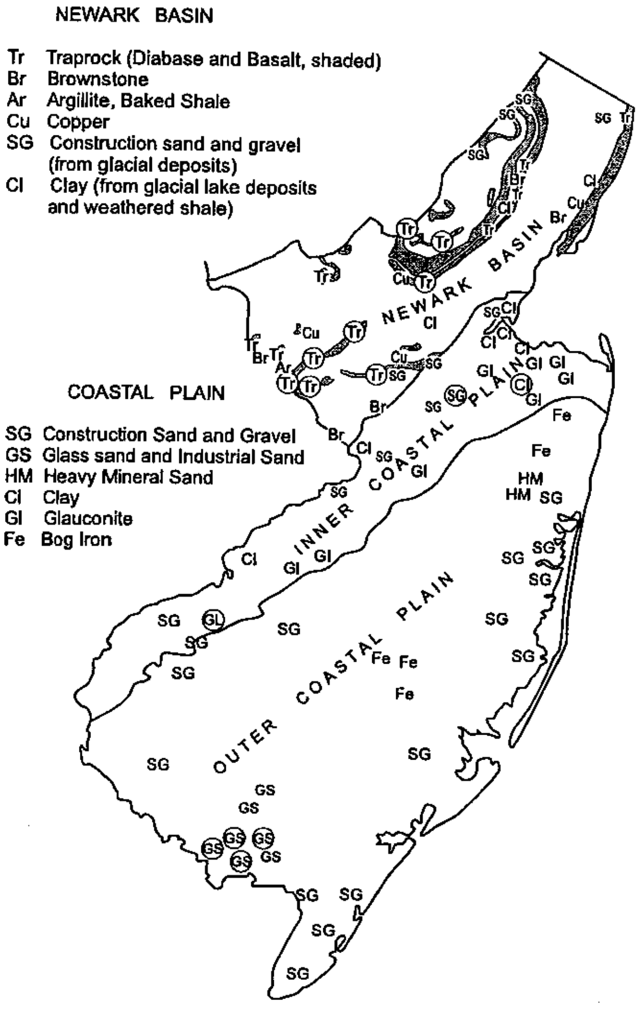
In the nineteenth century, bog iron and copper mining died out, but brownstone from the Newark Basin and clay and glauconite from the Coastal Plain came to be important. Brownstone, sometimes regarded as the state rock of New Jersey, was early on recognized the best building stone in the Delaware Valley, and was chosen for Nassau Hall at Princeton University. When completed in 1756 it was the largest building in the colonies. In the first half of the 19th century, thousands of tons of brownstone were shipped each year from quarries along the canals and rivers of New Jersey. The largest quarries, in the Belleville area near Newark, shipped more brownstone for building fronts than any other source in the country.

Like the brownstone quarries, New Jersey's largest clay pits were opened convenient to water transportation, particularly in Coastal Plain formations along the Raritan River and Raritan Bay. In time, these pits came to support some of the nation's largest ceramic works and brick yards. Brick clay was also dug in the Newark Basin from weathered shale and glacial lake deposits. Fresher shale was mixed as sizing with Coastal Plain clays for making ceramic water and sewer piping. A relatively small amount of clay is still dug each year in New Jersey, primarily for landfill cover.

“Greensand marl” is a local term for a continental shelf sediment variously including glauconite, quartz sand, silt, detrital mica, shell, and phosphatic nodules. Potassium from the glauconite together with lime, clay, phosphate and trace elements made the material an effective soil conditioner, and it was being used by the early 1700s to enrich the sandy soils of southern New Jersey. By the 1860s hundreds of thousands of tons were being dug each year. About 1920, long after the use of greensand marl as a soil conditioner had been superceded by artificial fertilizers, glauconite was found to be an effective ion exchange medium for treating hard water. For many years, the only glauconite mining operation in the United States has been the Inversand Pit in Sewell, Gloucester County. The glauconite is used for water treatment and, in lesser quantity, gardening.

The largest New Jersey mineral industries in tonnage, value, and employment are construction sand and gravel and crushed stone. Both are multi-million-dollar industries essential to New Jersey's economic health. Roughly 15 million tons of construction sand and gravel production, worth over 100 million dollars, is dug each year from dozens of pits on the Coastal Plain and a smaller number of pits in glacial deposits of the Newark Basin. A dozen or so traprock quarries produce roughly 10 million tons of crushed stone, worth about $80 million dollars, per year. Of the traprock features of New Jersey, the Palisades cliffs along the Hudson River are probably the best known. With their volume of rock and access to water transport, the Palisades might have been enormously profitable for quarrying. Fortunately, when stone quarries began expanding rapidly in the 1890s, citizen action led to public purchase of land for a park from Fort Lee, New Jersey to Piermont, New York.

MINERAL PRODUCTION SITES
(active operations circled)



In contrast to most New Jersey mineral deposits, which have been recognized for over two centuries, Miocene coastal deposits in the Lakehurst area of Ocean County were discovered in the late 1950s to have enough ilmenite (a dark-colored, heavy titanium mineral) for mining. (Black sand layers are common on New Jersey beaches and are sometimes mistaken for waste product. The layers consist mostly of ilmenite.) Ilmenite was mined from 1962 through the 1970s. In the 1980s the pits were re-opened for a few years to recover zirconium and titanium minerals (other than ilmenite) which had been concentrated in the process of separating ilmenite from quartz, then discarded.

While mineral production in any heavily developed area is contentious, the need for reasonably priced construction material favors continued New Jersey mineral production. Future New Jersey prospects include offshore sand for construction and beach replenishment and offshore heavy minerals. Natural gas was found in 1978 in drilling to over 17,000 feet in the Baltimore Canyon Trough, between 40 and 80 miles offshore, but not in sufficient quantities for immediate development.

THE PETROLOGY, GEOCHEMISTRY AND STRUCTURAL SETTING OF DIKES AND VEINS IN THE LAMBERTVILLE SILL AT THE 3M QUARRY, BELLE MEAD, NEW JERSEY

Stephen E. Laney
HYDRO-GEO CORPORATION
428 Sunset Road
Skillman, NJ 08558

Dr. Jonathan M. Husch
Dept. of Geological and Marine Sciences
RIDER UNIVERSITY
2083 Lawrenceville Road
Lawrenceville, NJ 08648

ABSTRACT

Oligoclase-rich pegmatitic dikes and zoned veins with amphibole cores and alteration halos occur in early formed fractures in the Jurassic Lambertville sill exposed in the 3M diabase quarry near Belle Mead, New Jersey. Hydrothermal veins of mainly calcite and quartz also occur but are unrelated to the older intrusive events. Geochemical data from pegmatite dikes with sharp contacts and minor wall rock alteration indicate a possible xenolith anatexic origin for these rocks. Geochemical data from younger zoned veins with alteration halos indicate a possible granophyric origin as a fractionation product of the parent magma. Other data indicate a mixing of these two genetic end members forming a third rock type. Zoned veins are twice as common as magmatic dikes.

Three fracturing events are mapped in the quarry. The earliest event formed NW and E-W striking fractures related to the rapid downwarping of the interior of the Newark basin. The magmatic dikes are associated primarily with the NNW-striking fractures and the zoned veins with both orientations. The second event formed SE-dipping fractures related to regional basin extension and accompanying hydrothermal activity. The third event involved dextral strike-slip faulting. The first and second events were non-coaxial and the second and third events were coaxial. There has been a counter-clockwise rotation of the maximum extension direction during deformation.

INTRODUCTION

Thin, leucocratic magmatic dikes and veins commonly intrude many Early Jurassic diabase sheets of the Eastern North America (ENA) Magmatic Province (Shannon, 1924; F. Walker, 1940, 1953; Robinson, 1988; Benimoff and others, 1989; Benimoff and Sclar, 1990). The origin and relative timing of emplacement of these dikes and veins add an important constraint to the overall petrogenesis of the sheets.

The Lambertville sill is one of eight major exposures of Early Jurassic diabase in the central Newark basin, New Jersey (Fig. 1). Because of structural and compositional similarities, the Lambertville sill and nearby Rocky Hill diabase are believed to be lateral extensions of the Palisades sill (Husch, 1990; 1992). Thus, the findings and conclusions presented in this paper have implications for the petrogenesis of similar magmatic dikes in the Palisades sill of the northern Newark basin (Benimoff

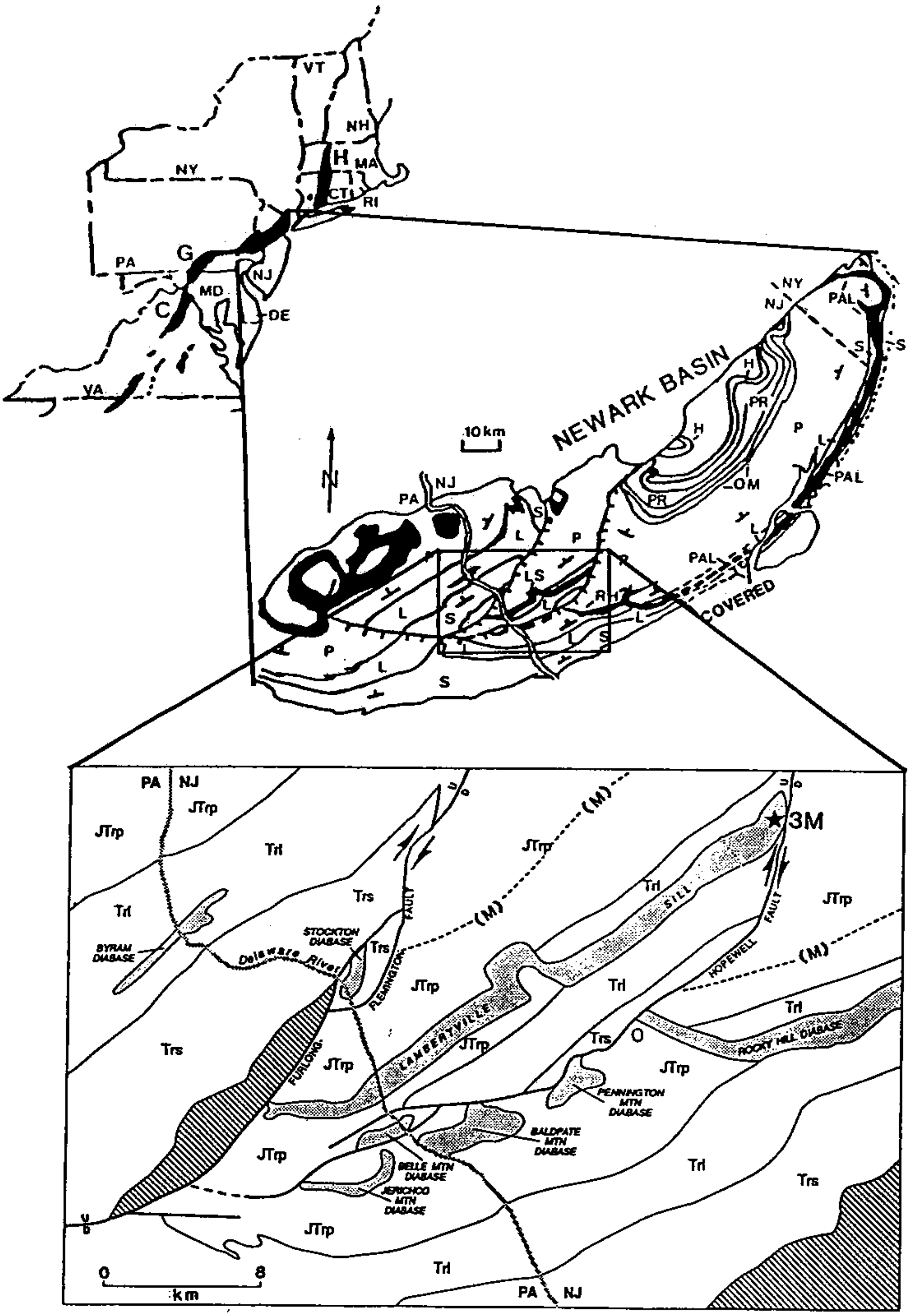


Figure 1. The top inset figure shows the eastern North American Mesozoic rift system and the location of the Newark basin. C= Culpeper basin; G= Gettysburg basin; H= Hartford basin. The middle inset figure is a simplified geologic map of the Newark basin. The darkened areas in the Newark basin are diabase sheets. The fault systems represented are the Hopewell and Flemington-Furlong-Chalfont, with the teeth on the hanging wall. The strikes and dips represent the orientations of the Upper Triassic sedimentary rocks. The rectangular area enlarged as the lower figure is a geologic map of the general study area. The star shows the location of the 3M quarry (Lat. 40° 27.5' N, Long. 74° 43' W). LS= Lambertville sill; RH= Rocky Hill diabase; PAL= Palisades diabase; S, Trs= Stockton Formation; L, Trl = Lockatong Formation; P, JTrp =Passaic Formation; (M)= Metlars Member, Passaic Formation; OM= Orange Mountain Basalt; PR= Preakness Basalt; H= Hook Mountain Basalt (Modified from Husch, 1992).

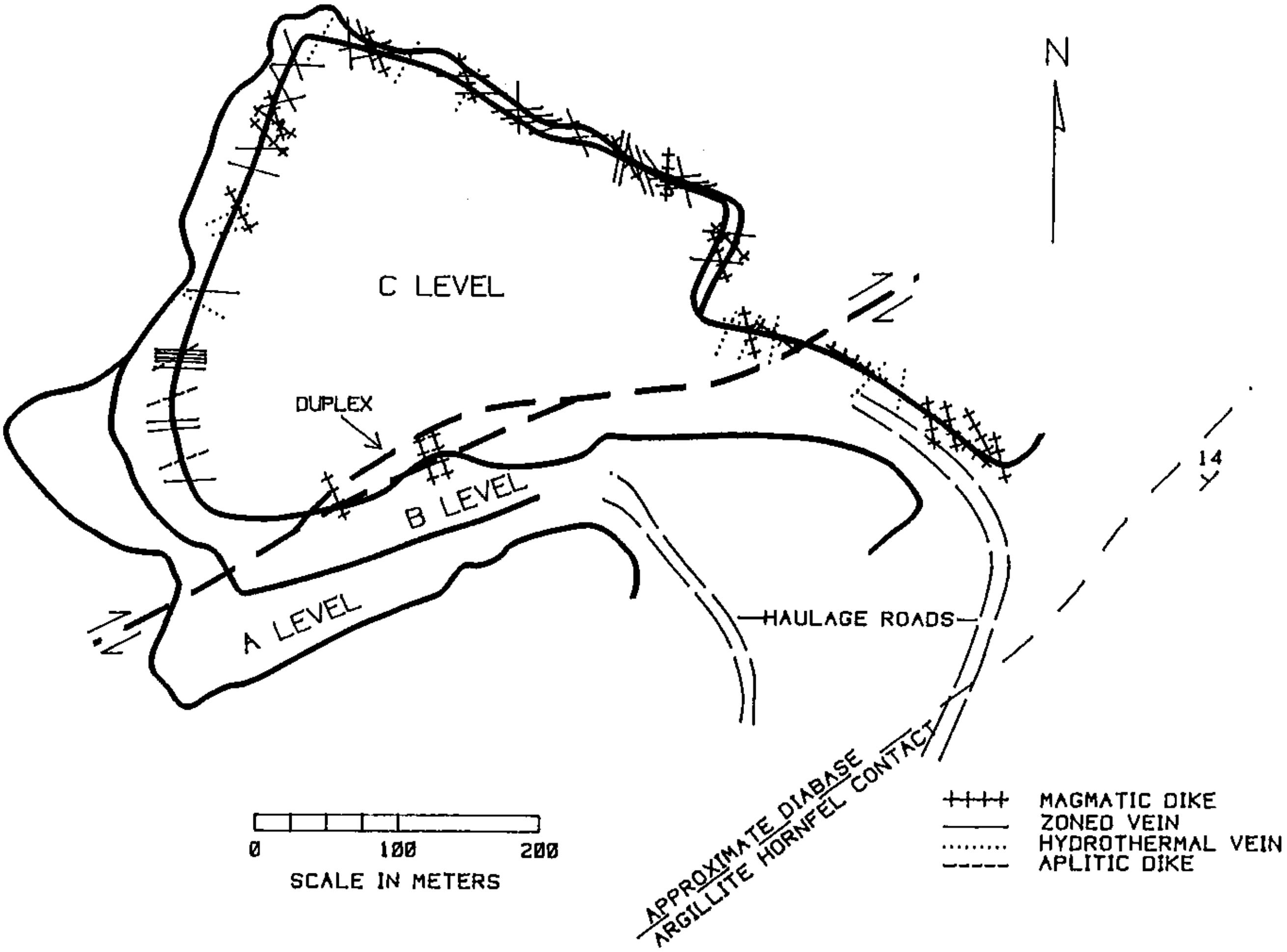


Figure 2. 3M mine plan showing three mining levels (A, B, and C - from top to bottom). The trace of the 3M dextral fault and duplex is shown oriented NE-SW. The approximate contact between the diabase and argillite hornfels is shown having an average dip of N14W. The distribution of the different dike and vein types are presented symbolically. The strikes of the early-formed pegmatitic (NW) and aplitic dikes are shown as pluses and dashes respectively. The strikes of the later-formed zoned veins (W and NNW) and hydrothermal veins (NE) are shown as solid lines and dots respectively. Detailed mapping did not include the south wall of the quarry although the dike/vein distribution did not appear to change during general reconnaissance.

and others, 1989; Benimoff and Sclar, 1990) and for the overall structural evolution of the Newark basin (Schlische, 1992).

This paper presents the results of a study on the petrology, geochemistry, and structural relationships of late-stage dikes and veins located at the northeast end of the Lambertville sill. The study investigates whether the dike and vein magmas were derived from granophyric melts produced by the fractionation of the diabase magma or from relatively undifferentiated melts generated by the anatexis of country rock. It also investigates whether the zoned veins formed penecontemporaneously with and under the same stress regime as the magmatic dikes or were formed during a separate event.

Study Area

All structural data and whole-rock samples for this project were collected from fresh exposures in the 3M Belle Mead quarry, New Jersey (Figs. 1 and 2). The quarry is located within the Rocky Hill U.S.G.S. 7 1/2 minute quadrangle and approximately 8 km north of Princeton, New Jersey. The quarry is approximately 0.5 km^2 in area and consists of three levels, designated A, B, and C from top to bottom, each separated by 7-10 m of highwall (Fig. 2). The east side of the C level in the quarry is located ~85 m above the lower contact of the Lambertville sill with the underlying Lockatong Formation (Late Triassic); the sill is ~500 m thick. A major dextral fault (referred to here as the 3M fault) striking ~N60E is exposed in the quarry and is interpreted as a splinter fault of the Hopewell fault, located approximately 1 km southeast of the quarry (Fig. 1). The Hopewell fault strikes N5-10E in the study area, dips moderately east, and occurs at the base of the Sourland Mountain escarpment (Parker and Houghton, 1990). The quarry is located on top of this escarpment.

GEOLOGIC AND STRUCTURAL SETTING OF THE NEWARK BASIN

The Newark basin is one of a series of rift basins that parallels the east coast of North America from New Brunswick, Canada, to Georgia. These basins formed as the result of the breakup of Pangea during the Late Triassic-Early Jurassic (175-230 Ma; Cornet and Olsen, 1985; Klitgord and Schouten, 1986; Schlische and Olsen, 1990). The Newark basin is a half-graben filled with redbed deposits generally dipping 10-20° northwest consisting of mudstone, siltstone, sandstone, and conglomerate of continental alluvial fan/shallow lacustrine origin and argillite of deep lacustrine origin with interbedded tholeiitic basalts and diabases (Olsen, 1980; Olsen, 1986; Schlische, 1992).

Diabase Sheets

Several diabase sheets were intruded into the sedimentary rocks approximately 201 Ma (Sutter, 1988; Dunning and Hodych, 1990). The eastern-most example of the diabase sheets is the Palisades sill, which together with the Rocky Hill diabase and the Lambertville sill, make up the 150 km long PRHL megasheet (Husch, 1992). Petrographic, structural, and geochemical data indicate a common overall petrogenesis for the diabase sheets (Husch, 1992). Regional chill-margin compositions are constant and are typical ENA high-titanium, quartz normative tholeiites (HTQ).

Various fractionation models (Husch and others, 1988; Husch, 1992; Steiner and others, 1992) show that the early differentiation of the HTQ parent was dominated by the removal of MgO-rich clinopyroxene, followed by plagioclase removal, then by Fe-Ti oxide and apatite with little or no olivine fractionation. Parker and Houghton (1990) mapped the diabase in the vicinity of the 3M quarry as being within a cumulate zone rich in orthopyroxenes. Husch (1992) estimates that large masses of residual granophyric compositions were produced by 70%-80% total crystallization with little or no contribution from large-scale crustal anatexis. Husch (1992) and Keely and Husch (1993) show that low-density residual, granophyric magmas are displaced both laterally and up-dip within an individual sheet, with the largest masses of granophyre often concentrated at the sheet's highest structural level.

Dikes

Early studies assumed that the leucocratic, late-stage magmatic dikes injected into the diabase sheets were derived from the residual granophyric magmas produced by crystal fractionation and depleted in alkali feldspars (F. Walker, 1940) or from a hydrothermal origin (K. Walker, 1969). Alternatively, Benimoff and others (1989) and Benimoff and Sclar (1990) propose that some of the dikes are produced by local anatexis of country rock xenoliths fused by the heat of the magma. Benimoff and Sclar (1984) described an exposed slab of Lockatong Formation included within the Palisades sill on Staten Island, New York. Surrounding the xenolith is a mantle of trondhjemite that they considered to be immiscible with the adjacent HTQ magma. Ion exchange took place across the melt/melt boundary resulting in the localized enrichment of the adjacent diabase magma in alkali (Na, Ba, and Rb) and depletion in Ca and possibly Mg and Fe (Benimoff and Sclar, 1984; Husch and Schwimmer, 1985).

Benimoff and others (1989) and Benimoff and Sclar (1990) noted that the xenolith melt and magmatic dike compositions were very similar, particularly in their extremely low K_2O/Na_2O values (typically <0.05). They concluded that the dike melts originated by the anatexis of unexposed xenoliths and then were injected into cooling fractures after the diabase had solidified. Similar rare earth element (REE) contents of the dike and anatectic melts (Benimoff and Sclar, 1992) and the highly sodic composition of clearly anatectic melts located immediately below the Orange Mountain Basalt (Puffer and others, 1993) support this scenario.

Veins

F. Walker (1940) and K. Walker (1969) describes zones of hydrothermally altered diabase near the top of the Palisades sill having sinuous fractures with sericitized and uralitized walls up to 1 cm thick, calcite-bearing veins in the upper levels of the sheet, and hydrothermal "residual veins" up to 3 cm wide in both the lower and upper contact regions. Hydrothermal veins are described as aplitic, sinuous, and containing turbid oligoclase, quartz, analcite, and minor diopside, clinozoisite, sphene, calcite, sericite, chlorite, and opaques.

Robinson (1988) reports diabase-hosted hydrothermal vein metal deposits in the Newark, Gettysburg, and Culpeper basins, which are typically associated with diabase pegmatite or granophyric dikes and commonly in shear zones. The diabase adjacent to the veins are "bleached" with zoned alteration halos. The veins contain chlorite, epidote, datolite, prehnite, calcite, various zeolites, magnetite, pyrite, clinopyroxenes, and secondary copper minerals (Puffer & Peters, 1974).

Laney (1992) described a vein of calcite and fluorite with minor chalcopyrite and opal within a shear zone in the Rocky Hill diabase near Kingston, New Jersey. He concluded that the vein was not penecontemporaneous with the diabase but was formed during a later (~175-165 ma) hydrothermal event associated with the opening of the Atlantic Ocean (Robinson and Woodruff, 1988). Recent fission track data reported by Steckler and others (1993) support a pervasive, relatively high temperature (100-250°C) hydrothermal system operating within the Newark basin until the Mid to Late Jurassic.

Basin Faulting

The Flemington and the Hopewell faults, two major intrabasinal faults, occurring in the basin (Figure 1),. are both considered to have undergone dip-slip and strike-slip movement. Schlische and Olsen (1988) interpret both faults to have developed late in the history of the basin to accommodate regional extension. The Hopewell fault developed after the Lambertville sill was intruded, giving a post-201 Ma timing to intrabasinal faulting.

Burton and Ratcliffe (1985a; 1985b) reported right lateral movement on the Flemington fault and Ratcliffe and Burton (1985, 1988) show the fault as a braided zone. Houghton and others (1992) report that the Flemington fault is a component fault within a braided system of branch and splay faults with up to 3100 m of dip-slip displacement on the main fault, less than 600 m on splay faults, and right lateral slip indicators throughout the system.

Sanders (1962; 1963) described 3000 m of dip-slip displacement and up to 20 km of right-lateral displacement on the Hopewell fault. Jones and Schlische (1993) report 2-3 km of dip separation on a predominantly normal fault for the Hopewell fault. Sinistral and dextral faulting was described by Klewsaat and Gates (1994) for the portion of the PRHL megasheet buried beneath Cretaceous and younger Coastal Plain sediments. Ratcliffe and Burton (1985) interpreted the strike-slip senses on the segments of the Ramapo border fault and the intrabasinal faults as the result of the orientation of the fault to the early Mesozoic extension direction (southeast). Fault segments oriented N-S in this stress field had right-lateral slip, whereas those oriented E-W had left-lateral slip.

Schlische and Olsen (1988) estimated the regional extension direction to be ESE, a direction normal to the average strike of Early Jurassic diabase dikes in the basin. They described the basin as a giant synform plunging northwest and having extensional fractures formed parallel with the synclinal hinge (striking northwest). Schlische (1992) described a regional orthogonal fracture system composed of near vertical northeast-striking faults related to the regional NW-SE extension direction (Pangea rifting) and northwest-striking fractures related to local extension developed by the downwarping of the basin. No temporal sequence for the fracturing was given.

PETROLOGY

Diabase at the 3M quarry is pyroxene rich and occurs in a cumulate zone within the Lambertville sill (Husch and others, 1988; Parker and Houghton, 1990). The diabase is relatively unaltered except in the proximity of veins and hydrothermal zones. Fresh diabase consists of plagioclase (An_{65-70}), augite, hypersthene, diopside, pigeonite, bronzite, chlorite, quartz, minor biotite, chalcopyrite, and magnetite. Other minerals observed with the diabase include rare prehnite, pectolite, stilbite, calcite, and datolite.

Three types of dikes and veins are associated with the diabase. These include pegmatitic dikes with relatively sharp contacts, zoned veins having gradational contacts and an internal amphibole-rich core (hereafter called amphibolite), and hydrothermal veins with associated alteration. Figure 2 shows the relative distribution and orientation of the dikes and veins on the C level.

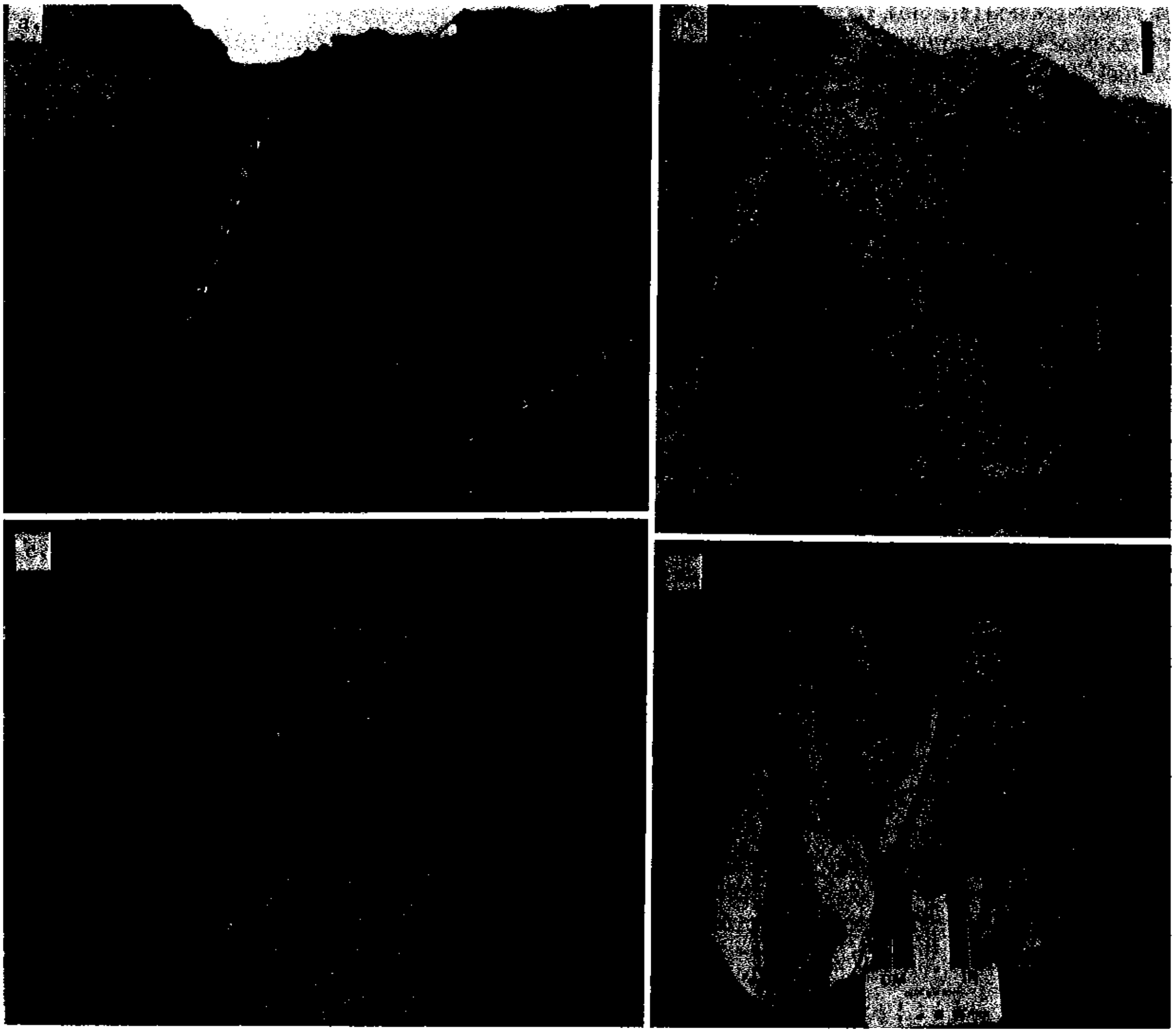


Figure 3. Photographs. a) View of contractional duplex in 3M fault looking south. Duplex is oriented NE-SW. Dashed lines show locations of bounding faults. Scale bar = 2 m; b) View of pegmatite dike in northwest corner of quarry looking northwest. Scale bar = 1 m; c) Pegmatite dike showing sharp contact with diabase; d) Zoned veins with actinolite core.

Magmatic Dikes

Structural data indicates that the oldest intrusives into the Lambertville sill are leucocratic, phaneritic dikes having a relatively sharp contact with diabase and little internal zonation. These dikes commonly are planar, subvertical and generally strike northwest. Dike thicknesses range from 1-2 cm to 1.3 m (Fig. 4b) with an average 3-4 cm size. Thin dikes preserved on joint surfaces appear as a white face composed of feldspar with patches of pyroxene 10-15 cm in diameter resulting in a "leopard rock" texture. The pyroxenes in the patches commonly are augite crystals (2-5 mm) in shallow miarolitic cavities with quartz, feldspar, and actinolite of similar size.

Megascopically, the thicker dikes have a pegmatitic texture with a smaller grain size adjacent to a sharp contact with the diabase and coarser grained toward the interior (Fig. 4c). Pyroxenes are more abundant near the diabase with many crystallized at high angles to the contact. The interior of the dike is dominated by feldspar with randomly oriented laths of greenish black pyroxenes. Accessory minerals are anhedral quartz, sphene, apatite, and epidote. Rare miarolitic cavities up to 3 cm in diameter occur within the thicker dikes and contain central vitreous, acicular actinolite sprays surrounded by yellow-green acicular epidote on white terminated feldspars. The minerals were identified using x-ray diffraction (XRD).

Petrographically, the contact with the diabase is abrupt and jagged. Feldspars are slightly altered and clinopyroxenes are very altered in the diabase adjacent to and within 1-2 cm of the dikes. Large, euhedral orthopyroxene and anhedral quartz increase in the diabase as the contact is approached. The magmatic dikes vary in the percentage of mafic minerals present from 30-40% to less than 5% (albitite). Mafics consists dominantly of actinolite in needles and blades 1-2 cm in length. Generally, the greater the mafic content, the more euhedral apatite present. Most clinopyroxenes are partially altered to amphibole (uralitization; actinolite rims around augite cores). Feldspars (0.5-3.0 cm) consist of predominantly oligoclase ($An_{25\text{-}35}$) and microcline. Feldpars are perthitic, granoblastic, commonly show a graphic (exsolution) texture, and are all moderately sericitized and/or sausseritized, with minor granophyric textures. Minor anhedral quartz and euhedral sphene and apatite crystals are present. Sphene occurs in all dike samples investigated as wedges 1-5 mm in length (modal 1-2%). Corroded opaques as rods and blebs of possibly ilmenite and rutile are present. Opaques are more abundant near the contact with the diabase as dendrites between crystals.

Typical magmatic dikes are represented by rock samples 3M923, 3M924, 3M92C11, 3M92A2, and 3M92C8. Most of these samples have Group 1 geochemical characteristics.

Zoned Veins

Cross-cutting relations indicate that the zoned veins are generally younger than the magmatic dikes and are nearly twice as abundant. Zoned veins typically dip 70-80° south, with a subsidiary near-vertical set striking NNW. These veins are more common on the west side of the quarry toward the top of the sill. Zoned veins average 2-3 cm in thickness although veins up to 0.5 m were observed in boulders. Most veins are subplanar but many are sinuous, bifurcate, and anastomose subparallel to fracture trends, and are less continuous than the dikes, tending to pinch and swell.

Megascopically, zoned veins consist of an inner olive-green core of amphibolite (nearly pure amphibole) between two outer bands of fine-grain feldspar (see Figures 4d and 7d). The feldspar is notably pyroxene depleted compared to the magmatic dikes. Thin selvages (2-5 mm) of amphibole also occur between the feldspar bands and the contact with altered diabase. The inner amphibolite core ranges from 0.5-3.0 cm in thickness and pinches and swells along its length. The amphibolite core was observed to pinch out completely resulting in the two feldspar bands merging into one band. The amphibole was identified as a solid solution series of ferro-actinolite and magnesium hornblende by x-ray diffraction. This core is compact and fibrous with overlapping mats and sprays of crystals and is nearly pure amphibole with rods and blebs of opaque minerals. The veins tend to split along the cores when broken. A band of reddish discoloration ending on the outer edges as a distinct iron-rich front extends on either side of the feldspar layers. Each alteration zone is approximately the same width as the composite feldspar-amphibole-feldspar vein.

Petrographically, the diabase adjacent to the vein is highly altered with alteration decreasing outward away from the vein. Diabase outside of the iron zone is relatively unaltered. Pyroxenes are uralitized to amphiboles and calcic feldspars are more sodic towards the vein. Large euhedral orthopyroxene and actinolite crystals along with opaques and anhedral quartz as blebs and stringers in microfractures increase toward the contact. There is a gradational contact between the diabase and the vein with a thin selvage of actinolite separating the two rock types.

The feldspar bands surrounding the central core are composed of slightly to moderately altered euhedral oligoclase (An_{30-40}) with albite/Carlsbad twinning. Microcline and perthite also are present. Feldspars are finer grained (5-10 mm) than the pegmatitic feldspars in the magmatic dikes. Accessory minerals include euhedral sphene (1-2%), anhedral quartz, actinolite, chlorite, and apatite. A less common rock type having a leucocratic, aplitic, sugary texture (albitite, 3M92C17A) is present in the southwest corner of the mine. This rock type contains 1-2 mm feldspar crystals (An_{25-35}) in an anhedral calcitic groundmass. Minor sphene and no quartz or mafic phases are present in this rock type.

Zoned veins are represented by samples 3M92C15, 3M926A1, and 3M92C9 (Table 1). More zoned veins have Group 2 geochemical affinities than the other two groups. Many intrusions are present that have characteristics of both dikes and veins. These typically consist of oligoclase with a lower percentage of pyroxenes, no actinolite cores, and a zone of alteration within an iron front extending into the diabase.

Hydrothermal Veins

In the north and west highwalls of Level C, eleven hydrothermal zones were mapped that generally dip steeply southeast. Hydrothermal zones are characterized by a bleached, clayey, quartz-flooded, and leached area from 0.2-2.0 m wide having calcitic crusts and/or green-black greasy chloritic scale. Most of these zones have central veins (2-4 cm thick) of coarse grained (1-2 cm), rhombohedral, translucent calcite associated with granular quartz. Calcite is more common than quartz. Calcite appears to be replacing the feldspar in a magmatic dike sample studied (3M92C11). The quartz is generally not well crystallized but a terminated milky quartz crystal approximately 30 cm long and 8 cm in diameter having a datolite rind approximately 2 cm thick was found in a mud seam in the quarry. Minor minerals associated with calcite and quartz include datolite (XRD), epidote, and chalcopyrite.

GEOCHEMISTRY

Analytical Methods

Major- and trace-element compositions for magmatic dikes, zoned veins and host diabase are presented in Table 1 (Coffee, 1993). All compositions were determined on an SMI direct current

Table 1. Whole rock analyses for diabase, dike and vein samples, 3M Quarry diabase

Sample #	3M92C15A	3M92C15B	3M92C10Z	3M92C18	3M926A2	3M926A3	3M923DB	3M927
SiO_2	52.10	52.50	51.60	52.20	52.10	51.80	52.40	51.20
TiO_2	0.92	1.02	0.59	0.99	0.85	0.88	0.95	0.85
Al_2O_3	14.50	13.90	15.40	12.80	12.30	12.40	12.40	12.10
FeO	9.54	10.20	8.66	9.72	9.53	9.69	9.33	9.40
MnO	0.17	0.18	0.15	0.18	0.16	0.16	0.17	0.17
MgO	8.23	8.37	8.47	9.48	9.49	9.51	9.74	11.30
CaO	11.50	11.40	12.30	12.30	12.10	12.10	11.50	11.20
Na_2O	2.06	1.96	2.07	1.67	1.98	1.91	1.70	1.64
K_2O	0.70	0.40	0.35	0.48	0.38	0.42	0.49	0.45
P_2O_5	0.11	0.11	0.05	0.09	0.13	0.11	0.09	0.12
Total	99.83	100.04	99.64	99.91	99.02	98.98	98.77	98.93
Ba	128	106	91	115	82	90	100	116
Cr	292	290	337	375	733	743	527	729
Cu	64	96	53	83	151	127	146	83
Ni	92	100	97	107	149	144	118	184
Rb	25	7	18	19	19	18	15	6
Sc	41	42	41	43	44	44	45	45
Sr	183	164	189	152	144	151	162	177
V	276	286	229	268	276	260	286	273
Zr	101	109	45	99	88	108	88	115

Group 1 - Magmatic Dikes

Sample #	3M92C17A	3M92B6	3M923	3M924	3M926A1	3M92C11(?)
SiO_2	55.10	60.70	65.60	70.10	76.80	49.50
TiO_2	0.64	0.38	0.35	0.51	0.72	5.02
Al_2O_3	15.00	21.30	12.30	13.40	12.40	13.60
FeO	0.32	0.96	5.14	2.93	0.32	9.46
MnO	0.09	0.02	0.13	0.05	0.01	0.25
MgO	0.22	0.31	4.42	2.74	0.25	4.13
CaO	13.00	8.62	5.10	2.71	2.14	8.70
Na_2O	7.90	7.14	6.02	6.83	6.67	5.08
K_2O	0.03	0.24	0.20	0.06	0.09	0.25
P_2O_5	0.02	0.12	0.38	0.21	0.77	0.09
Total	92.32	99.79	99.64	99.54	99.17	96.08
Ba	1	2	7	1	1	3
Cr	63	7	19	2	10	31
Cu	1	4	4	83	17	1
Ni	11	12	24	21	8	42
Rb	5	7	6	3	4	3
Sc	4	5	30	8	2	29
Sr	37	54	76	30	20	204
V	31	25	30	61	11	306
Zr	136	121	193	178	77	151

Group 2 - Zoned Veins

Sample #	3M926	3M92C9	3M92C15	3M92A2
SiO_2	55.20	56.90	54.20	53.40
TiO_2	1.72	2.38	2.78	1.97
Al_2O_3	16.20	17.60	17.60	13.60
FeO	14.80	4.48	5.91	10.30
MnO	0.11	0.10	0.14	0.20
MgO	2.68	2.67	3.17	6.74
CaO	3.57	8.39	8.55	8.91
Na_2O	3.76	5.89	5.07	4.12
K_2O	2.21	0.44	0.94	0.91
P_2O_5	0.28	0.69	0.94	0.11
Total	100.53	99.54	99.12	100.26
Ba	250	84	103	127
Cr	5	7	3	305
Cu	174	1	2	2
Ni	16	34	38	85
Rb	71	1	27	25
Sc	18	27	27	48
Sr	230	456	357	248
V	14	24	14	220
Zr	536	158	120	85

Group 3

Sample #	3M92C7	3M92C8	3M92C10
SiO_2	46.80	45.70	48.50
TiO_2	5.07	3.16	3.10
Al_2O_3	14.10	15.00	14.50
FeO	14.10	17.40	12.00
MnO	0.32	0.26	0.19
MgO	6.07	4.41	4.71
CaO	7.80	7.80	11.30
Na_2O	2.82	3.43	3.72
K_2O	1.50	0.92	0.35
P_2O_5	0.09	1.45	0.73
Total	98.67	99.53	99.10
Ba	217	135	31
Cr	25	3	17
Cu	242	5	142
Ni	47	26	44
Rb	90	34	6
Sc	57	31	29
Sr	274	328	236
V	573	332	309
Zr	143	80	124

Table 2. Major- and Trace-element analyses of rock standards

	BCR	BCRA	BHVO	BHVOA	W2	W2A	RGM	RGMA	BIR	BIRA	IZ	IZA
SiO_2	54.30	54.35	49.90	49.90	52.70	52.68	73.70	73.15	47.10	47.96	53.90	54.76
TiO_2	2.19	2.22	2.60	2.66	1.10	1.06	0.27	0.29	0.96	0.96	0.92	0.95
Al_2O_3	13.80	13.66	13.70	13.75	15.30	15.45	14.00	13.88	15.20	15.53	16.40	16.40
FeO	12.10	12.07	11.00	11.20	9.98	9.74	1.69	1.75	10.10	10.16	7.51	7.66
MnO	0.18	0.18	0.17	0.16	0.17	0.17	0.04	0.04	0.17	0.18	0.13	0.13
MgO	3.50	3.45	7.31	7.35	6.56	6.37	0.30	0.39	9.66	9.70	5.98	6.15
CaO	6.96	6.95	11.60	11.40	11.20	10.86	1.27	1.24	13.20	13.32	7.96	8.10
Na_2O	3.14	3.27	2.26	2.18	2.13	2.20	4.00	3.92	1.83	1.82	3.40	3.35
K_2O	1.62	1.67	0.52	0.53	0.59	0.63	4.20	4.21	0.02	0.03	2.03	1.98
P_2O_5	0.37	0.37	0.28	0.28	0.14	0.14	0.05	0.04	0.03	0.02	0.35	0.35
Ba	675	678	162	132	164	174	814	827	1	6	800	782
Cr	11	16	265	250	84	92	4	3	354	373	205	200
Cu	17	19	132	133	99	106	14	10	105	125	139	136
Ni	19	13	117	118	72	70	7	14	161	166	100	101
Rb	35	47	13	10	21	21	148	149	10	2	58	49
Sc	32	33	34	31	35	36	4	6	43	43	22	23
Sr	352	330	410	394	193	194	98	116	101	107	789	790
V	408	404	311	317	248	259	11	14	321	312	208	205
Zr	201	191	201	180	109	100	201	210	19	18	171	168

Table 3. Relative percent error of analyses for USGS and Rutgers University rock standards

	BCR	BHVO	W2	RGM	BIR	IZ
SiO_2	0.91	0.00	0.37	0.75	1.79	1.57
TiO_2	1.35	2.31	3.77	6.91	0.00	3.16
Al_2O_3	1.25	0.36	0.97	0.87	2.12	0.00
FeO	0.25	1.79	2.46	6.00	0.59	1.96
MnO	0.00	6.25	0.00	0.00	5.55	0.00
MgO	1.45	0.54	2.98	23.08	0.41	2.76
CaO	0.00	1.75	3.13	2.42	0.90	1.73
Na_2O	3.98	3.67	3.18	8.00	0.55	1.49
K_2O	3.00	1.89	4.00	0.24	33.33	2.53
P_2O_5	0.00	0.00	0.00	25.00	50.00	0.00
Ba	0.44	22.73	5.75	1.57	77.05	2.30
Cr	30.63	6.00	9.02	33.33	5.09	2.50
Cu	11.58	0.75	6.80	35.30	16.00	2.21
Ni	48.68	0.85	2.43	51.42	3.01	0.99
Rb	26.60	32.00	1.42	0.67	340.90	17.55
Sc	2.42	9.68	2.78	26.66	0.22	3.04
Sr	6.67	4.06	0.52	15.35	5.61	0.13
V	0.99	1.89	4.28	18.57	2.89	1.50
Zr	5.24	11.67	9.00	4.29	3.89	1.79

plasma (DCP) atomic emission spectrometer located in the Department of Geological Sciences at Rutgers University, New Brunswick, New Jersey. Details concerning quality assurance/quality control and analytical procedures are discussed in Laney, Husch, and Coffee (1995).

Analytical Results

Analyzed whole-rock samples are either diabase or one of three different compositional groups. The sodic dikes and veins described in the petrology section of this study can be generally correlated with two geochemical groups as follows: Group 1 - Magmatic dikes and Group 2 - Zoned Veins. A third group is described that has characteristics of both geochemical groups.

Diabase

All of the host diabase samples are considered to be high-MgO examples of the ENA-HTQ diabase type. Diabase samples 3M92C15A, 3M92C15B, and xenolith sample 3M92C10Z contain slightly more MgO, Cr, and Ni than the average HTQ chill margin from the region (Husch, 1992). Petrographically, they contain less modal cumulate pyroxenes than the more MgO-rich diabase. No granophyric diabase is observed within the quarry. The diabase is similar to compositions reported by Husch and Roth (1988) for samples from the Lambertville sill, approximately one km to the southwest, suggesting a reasonably well-developed magmatic stratigraphy within the sheet in this area.

Diabase samples 3M926A2 and 3M92C15A were taken within 1 cm of zoned vein samples 3M926A1 and 3M92C15, respectively. Diabase samples 3M926A3 and 3M92C15B were taken within 4-5 cm of the same vein samples. None of these diabase samples show signs of selective contamination by ion exchange (Benimoff and Sclar, 1984, 1988; Husch, 1992). This lack of diffusion suggests that the diabase had already completely solidified prior to vein formation.

Group 1 - Magmatic Dikes

Group 1 magmatic dikes have low abundances of K_2O, Ba, Rb, and Sr (with one exception) and high abundances of Na_2O. They exhibit a wide range in SiO_2, TiO_2, FeO, CaO, and P_2O_5 abundances. Some of this variation is due to secondary calcite (3M92C17A and 3M92C11). Group 1 dikes have low K_2O/Na_2O ratios making them similar to the trondhjemite and albitite dikes found in the Palisades sill of the northern Newark basin by Benimoff and Sclar (1984; 1988; 1990) and Benimoff and others (1989) and to a fused zone in the Passaic Formation directly beneath the Orange Mountain Basalt (Puffer and others, 1993). These authors have shown that many of the trondhjemite and albitite melts were produced by the anatexis of Triassic sedimentary rocks by the heat (~1200°C) of the adjacent basalt or diabase. Group 1 dike magmas may have a similar origin although they have higher Ba contents than previous reports. Supporting this model is a xenolith of baked, granoblastic sedimentary rock (sample 3M92B6; Table 1) that has identical geochemical characteristics to the rest of the Group 1 samples. The distinctive geochemical traits of the Group 1 magmas, therefore, were inherited from their sedimentary source.

The derivation of Group 1 magmas by the fractionation of the diabase appears unsupported by the available geochemical data. Highly fractionated granophyres derived from more mafic HTQ diabase by crystal fractionation are distinctly richer in K_2O (10-100 times), contains approximately half the

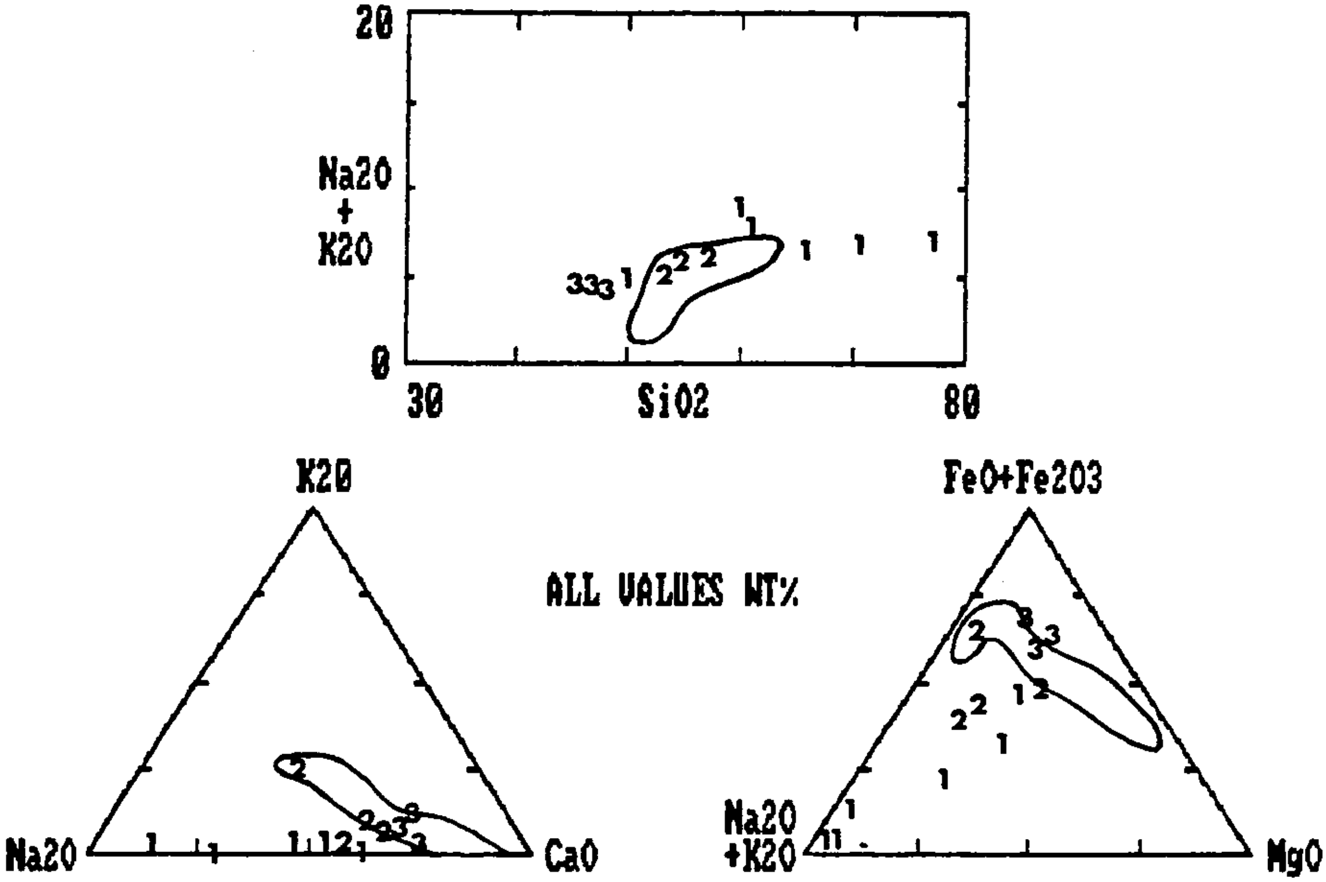


Figure 4. Major-element variation diagrams for the three dike groups. Individual dike compositions are numbered according to the dike group to which they belong. Because of overlap, not all samples are shown. Enclosed areas are the variation fields for the diabases of the central Newark basin and are based on data from Husch and others (1988) and Husch (1992). Diabase field also includes new data for host diabase samples from the 3M quarry.

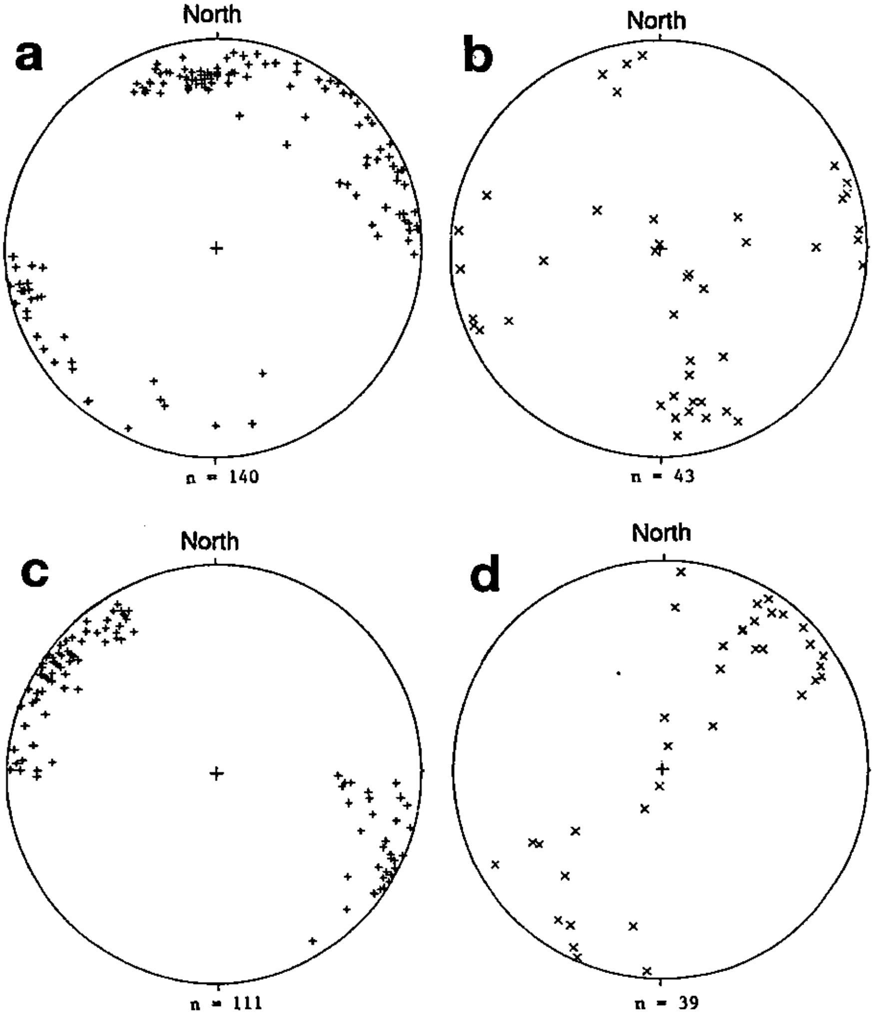


Figure 5. Stereoplots (SPLOT, 1988) of poles to fractures (joints and faults) and plunge and trend of mineral lineations (slickenfibers); a) Poles to older fractures (NW- and E-W striking, first fracturing event); b) Mineral lineations on older faults; c) Poles to younger fractures (NE-striking, second fracturing event); d) Mineral lineations on younger faults. Plots form a girdle with a clustering of points in the NE quadrant indicating strike-slip faulting with slickenlines plunging NE 2-20°.

Na_2O, and shows elevated values of Ba, Rb, and Sr (Husch, 1992). Group 1 compositions plot outside compositional fields of the central Newark basin diabases (Fig. 4).

Group 2 - Zoned Veins

Group 2 veins are characterized by higher K_2O/Na_2O ratios and Ba, Rb (with one exception), and Sr abundances than Group 1 dikes. Their overall compositions are more similar to fractionated diabase compositions found in the central Newark basin (Husch and others, 1988; Husch, 1992) than to fusion magmas. Samples 3M926 and 3M92A2 show marked similarities with highly fractionated granophyre diabase and moderately fractionated diabase, respectively. Both samples plot along the diabase fractionation trend on various major-element variation diagrams (Fig. 4), although at distinctly different positions.

The magmas for these dikes were possibly derived from the fractionating HTQ magma and intruded into fractures formed late in the cooling history of the sill. The zoned veins are more abundant on the west side of the quarry, which is higher in stratigraphic position within the diabase sheet, further supporting the granophyric origin for this rock type.

Group 3

Group 3 samples are characterized geochemically by higher abundances of TiO_2, FeO (Fig. 3), and V and are depleted in SiO_2 as compared to Group 1 or 2. Petrographically, this group is distinguished by higher modal abundances of Fe-Ti oxides and sphene.

The origin of the Group 3 dikes and veins are enigmatic. Their K_2O/Na_2O ratios are not as low as the Group 1 dikes, making derivation by anatexis of sedimentary rock unlikely. Their high TiO_2 content makes them similar to granophyres (Group 2) yet their low SiO_2, Ba and Zr values does not support a fractionation origin. More detailed geochemical work, including REE and isotopic data, are required before the origin of the Group 3 samples can be determined with any degree of certainty.

STRUCTURAL DATA

One hundred and fifty faults and 235 joints were mapped in ten traverses along the southwest, west, and north walls of the C level (Fig. 2). Each traverse was ~100 m long resulting in a total mapped length of ~1 km. Eighty-six faults were mapped that had reliable kinematic indicators to determine movement sense. The kinematic indicators used were stepped and grooved slickensides (Hancock, 1985), small-scale drag folding, offsets to older fractures (Hills, 1940; Billings, 1954), and sharp fibrous imbricated slickenline terminations (Durney & Ramsey, 1973; Fleuty, 1975).

Detailed mapping of fractures indicates that there are at least three fracture sets present at the quarry. These sets can be separated into early, middle, and late events based upon offsetting relationships. An early pervasive set consists of a poor conjugate set with the dihedral angle oriented roughly NW-SE (Figs. 5a & 7a). The E-W striking fractures of this set are well developed, have a tight polar grouping and dip south 75-85 degrees. The NNW striking fractures have a more diffuse polar distribution and dip steeply to both the NE and SW. Faults consist of right and left lateral oblique faults which appear to be coeval. Slickenline data for this early-formed fracture set are shown on Fig. 5b.

A second fracture set exists that strikes consistently NE and dips within 25 degrees of vertical (Figs. 5c, 5d & 7b). These fractures generally offset the earlier formed fractures by 1-50 cm. Fault

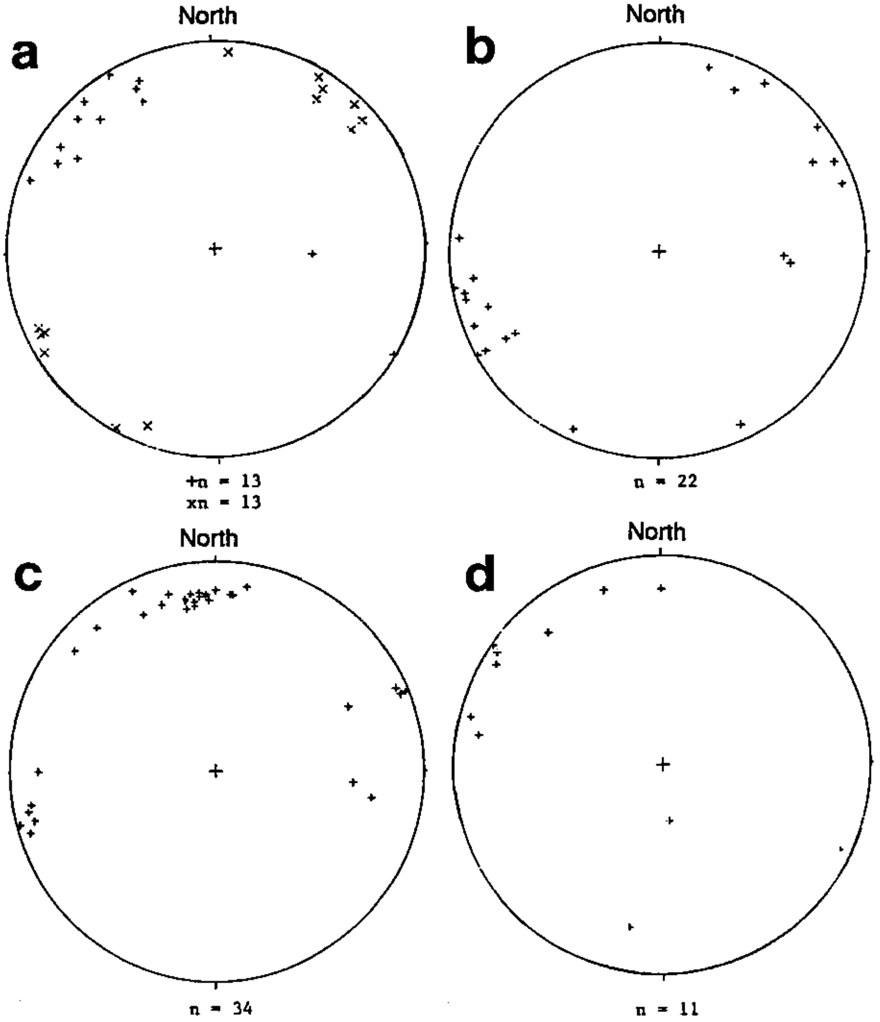


Figure 6. a) Stereoplot of poles (n = 13) from dextral fault zone (+) and plunge and trend of mineral lineations (x). The distribution is very similar to Figs. 5c and 5d; b) Poles to pegmatite dikes having a distribution similar to Fig. 5a, primarily NW striking dikes; c) Poles to zoned veins showing a distribution similar to Fig. 5a but with more E-W striking veins; d) Poles to hydrothermal veins having similarities with Fig. 5c.

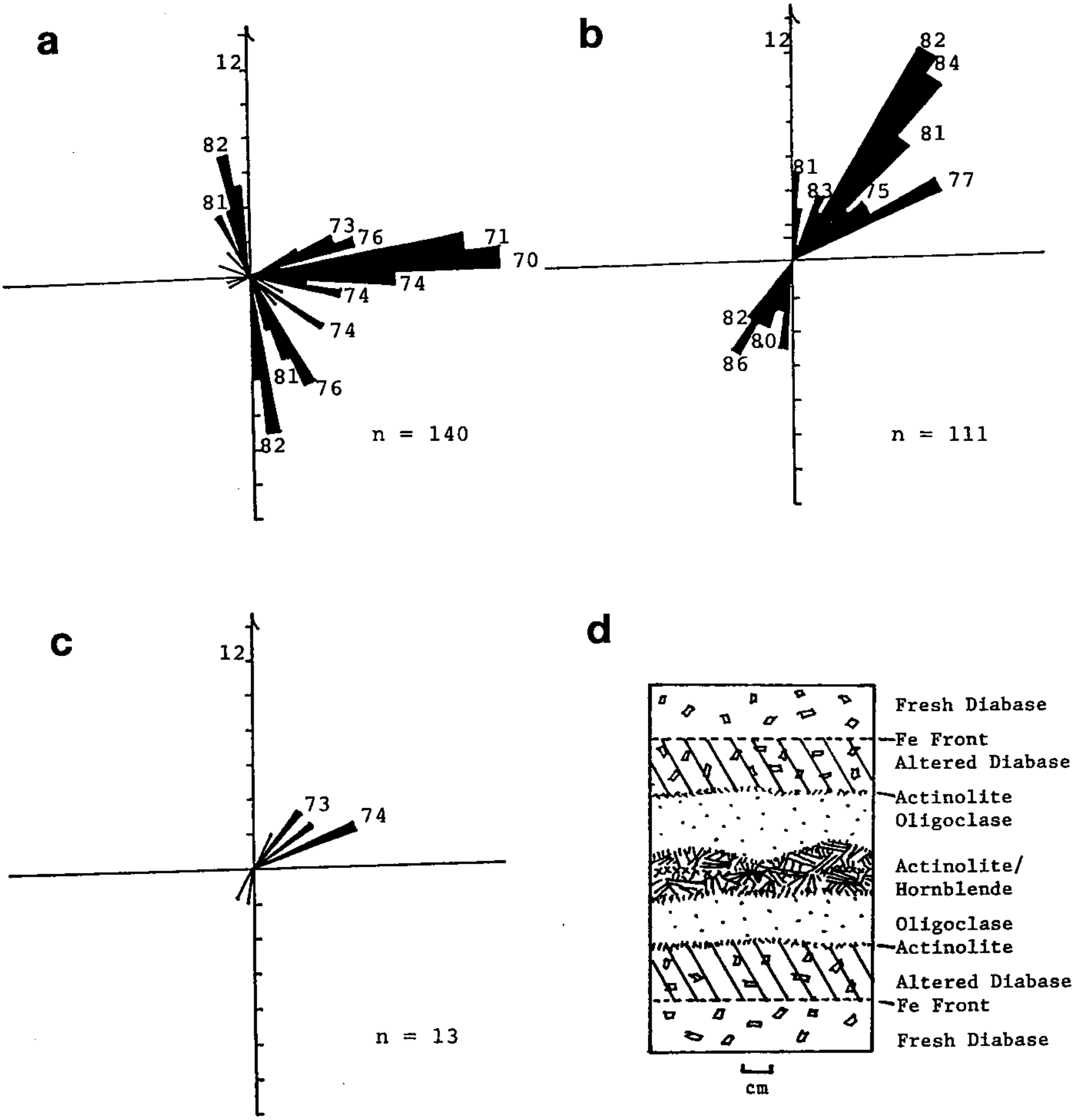


Figure 7. Rose diagrams showing fracture strike frequency and average dip (at end of petal) using the right-hand rule; a) First fracture event; b) Second fracture event; c) Third fracture event, dextral faulting; d) schematic of typical zoned vein.

classes consists of a sub-equal number of lateral, oblique, and normal faults. Some normal faults have two poorly developed slick directions with the younger slicks forming at 70-90 degrees to the older set.

A third fracturing event involved dextral strike-slip faulting. A right-lateral fault zone, striking approximately N60E (Fig. 2), is exposed in three locations in the quarry for a strike length of ~400 m (Figs. 3a, 6a & 7c). This fault zone appears to offset all previous fracturing. This fault forms a sinuous zone thinning and swelling to ~10 m wide, dips SE 70-80°, and has grooves and slickenlines plunging 5-10° SW and NE. A contractional strike-slip duplex ~80 m long by 15 m wide was mapped on the south side of the quarry on the C level (Woodcock & Fisher, 1985; Swanson, 1988; Laney & Gates, 1996).

Fault Population Analyses

A fault population (tensor) analysis was performed using fault plane and slickenside data for each of the three fracture events to determine the orientation of the stress ellipsoid at the time of each deformation. A stress inversion program developed by Hardcastle (1987) and based upon Reches' (1987) work was utilized. This program calculates sigma 1, 2, and 3 orientations for faults using a least squares regression method.

Using this method and data from 43 faults, the stress ellipsoid orientation for the oldest fracturing event was determined to be sigma 1 - 159°:78° (trend:plunge), sigma 2 - 272°:5°, and sigma 3 - 3°:11°. The maximum extension direction (sigma 3) plunged north at 11 degrees below horizontal.

The stress ellipsoid orientation for the second fracture family was sigma 1 - 198°:78°, sigma 2 - 66°:8°, and sigma 3 - 335°:9°. This analysis is based upon 38 faults. The maximum extension direction plunged NNW at 9 degrees below horizontal.

Tensor analysis for the dextral strike slip fault resulted in a stress ellipsoid orientation of sigma 1 - 171°:82°, sigma 2 - 62°:3°, and sigma 3 - 331°:8°. This orientation is similar to that for the second fracture event.

Structural Control of Dikes and Veins

The poles to 22 magmatic dikes were plotted on an equal area net (Fig. 6b). These dikes generally dip steeply to the NE and SW. This structural distribution is similar to that shown by the older NW-striking fractures (Fig. 5a).

Poles to 34 zoned veins (Fig. 6c) show polar distributions similar to the first fracture event (Figure 5a) although few are associated with the NW striking fracture. A tighter grouping is associated with the south-dipping fracture set.

The poles to eleven hydrothermal veins consisting of calcite and/or quartz (Fig. 6d) have a more diffuse distribution. They generally strike northeast, dip southeast, and show a pattern similar to the second fracture event (Figs. 5c and 6a).

DISCUSSION

Mesozoic sedimentation, lithification, and fracturing occurred synchronously with rift basin growth (Schlische & Olsen, 1990). No intrabasinal fracturing can be older than approximately 230 Ma. Schlische (1992) described two preferred fracture orientations forming an orthogonal system in the basin but did not describe their relative timing.

The structural analysis conducted at the Belle Mead quarry confirms Schlische's (1992) findings and also gives a relative timing to deformational events, including dextral strike-slip faulting. The diabase was not intruded until approximately 30 million years after the basin formation began. The first fracturing event occurred as the diabase solidified in a downwarping stress field with the formation of the NW-striking fractures (Figure 5a) followed closely by the E-W striking fractures. Fracturing due to local downwarping (NW fractures) may have been ending and those due to regional extension (E-W) may have been increasing. A N-S extension (sigma 3) was occurring in the basin at that time.

The second fracture event (Figure 5c), dominated by NE-striking fractures, is related to the ESE regional extension direction determined by the tensor analysis and reported by Schlische (1992). The stress ellipsoid orientation for the first and second fracture sets are not the same, indicating non-coaxial deformation. The maximum extension direction (sigma 3) rotated counterclockwise approximately 30 degrees and the maximum compression direction rotated clockwise between deformations. Some of the older fractures having E-W strikes may have been reactivated during the younger event resulting in faults with two sets of slickenlines. The clockwise rotation of the maximum compression direction is consistent with that reported by Costa and Gates (1993) for post-Triassic brittle faulting along the Ramapo Fault in New Jersey.

The tensor analysis results for the dextral fault are very similar to that for the second fracture event. Since the dextral fault appears to truncate all previous fracturing, strike-slip movement may have occurred as a culmination to the second fracturing event.

The magmatic dikes (Group 1) are associated with the early formed NW-striking fractures. The dikes have a geochemistry more consistent with xenolith anatexis modified by subsequent magmatic fractionation. Dike magmas were injected into the first fractures formed after sufficient solidification of the diabase had occurred.

The zoned veins (Group 2) are associated with both the early formed NW- and E-W striking fractures but are better developed in the south-dipping fractures (Fig. 6c). The zoned veins are highly altered, with the alteration grading into the surrounding diabase. Zoned veins represent the last of the residual melt and were emplaced during the later phase of the first deformation when early regional extension was beginning. The diabase magma had cooled sufficiently so that less country rock was being assimilated. Zoned veins have geochemical characteristics more indicative of granophyric fractionation modified by country rock fusion. The residual magma may also have been affected by hydrothermal activity related to the heat of the sill intrusion mobilizing connate water from the country rock. This hydrothermal modification would result in a less chemically compatible residual magma resulting in more alteration effects. The location of the zoned veins in a higher stratigraphic position in the sill also supports a granophyric origin.

Robinson and Woodruff (1988) described a hydrothermal event that occurred at approximately 175 Ma, toward the end of basin rifting. Evidence for this event also were mapped at 3M as veins of calcite, datolite, chlorite, and/or quartz. Hydrothermal veining and chloritic clay-alteration seams appear to be associated with SE-dipping fractures belonging to the second fracture event (Figs. 6d and

5c). Hydrothermal fluids generated deep in the basin traveled updip along the most active and open conduits, which were the younger SE-dipping extensional fractures.

CONCLUSIONS

Three types of post-solidification intrusives have affected the diabase at the 3M quarry. Magmatic dikes formed first and occur mainly in NW-striking fractures. Zoned veins formed after the dikes and occur primarily in E-W striking but also NW-striking fractures. Hydrothermal veins formed last and occur mainly in NE-striking fractures.

The magmatic dikes are pegmatites composed of oligoclase and pyroxenes that are partially uralitized to actinolite. Sphene, epidote and apatite are common. The dikes have a relatively sharp contact with fresh diabase. Although examples of both dikes and zoned veins can be found in all three geochemical groups previously described, samples from magmatic dikes were more abundant in Group 1, indicating an anatectic origin for these early-formed pegmatites.

The zoned veins consist of medium-grained oligoclase layers sandwiching a core of actinolite-hornblende. Few pyroxenes are crystallized within the feldspar layers but sphene is common. Gradational contacts with the highly-altered diabase are typical. More zoned vein samples occur in Group 2 than in the other two groups. Later-formed zoned veins probably originated as granophyric fractionations from the diabase.

Late-stage hydrothermal veins consists of mainly calcite, quartz, chlorite, and datolite. These veins were formed much later than the sodic dikes and veins and are not associated with the diabase magma petrogenesis.

At least three fracturing events, occurring between 201-175 Ma, affected the diabase. The oldest fractures formed ~30 Ma after rifting began and form a semi-conjugate set oriented NW and E-W with the east-striking fractures dominating. The second fracturing event formed NE-striking faults. Maximum extension was NW-SE and associated with the main rifting of the Newark basin. Approximately 30 degrees of counterclockwise rotation of the stress ellipsoid occurred between the first and second event indicating non-coaxial deformation.

The third deformation involved dextral strike-slip faulting most likely developed synchronously with the Hopewell fault. The sequence of fracturing at the Belle Mead quarry suggests that major lateral movements on intrabasinal faults did not develop until after the pervasive extensional fractures were formed in the basin. The splay exposed in the quarry indicates that the Hopewell fault is most likely a braided fault system as previously reported for the Flemington fault.

The hydrothermal event at 175 Ma occurred after the dextral faulting. No hydrothermal veins were mapped being offset by the 3M fault. These veins occur in SE-dipping normal faults having overprinted slickenline orientations indicating fault reactivations from continued extension of the basin after the dextral faulting occurred.

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GEOLOGY OF THE CHIMNEY ROCK COPPER OCCURRENCE
A DEPOSIT TYPICAL OF THE WATCHUNG BASALTS

by Warren Cummings
1191 Parkside Ave.
Ewing, NJ 08618

Native copper and chalcocite attracted the attention of prospectors to the southern end of the Watchung Basalts of northeastern New Jersey (Fig. 1) during most of the 19th century and into the first decade of the 20th century. Most of the digging amounted to no more than the excavation of test pits although the American Mine, near Pluckemin, and the Chimney Rock Mine, north of Bound Brook, had significant underground workings and actually produced a little copper. The Chimney Rock Mine is now the most important of the area's copper mines because of the excavation of the large Chimney Rock Quarry which exposes the ore zone immediately adjacent to the mine's old workings. The Chimney Rock Quarry is currently owned by Stavola Construction Materials, Inc. It has always been the policy of this operator to keep access to the quarry extremely restricted.

In addition to copper concentrations the Watchung Basalts contain a world famous prehnite-zeolite assemblage and have been a source of mineral specimens for at least 150 years. Well developed occurrences of this group of secondary minerals are much more widespread than the native copper-chalcocite concentrations. The prehnite-zeolite assemblage is most spectacularly developed in the Paterson-Great Notch area approximately 25 airline miles northeast of the Chimney Rock Quarry.

Historically the copper-chalcocite and the prehnite-zeolite mineral assemblages have been treated in the literature as separate entities. Although the prehnite-zeolite assemblage occurs abundantly at the Chimney Rock Quarry it is not as aesthetically well developed as it is at other localities to the northeast. The mineralogy of the quarry was first described in detail by Sassen (1978) following the discovery of very large natrolite and analcime crystals. In his work both mineral assemblages received an integrated treatment.

Small amounts of chalcocite are sporadically present at the base of the Orange Mountain Basalt and in veins northward to at least the Paterson area. The more northerly copper occurrences have produced a few interesting mineral specimens but otherwise were neither common enough nor attractive enough to receive much attention.

Early in this century Fenner (1910) published the first comprehensive description of the mineral assemblages present in the Watchung Basalts. His work concentrated on material from a zone of pillow lavas that had recently been exposed in several quarries in the Paterson-Great Notch area. Fenner's work was later refined by Schaller (1932) who also worked in the Paterson-Great Notch area. Together these two papers have formed the foundation of most subsequent work on the secondary minerals of the Watchung region.

Both Fenner (1910) and Schaller (1932) gave detailed paragenetic sequences of

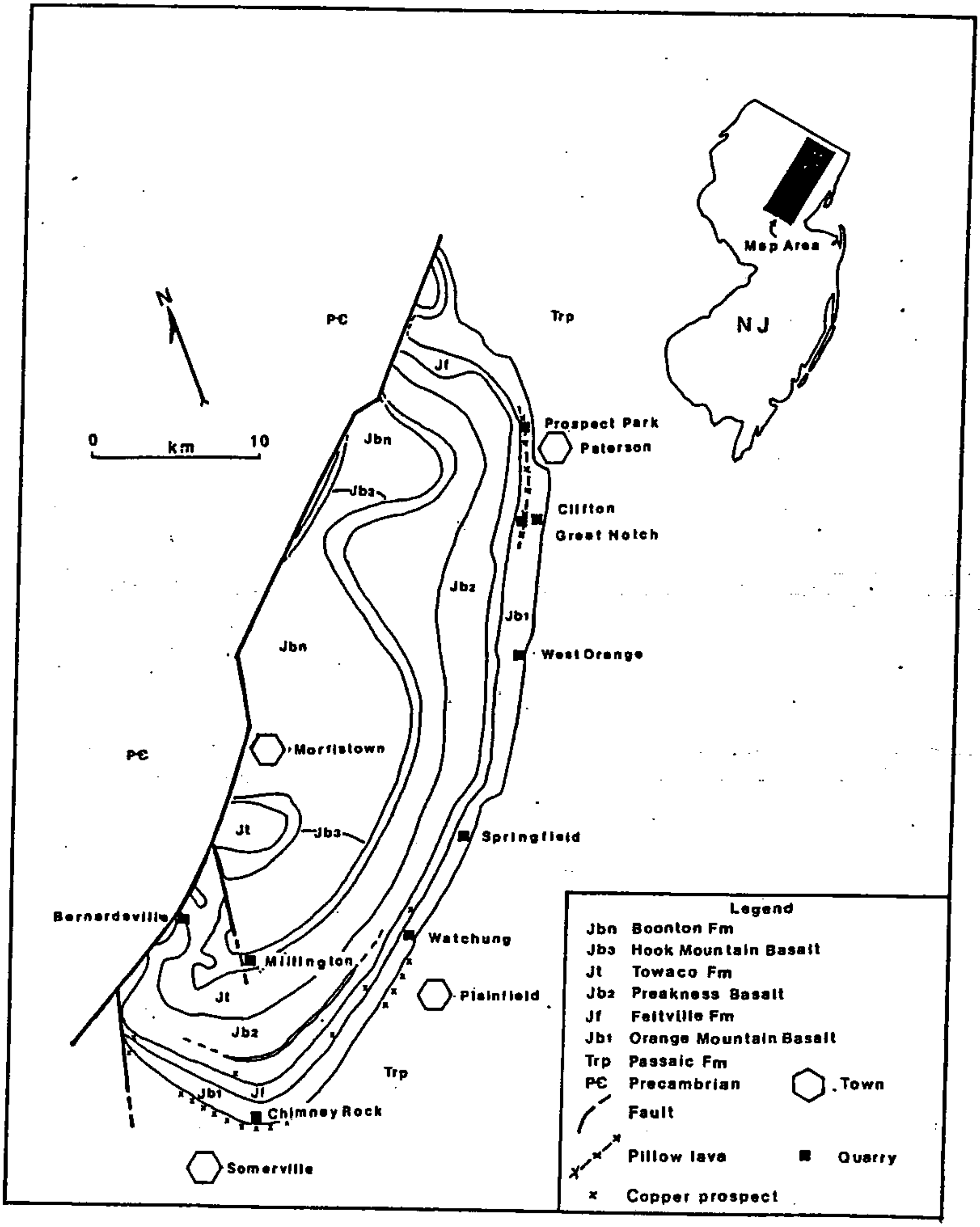


Fig. 1: Geologic sketch map of the Watchung Syncline area, northern Newark Basin, indicating localities mentioned in the text.

the secondary minerals they found in the Paterson-Great Notch area. These sequences were painstakingly pieced together from the fragmentary record found in individual specimens and have stood the test of time. More recent studies of other localities have shown that a similar suite of secondary minerals and paragenetic sequence occur throughout most of the extent of the Watchung Basalts. Neither Fenner (1910) nor Schaller (1932) recognized any systematic spatial distribution of the secondary minerals in their limited, albeit spectacularly mineralized, area of study.

The copper deposits associated with the Orange Mountain Basalt have never been studied in detail. Only general information, much of it predating the First World War, is available concerning the copper minerals or the associated alteration. This paper will concern itself with the relationships between all the secondary minerals in the Chimney Rock Quarry and the Watchung Basalts generally. Its goal is to provide a framework in which the copper concentrations of the Chimney Rock region can be better understood relative to the prehnite-zeolite assemblage and the mineral depositing system as a whole.

GEOLOGY

The three Watchung flood-basalts occur in the upper third of the stratigraphic section preserved in the Newark Basin, a block faulted half graben, of late Triassic and early Jurassic age. The sedimentology, paleontology and structural evolution of the basin have been intensively studied in recent years. This has resulted in a voluminous literature that makes a discussion, here, of the regional geology unnecessary. For discussions of other aspects of the geology of the Newark Basin the reader is referred to Olsen, et al (1996) and references therein.

Each of the three Watchung Basalt Formations is composed of two or three distinct flow units. The flow units typically have a thin amygdaloidal base, a jointed interior and a thick amygdaloidal top (Faust, 1975, 1978; Cummings, 1985, 1987; Puffer and Student, 1992). Local structures containing open space include zones of pillow and block lava, mounds of scoriaceous breccia, and isolated concentrations of amygdules unrelated to true flow tops. Some of these features have been described by Puffer and Laskowich (1984), Laskowich and Puffer (1990) and Manspeiser (1980). Both the flows and the associated sedimentary rocks are traversed by joints and numerous, mostly high angle, faults. The faults also interconnect the porous, permeable lithologies within the basalts. The faults and joints together form a vertically and horizontally integrated plumbing system, of great extent.

Extrusion of the Orange Mountain Basalt followed the accumulation of a sedimentary pile whose compacted thickness in the Chimney Rock area is more than 15000 feet (Olsen, et al, 1996). Deposition of most of these sediments occurred in lacustrian and fluvial environments and was highly cyclic. Climate variations, driven by several celestial cycles, superimposed on one another, caused the reciprocal expansion and contraction of lakes and alluvial plains. These cycles were first recognized by Van Houghton (1964) and have been described in detail by Olsen (1986).

Schlishe and Olsen (1990) have shown that the Passaic Formation, the unit immediately underlying the First Watchung Basalt, accumulated during a period of declining lake depth and sedimentation rate. In the northern Newark Basin, regionally extensive gray beds, indicative of greater lake depth, are only a very minor component of the middle and upper Passaic Formation. In the Chimney Rock area core drilling (Olsen, et al, 1996) indicates that gray beds are less than 1% of the 3000 feet of Passaic sediments immediately underlying the Orange Mountain Basalt and less than 5% of the next 1500 feet beneath that. Conversely, thin layers of cavities left by evaporite minerals are locally abundant. The shapes of the cavities suggest that glauberite and gypsum were the dominant species. Casts of preexisting glauberite crystals were recognized in the Newark sediments by Wherry (1916) and in subsequent years by others, including Schaller (1932, Plate 1c), Manspeizer (1980), Smoot and Robinson (1988), and Van Houten (1988). Lake depth and sedimentation rate increased abruptly coincident with the extrusion of the Orange Mountain Basalt (Schlishe and Olsen, 1990). Beginning with the Feltville Formation, immediately above the Orange Mountain Basalt, and extending upward through the Towaco and Boonton Formations, gray and black beds again make up a substantial portion of the stratigraphic section.

Several lines of evidence have emerged in recent years that suggest that the Newark Basin experienced a pulse of hydrothermal activity and high heat flow late in its history. The time of onset and duration of this activity is poorly constrained. Fission track analysis (Steckler et al, 1993), ^{40} Ar/^{39} Ar dating (Sutter, 1988) and paleomagnetics (Witte and Kent, 1991) all record a date of approximately 175 mybp. This date marks the decline of temperature below the closure temperatures of the respective methods.

The structure of some sedimentary basins is conducive to gravity driven circulation of fluids. Bethke (1986), studying the Illinois Basin, demonstrated that gravity could move large amounts of fluid and heat long distances from the depths of a basin to more shallow regions. Steckler et al (1993) found evidence suggesting that gravity driven fluid migration occurred in the Newark Basin and that temperatures in the rocks presently exposed in the northern Newark Basin reached more than 220°C except within 3 to 6 miles of the border fault. This estimate is consistent with the fluid inclusion measurements of Lawler (1981) from the western Newark Basin and the occurrence of minor amounts of epidote at Chimney Rock and elsewhere in the Orange Mountain Basalt. Observations in Iceland and elsewhere (Kristmannsdottir, 1979; Seki, 1972) indicate that the minimum stability limit of epidote in hydrothermally altered basalts is approximately 200°C - 225°C. Epidote becomes abundant around 260°C (Palmason et al, 1979). These temperatures are higher than the 90°C to 130°C estimated by Pratt et al (1988) based on studies of organic matter.

LOCAL STRATIGRAPHY

The Chimney Rock Quarry exposes approximately 100 - 120 feet of Passaic Formation. The Passaic Formation beds are mudstones ranging from thick bedded to laminated. Some beds are riddled with small cavities left by preexisting evaporite minerals. Within approximately 3 feet of the overlying basalt the sediments have been darkened due to the recrystallization of hematite pigment to specularite. Chemical analysis (Woodward, 1944) do not indicate significant conversion to magnetite. This darkened rock, is widespread in areas where copper is abundant and has been referred to as "hornfels". However, this alteration may be of hydrothermal origin since it is only associated with copper deposition. The true hornfels is probably no thicker than the approximately 2 inches seen at other exposures of the base of the Orange Mountain Basalt where copper minerals are not present.

There is some question concerning the total amount of basalt exposed. Although the Chimney Rock Quarry exposes an apparent thickness of some 350 feet of basalt it does not expose an unequivocally identifiable flow top (Fig. 2). Measurements of the lower flow unit of the Orange Mountain basalt at the Weldon Quarry, 10 miles northeast of Chimney Rock, indicate a thickness of approximately 225 feet (Puffer & Student, 1992). Core drilling approximately 2.5 miles northwest of the quarry (Olsen, et al, 1996) indicate that the lower flow unit is approximately 270 feet thick. The discrepancy between measured and apparent thickness suggests that there is repetition of the section by faulting in the Chimney Rock Quarry.

The basal 4 to 6 inches of the basalt contains numerous tiny amygdules, up to 0.2 and, rarely, 0.4 inches . Much larger amygdules, 2.5 to 6 inches in diameter, occur isolated and sparsely scattered through the basal meter of the flow. Most of the larger amygdules are subround, but pipe vugs are occasionally seen and are up to 2 inches across and 20 inches long. Alteration associated with these amygdules is very minor.

Above the amygdaloidal base the lower flow unit is massive, except for fault zones and the typical compliment of joints (Faust, 1978). The curvicolumnar joint sets, common in flow interiors at many places in the Watchungs, are generally not well developed at Chimney Rock, but local good examples are common.

The Chimney Rock Quarry is transected by numerous faults, most of which are nearly vertical. Fault movement is difficult to assess. Displacements the basalt/sediment contact up to 9 feet vertically can be seen along the pit's south side. The strikes of most of these faults fall into two groups, N30°W and N10°E. The width and intensity of fracturing within individual fault zones can vary greatly within short distances. Extensional structures range up to 6 feet wide and are often vuggy. Fracturing commonly occurred during secondary mineral deposition as evidenced by the brecciation of earlier phases and crosscutting relationships.

Near the stratigraphic top of the quarry exposure, a mass of amygdaloidal rock with limited lateral continuity, has been exposed (Fig. 2). The nature of this amygdaloidal horizon is still unclear. The exposure is crosscut by a prominent N10°E fault which presently (June 1998) marks the limit of quarrying. This fault extends across the quarry where it displaces the basalt/sediment contact approximately 9 feet vertically. The area beyond this fault, to the east, is inaccessible so the continuation of the amygdaloid cannot be investigated.

Near the fault the amygdaloid is approximately 40 to 45 feet thick and has a stratigraphy similar to flow top amygdaloids (Cummings; 1985, 1987). The scoriaceous rock at the top of the amygdaloid is brecciated and reddened to varying degrees suggesting subareial formation. Northwestward from the fault the character of the amygdaloidal horizon changes rapidly. The rubbly, slag-like unit that commonly marks a flow top disappears, the normal vertical distribution of cavities becomes indistinct, and their average size and density decrease. Approximately 220 feet west of the fault the amygdules and the associated alteration end abruptly, and the massive, relatively unaltered basalt above and below the amygdaloid join with no sign of discontinuity. In

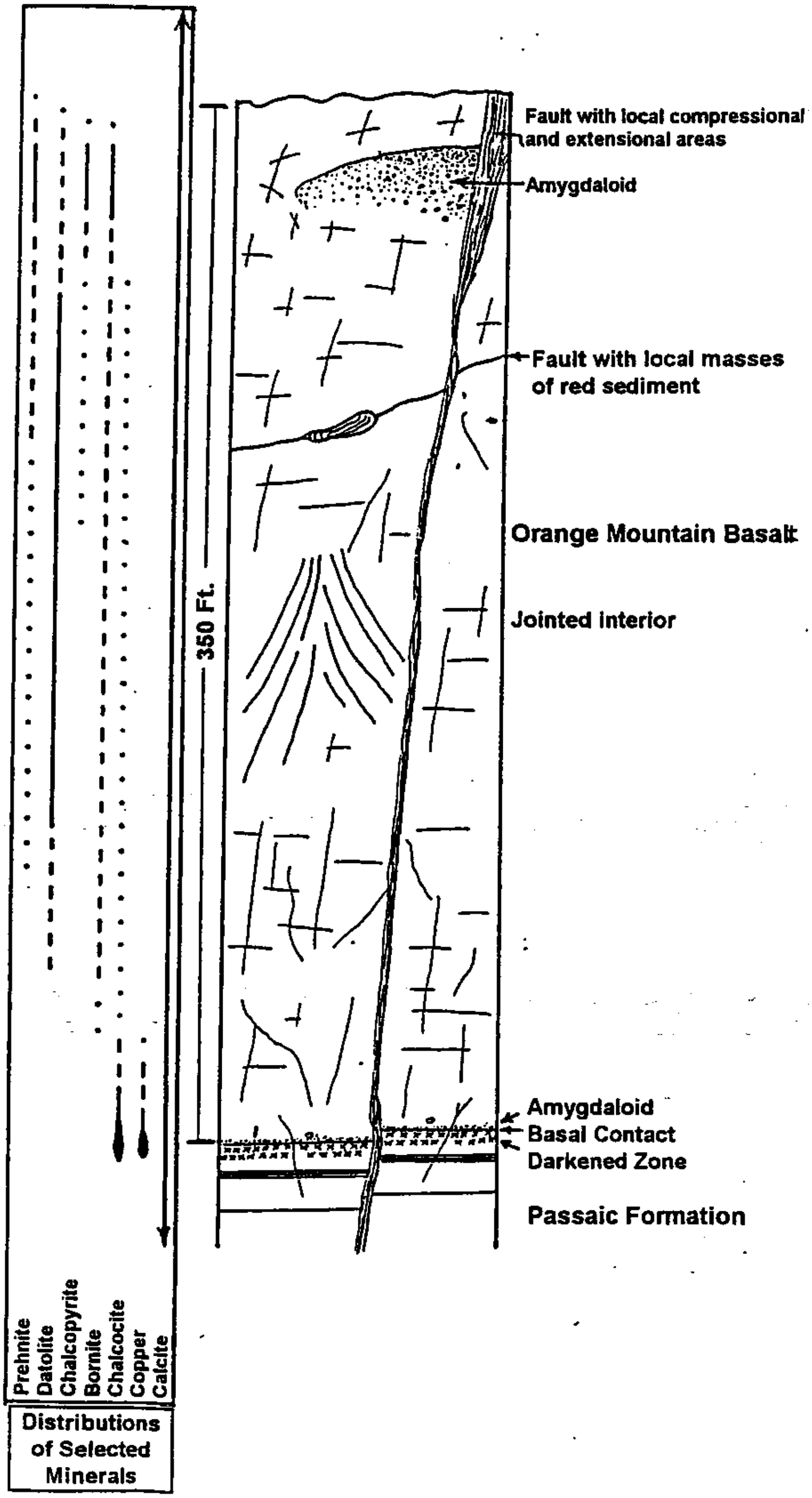


Fig. 2: Stratigraphic column and distributions of selected secondary minerals at the Chimney Rock quarry.

spite of the apparent stratigraphic extent of the exposure at the Chimney Rock Quarry neither a laterally extensive amygdaloid nor any of the other features normally associated with flow contacts are seen.

SECONDARY MINERAL DISTRIBUTIONS

The Watchung Basalts have been altered to varying degrees, throughout their extent, by diagenetic and hydrothermal activity. Fluid/rock reactions have resulted in the replacement of parts of the basalt by a very fine grained, chlorite-rich assemblage, and secondary mineral deposition in open spaces. In general the chemistry of the secondary mineral assemblage reflects that of the basalt, calcium-rich and intermediate in silica content. However, many of the secondary minerals include chemical components unlikely to have been derived from the basalts in quantities sufficient to account for the observed secondary mineral mass. These componants include carbonate, sulphate, boron, copper and sodium.

At Chimney Rock, as at many other localities in the Watchung Basalts, the secondary minerals do not occur at random but are distributed in a systematic pattern. In those parts of the basalt most closely connected to the underlying sediments by zones of permeability the secondary mineral assemblages are dominated by species containing chemical components that are likely to have been introduced into the basalt. In the interior of the flow complexes hydrous calcium-aluminum silicates, that reflect the composition of the basalt, form a larger proportion of the secondary assemblages. The movement of chemical components out of the sediments and into the basalts is illustrated by the spatial distributions of several mineral groups including (1) anhydrite - glauberite, (2) calcite - datolite - prehnite, (3) native copper - metallic sulphides, and (4) sodium zeolites - calcium zeolites.

Anhydrite - Glauberite

Fenner (1910) and Schaller (1932) recognized that anhydrite, $CaSO_4$, and glauberite, $CaNa_2(SO_4)_2$, were among the earliest open space secondary minerals to crystallize in the Watchung Basalts. Both minerals formed euhedral crystals, often quite large, whose growth was complete early in the paragenetic sequence. They were subsequently overgrown by silica, datolite and prehnite. During the later stages of mineral deposition both anhydrite and glauberite were largely leached away leaving cavities, similar to those found in the Passaic Formation sediments (Schaller, 1932).

The pillow lava zone of the Paterson/Great Notch area, where Fenner and Schaller worked, is the only locality in the Watchung Basalts where glauberite crystallized abundantly. Elsewhere, including Chimney Rock, glauberite casts are limited to large veins where they are rare and local. The geology of glauberite-bearing environments suggests that they probably experienced a higher fluid flux than normally prevailed in the hydrothermal plumbing system. The chemistry of secondary mineral deposition at glauberite-bearing sites was more fluid dominated and sodium-rich.

Anhydrite cavities occur in all types of mineralized open space and are present at all significantly mineralized localities in the Watchung Basalts. Anhydrite cavities are least abundant in veins and were uncommon in the Chimney Rock Quarry until the exposure of amygdaloidal rock. Cavities left by anhydrite are abundant in this lithology as they are in amygdaloidal flow tops at other localities.

Silica

After the initial "saline period" both Fenner (1910) and Schaller (1932) recognized a distinct period of silica deposition. Although this period is distinct at many localities in the Watchung Basalts the Chimney Rock Quarry is not among them. As was noted by Sassen (1978) silica, as jasper, chalcedony and quartz, is abundant only in the sparsely scattered amygdules immediately above the basal contact of the basalt. Elsewhere in the quarry silica is very rare.

Native copper and copper sulphides are occasionally found with quartz in the basal amygdules. The onset of native copper deposition clearly predated the cessation of quartz deposition. Copper sulphides followed native copper and coincided with the calcite that commonly follows quartz in these amygdules. Given the proximity of the basal amygdules to the principal zone of copper mineral deposition, copper minerals within the amygdules are remarkably rare.

Calcite - Datolite - Prehnite

The next stage of the paragenetic sequence was referred to by Fenner (1910) as the "boric acid period" and by Schaller (1932) as the "prehnite period". At Chimney Rock the most characteristic secondary mineral of this paragenetic stage is neither datolite nor prehnite but calcite. In the lower 50 - 70 feet of the basalt and in the immediately underlying sediments veins may contain local concentrations of copper minerals, minor quartz, chlorite and other country rock alteration products but they are all essentially calcite veins. Calcite veins, containing occasional crystal lined vugs, are common throughout the Chimney Rock Quarry. This locality has long been known for it's calcite crystals which are up to 3.5 inches and exhibit a wide variety of habits.

Datolite, $CaBSiO_4(OH)$, is a very common secondary mineral throughout the Watchung Basalts even though it contains the rare element boron. In the fault system exposed in the Chimney Rock Quarry, datolite is second in abundance only to calcite. Datolite is encountered with increasing frequency at distances greater than approximately 70 feet above the basal contact of the basalt.

The boron present in a mineral as abundant as datolite is interesting because boron rarely exceeds 10-15 ppm in most lithologies. The major exceptions are clay-rich mudrocks, graywackes and shales deposited in marine and in some lacustrine environments which commonly contain up to 100-125 ppm (Goldschmidt, 1954; Shaw and Bugry, 1966). During deposition of these types of sediment boron is adsorbed on clay minerals. During diagenetic recrystallization, clays release boron to the formation water. It is also possible that soluble borates were part of the sulphate-rich evaporites. The boron geochemistry of the Newark sediments has never been studied in detail. Given the saline lacustrine environment in which much of the sediment was deposited and its argillaceous nature, elevated boron contents are possible. Ratcliffe and Burton (1988) found 450 ppm and 260 ppm in samples of mildly altered red mudrock at a site in the central Newark Basin. They concluded that boron was highly mobile during faulting and alteration, and suggested the sediments as a possible source.

Prehnite, $Ca_2Al_2Si_3O_{10}(OH)_2$, is much less common than datolite and is rare below approximately 150 feet above the basal contact . When prehnite is encountered in a fissure it is often associated with much heavily altered gouge or breccia. Prehnite is also abundant in the recently exposed and highly altered amygdaloidal rock near the northern limit of the quarry.

The precise relationship between calcite, datolite and prehnite is difficult to assess because of highly variably vein architecture and the difficulty of tracing individual faults over significant distances. All three minerals, especially datolite and prehnite, tend to be mutually exclusive and form monomineralic veins diluted only by local concentrations of copper minerals, minor quartz, chlorite and other country rock alteration products. Calcite is found in vugs in datolite or prehnite, especially in the amygdaloidal rock. Examples of datolite or prehnite following either calcite or one another are quite rare. Both datolite and prehnite appear to have deposited locally in fault zones that elsewhere contain calcite.

Calcite is clearly favored by proximity of the deposition site to the basal contact of the basalt. Additionally, calcite and datolite are favored in sites where the geological relationships indicate that fluid-rock reaction was limited or where fluid flux was high. Prehnite occurs at sites remote from the basal contact of the basalt and/or where alteration of the country rock is more intense and pervasive.

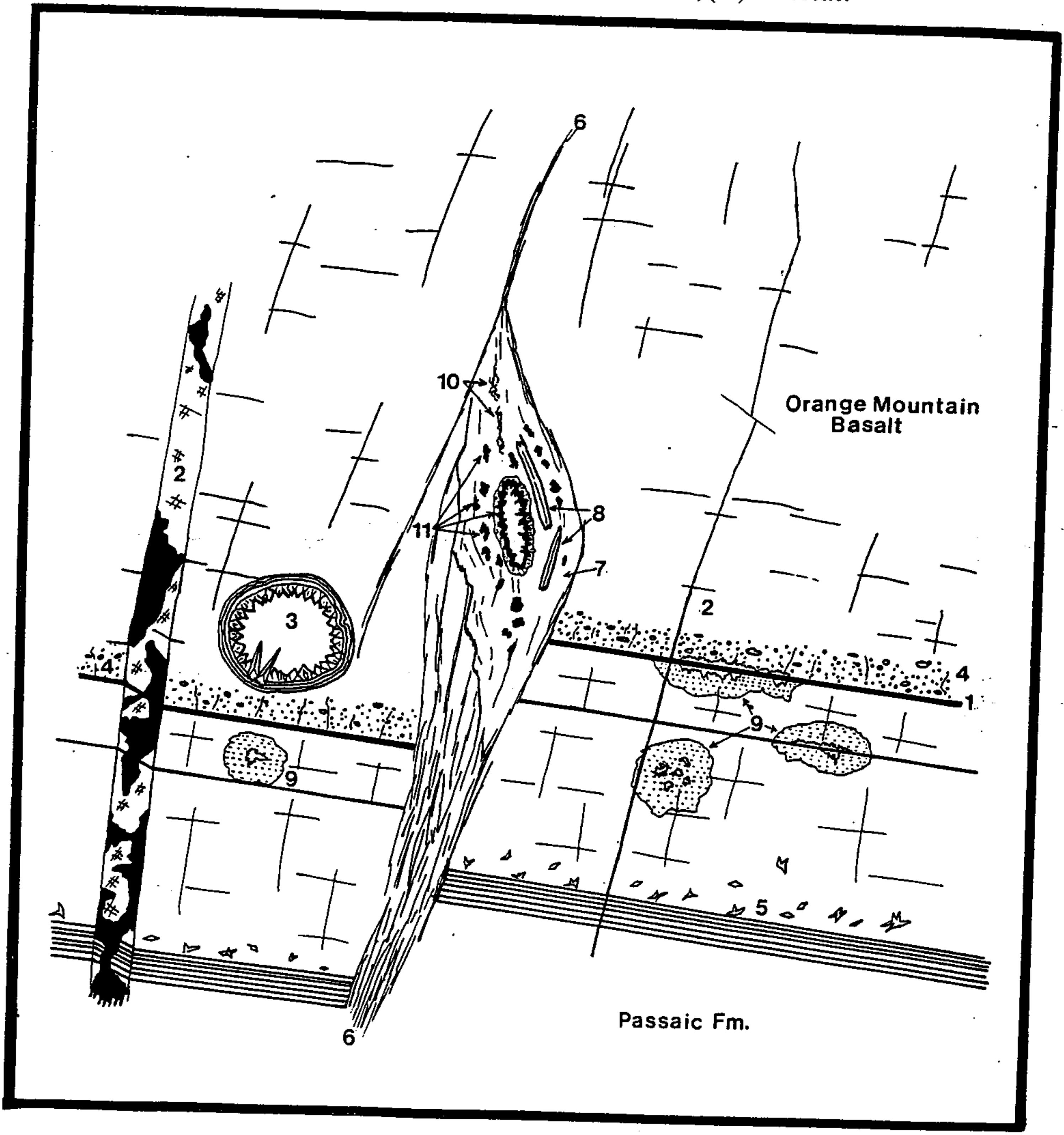
Native Copper and Base Metal Sulphides

Native copper and chalcocite are abundant in a conformable zone just beneath the basal contact of the Orange Mountain Basalt and in fissures within the basalt. In the sediments immediately beneath the basalt most of the native copper occurs in a crudely polygonal network of veinlets oriented perpendicular to bedding. Native copper in the veinlets occurs as sheets, commonly 1/8 inch thick, that replace the adjacent mudrock (Fig. 3). The polygonal blocks are approximately 1.5 feet across. The veinlet network has some superficial similarities with mudcracks but the polygons are larger and less regular in shape. The veinlets that outline the polygons are crosscut by the joint system and may be dewatering structures.

Other native copper replacements occur throughout the mineralized sediments. Many of these are localized by an identifiable feature, such as a bedding plane or a concentration of root casts. Some appear randomly scattered and unrelated to any identifiable permeable pathway. At Chimney Rock, native copper replacements of the sediments are always surrounded by a relatively wide halo of bleaching (Fig. 3). The bleaching, from dark maroon to tan, is due to the reduction of ferric iron and the partial leaching of ferrous iron (Woodward, 1944). It is similar to the bleaching commonly observed in the native copper area of Michigan (Butler and Burbank, 1929).

Chalcocite is abundant in the same thin sedimentary interval as native copper but occurs almost exclusively as an open space filling in minor fractures. Chalcocite bearing veinlets are not flanked by bleached halos. They are often seen to crosscut the native

Fig. 3: Idealized sketch of copper-rich basal contact zone at the Chimney Rock quarry. Numbered features are (1) basalt-sediment contact, (2) chalcocite-calcite veinlet, (3) large, isolated, silica-calcite filled amygdule, (4) basal chill zone with tiny amygdules, (5) evaporite mineral casts, (6) larger fault, (7) extensional lens filled mostly by calcite. (8) highly altered basalt fragments, (9) native copper replacement masses with bleached halos, (10) native copper sheets and dendritic masses in calcite, (11) chalcocite.



copper replacements.

In the Orange Mountain Basalt native copper and chalcocite are limited to fissures. Most, perhaps 90%, of the copper in the basalt was deposited as native copper and chalcocite within 25 feet of the basalt-sediment contact. The most favorable sites were just above the contact where contrasting competencies of the rocks caused deflection of fault planes (Fig. 3). Fault movement at the deflections often resulted in extensional openings which remained incompletely filled at the onset of copper-chalcocite deposition. Some of the extensional lenses were large enough to retain a central vug, the site of the largest and best developed chalcocite crystals .

Native copper and chalcocite occurrences above the lowermost 25 feet of the basalt are sparse and isolated but are occasionally of significant size. All the occurrences, remote from the basal contact, have been in faults that exhibit features that suggest above normal hydraulic conductivity. These features include wide zones of fracturing containing thick, vertically extensive veins of calcite or datolite and, occasionally, horses of red mudstone.

More typically, at distances greater than 25 feet above the basal contact of the basalt, bornite and then chalcopyrite become the dominant copper minerals. Bornite is found through most of the quarry as isolated, anhedral masses, up to 2 inches, in calcite or datolite filled fissures. Sassen (1978) reported that bornite forms massive vein fillings. Chalcopyrite occurs in a manner similar to bornite but is rare below the stratigraphically highest parts of the quarry. Chalcopyrite is the most abundant sulphide in the amygdaloidal rock, as is typical of other localities in the Orange Mountain Basalt.

Sodium Zeolites - Calcium Zeolites

As was recognized by Schaller (1932) the "zeolite period" is limited to the later stages of mineral deposition. At the Chimney Rock Quarry zeolite mineral deposition is associated with intense country rock alteration and clearly postdates the copper minerals. Zeolites occur only locally in faults, usually in vugs in extentional lenses with abundant breccia fragments. Zeolites are much more abundant in the intensely altered parts of the amygdaloidal rocks. In general throughout the Watchung Basalts the calcium-rich species stilbite and heulandite are by far the most common zeolites . Sodium zeolites, mainly analcime and natrolite, occur only locally, but when encountered, are often very abundant. Stilbite and heulandite are frequently either absent from the analcime/natrolite assemblage or occur as minor late phases.

Many years of collecting experience suggest that in fault filling veins the abundance of analcime and natrolite relative to stilbite and huelandite is substantially greater than is typically found in other environments. In the northern end of the Chimney Rock Quarry, where amygdaloidal rock is intersected by a prominent fault, analcime is abundant in cavities near the fault while heulandite appears to be the only zeolite present elsewhere.

DISCUSSION

The work of Steckler, et al (1993) indicates that gravity driven hydrothermal circulation was widespread in the Newark Basin. Fluid circulation through most of the stratigraphic section must have been largely fracture controlled. The Stockton Formation, the basal sedimentary unit and predominately sandstone, is the only extensive formation beneath the basalts that may have acted as an aquifer. Vigorous fluid circulation within the Newark Basin was dependant on the development of a dense fracture network throughout the basin. There is little question that extensive hydrothermal circulation occurred but its time of onset and duration are poorly constrained. Also unclear are the relative effects on temperature of upwelling fluid flow and burial.

Veins in the unmetamorphosed sedimentary rocks of the Newark Basin are very common. Like their counterparts in the Hartford Basin (Gray, 1988), they show little or no alteration of the wall rocks. Most veins in the Lockatong and Passaic Formations contain calcite and minor quartz, minerals that are ubiquitous in the country rocks, indicating that the hydrothermal fluid chemistry was in equilibrium with the sediments.

By contrast porous and permeable lithologies in the Watchung Basalts were not in equilibrium with the hydrothermal fluids and were intensely altered. The secondary mineral assemblages, present in the open spaces in the basalt, are far more diverse than those in the sediments. Many of the secondary minerals found in the basalts, including some of the most abundant, are not the products of an isochemical recrystallization of the basalt. Secondary minerals deposited at all stages of the paragenetic sequence incorporate major amounts of carbonate, sulphate, boron, copper and sodium, ions that are unlikely to have been adequately supplied by the basalt.

The most obvious evidence for the introduction of chemical species from the Passaic sediments into the basalt at the Chimney Rock Quarry is the continuity of calcite veins from the Passaic Formation into the overlying Orange Mountain Basalt. In addition, the greatest concentration of copper is in the sediments immediately beneath the basalt. Copper deposition in calcite veins begins in the same interval of sediments and crosscuts the basal contact of the basalt. As will be discussed subsequently the pattern of copper minerals conforms to that which would be expected from deposition by an upward moving fluid.

There is an extensive literature concerning the secondary mineralogy of basalts. Many of the described occurrences are plateau lavas, largely olivine basalts, that were subject to burial metamorphism, a process during which fluid circulation was apparently sluggish (Walker, 1951, 1960a, 1960b; Murata, et al., 1987; Sukheswala, et al., 1974; Neuhoff, et al., 1997). The plateau lavas are commonly thick sequences of basalt with little interbedded sediment. The secondary mineral assemblages present in these rocks and their spatial distributions are quite different from those seen in the Watchung Basalts.

In plateau basalts secondary mineral assemblages occur in distinct, nearly conformable zones, ranging from approximately 350 feet to more than 3500 feet thick. In undeformed lavas these mineralogical zones may appear conformable but on a regional scale they often crosscut the basalt stratigraphy. They are disrupted only around intrusives and are interpreted to reflect depth of burial.

By contrast in the Watchung Basalts the secondary mineral assemblage is similar throughout their stratigraphic interval, approximately 3500 feet. Mineralogical differences in the Watchungs are controlled on a local scale by lithology and permeability. Mineral zones similar to those recognized in plateau lavas have not been recognized.

In the mineral assemblages typical of plateau basalts calcite may be common but is only locally a dominant component. Sulphur, as sulphide in pyrite, is a trace mineral and as sulphate in anhydrite, is present only in basalts that were altered by seawater. Moore and Schilling (1973) found that basalts erupted subaerially or under very shallow water cover lost most of their sulphur by degassing. Studies of active and fossil geothermal systems in Iceland (Mehegan, et al., 1982; Ragnarsdottir, et al., 1984) indicate that carbonate and sulphate are introduced by circulating meteoric and sea waters. Carbonate uptake by the basalt, through calcite deposition, is one of the major changes effected by the alteration process in environments where carbonate is available.

Copper-bearing minerals (chalcopyrite) are very minor or absent and boron-bearing minerals are generally unknown.

Sodium, released by alteration is commonly fixed in albite and analcime. The sodium zeolite, natrolite, is rare or absent in the plateau lavas while scolecite and mesolite, similar to natrolite but more calcium-rich, are often abundant. In the Watchung Basalts natrolite is locally abundant, while mesolite and scolecite are unknown, and is favored by sites of relatively high fluid flux. These factors suggest that an external source of sodium is required for natrolite to crystallize rather than mesolite or scolecite.

Studies of plateau basalt areas yield consistent evidence that alteration of basalt in an environment of sluggish fluid circulation does not provide the chemical species that are major, often dominant, components of secondary mineral assemblages in the Watchung Basalts. Basalts, such as the Keweenawan, that have experienced large scale fluid migration, show more evidense of the introduction of chemical species.

At the Chimney Rock Quarry the relative abundances and spatial distributions of the secondary minerals indicates that copper and other chemical species were introduced from the Passaic Formation into the basalt where hydrothermal mineral deposition was controlled by fluid/rock reactions. The pattern of deposition of copper minerals, uniquely abundant at Chimney Rock among presently active Newark Basin quarries, is the strongest indicator of fluid flow and evolution.

The copper occurrence exhibits many features consistent with red-bed type copper deposits, first described by Lindgren (1933) and by many workers since, including Rose (1976). Red-bed type copper deposits are usually associated with evaporite bearing, first cycle red bed sediments deposited in rifts such as the Newark Basin. The igneous and metamorphic minerals typical of this type of sediment tend to contain metal trace elements and be highly susceptible to diagenetic breakdown which releases the trace metals (Walker, 1989). Much of the metal is adsorbed on iron oxides (Zielinsky et al, 1983). Oxidized, saline formation water is able to leach copper and transport it as cuprous chloride complexes, $CuCl^{-2}$ and $CuCl^{-3}$ (Rose, 1976, 1989). If the metal-bearing brines migrate and encounter reducing conditions sufficient reduced sulphur may become available to cause the deposition of copper minerals (Rose, 1976; Sverjenski, 1987). The reducing agent is usually a black shale rich in pyrite and organic matter. Reduced sulphur is usually supplied by the dissolution of pyrite or the reduction of sulphate either by organic matter, or by bacteria in the presence of organic matter.

In a typical red-bed type copper depositing system an oxidized metal-bearing solution enters and passes through a reducing environment along an established flow path. A continuous flux of solution progressively oxidizes the available reducing agents. This begins at the point of entry of the oxidizing solutions into the reduced rocks and advances along the flow path as a series of chemical fronts. Copper minerals deposit in a characteristic spatial and paragenetic sequence along the resulting chemical gradient (Barnes, 1975; Brown, 1971; Haynes, 1986; Haynes and Bloom, 1987; Ripley, et al, 1985, Robertson, 1975; Sverjenski, 1987; Wilton and Sinclair, 1988).

If the metal-bearing fluid enters a pyritic shale, where iron and sulphur are abundant, chalcopyrite deposits first, replacing pyrite, where the metal-bearing fluid enters the reducing environment. As chalcopyrite deposition advances progressively into the shale the site of initial deposition becomes more oxidized. Bornite begins to replace or overgrow chalcopyrite. This is repeated with chalcocite and native copper. In the ideal prograde sequence, native copper occurs in the most oxidized sites, nearest the fluid source. It is followed, at increasing distances into the reducing environment, by chalcocite, bornite, chalcopyrite, galena-greenockite, sphalerite and pyrite. The paragenetic sequence at a specific site would begin with pyrite and end with native copper.

Chimney Rock is unusual because no evidence has been seen that either pyrite or organic matter were present. The only reducing agent in proximity to copper deposition appears to be the ferrous iron bearing minerals, such as magnetite, in the basalt. This suggests that the reduced sulphur that precipitated the copper minerals resulted from the inorganic reduction of sulphate by ferrous iron in the basalt. Mottle, et al. (1979) determined that the minimum temperature required for sulphate reduction by reaction with basalt to operate with effective speed is approximately 200^0C. Fission track data (Steckler, et al, 1993) and the presence of epidote indicate that 220^0C was exceeded, but not greatly exceeded, during the hydrothermal event. Oxidation of ferrous iron is suggested by the presence of hematite (and goethite) in minor fractures, amygdules and local permiable zones especially in the basal 25 feet of the basalt. The age of the hematite, relative to the copper minerals, is unclear. Where copper minerals are found in close enough proximity to hematite to determine relative age, hematite is always earlier.

Although the the copper deposit at Chimney Rock has many features in common with red-bed type copper deposits there are some variations from the norm. In the uppermost 18 inches of the Passaic Formation native copper deposited prior to chalcocite and in the vein system in the basalt prograde overgrowths among copper minerals are very rare. These abnormal features may be due to the sulphur deficient nature of the depositional environment.

The deposition of copper minerals at Chimney Rock took place in an environment where reduced sulphur was never more than minimally available. Hydrothermal fluid flux began prior to the attainment of temperatures sufficient to produce H_2S. It is likely that the temperature passed the threshold for sulphate reduction slowly and that H_2S production was at first very sluggish. The amount of copper present in solutions occupying the joints in the basalt as H_2S became available was very small and would have been removed and deposited as a trace mineral. The creation of H_2S in the basalt's restricted joint system would effectively create a barrier to the migration of copper into the basalt and limit it to the more permeable structures such as faults and amygdaloidal flow tops.

Beyond the obvious zones of high fluid flux permeability appears to have been low enough that the diffusion rate of H_2S exceeded the upward fluid velocity. H_2S was able to diffuse downward into the sediments. Initially, the first faint wiffs of H_2S provided only enough reduction to deposit native copper(Ag). Deposition of copper created significant acidity. The corrosive environment may have created secondary porosity, caused copper to replace the mudstone and mobilized iron resulting in the observed bleaching.

Chalcocite, very commonly associated with calcite, occurs in veinlets that crosscut the native copper replacements. These veinlets have not been studied sufficiently to determine if they are related to the joint system. The deposition of chalcocite required an increased availability of H_2S and is clearly later than the native copper. It may represent deposition in fissures that were newly opened and allowed an increased flux of H_2S because permiability or temperature was higher. The deposition of chalcocite, bornite and chalcopyrite coincided with the crystallization of prehnite and datolite.

At Chimney Rock copper minerals are distributed throughout the hydrothermal plumbing system in a pattern typical of red-bed type copper depositing systems. They are concentrated in, and an integral part of, the middle part of the Fenner/Schaller paragenetic sequence concurrent with minerals most likely to have been deposited during the time of peak temperature. Sulphides did not crystallize significantly later than the end of datolite-prehnite deposition. Because there is no evidence that the minimum temperature required for the reduction of sulphate to sulphide was substantially exceeded, the onset of decline of fluid flow and temperature effectively ended sulphide deposition.

Locally, significant copper remained in hydrothermal fluids that reached the top of the Orange Mountain Basalt. Immediately above the Orange Mountain Basalt is the Feltville Formation which contains an extensive gray-black shale in its lower part indicative of sharply increased lake depths (Schlische and Olsen, 1990). The Feltville Formation water may have been significantly less saline and more reduced than that of the Passaic Formation, conditions not conducive to the leaching and transport of copper. Abrupt dilution and chemical reduction would account for the observed deposition of nearly all copper leakage that reached the top of the Orange Mountain Basalt in the amygdaloid just beneath the basal contact of the Feltville Formation. Above the Orange Mountain Basalt it appears that conditions in the sediments were not conducive to copper mobilization. In the Preakness and Hook Mountain Basalts, only very minor amounts of chalcopyrite, probably representing copper derived locally from the basalt, are present .

Although copper minerals are associated with the Orange Mountain Basalt throughout much of its extent they are abundant only near the southern end of the Watchung Syncline. This pattern of distribution may be due to the proximity of the Chimney Rock area to the central part of the Newark Basin. Because the upper part of the Passaic Formation was deposited during a relatively arid period evaporites may have been more abundant in the central part of the basin. A higher salinity of the formation water in this region would tend to increase the mobility of copper and the chance of depositing more significant concentrations.

CONCLUSION

At the Chimney Rock Quarry the most important factor in the deposition of secondary minerals was the reaction between a generally upward migrating hydrothermal fluid and the basalt. As suggested by Gray (1988) the available evidense indicates that the hydrothermal fluid was hot formation water. The chemistry of the secondary minerals depended on the chemistry of the fluid from which they crystallized. The chemistry of the fluid evolved through fluid/rock reaction which is dependant on permiability, lithology and temperature. Progressive alteration of fluid chemistry has produced the paragenetic sequence and spatial distributions of the secondary minerals seen today.

The paragenetic sequence developed in the Paterson-Great Notch area by Fenner (1910) and Schaller (1932) was shown by Sassen (1978) to be applicable to the secondary minerals of the Chimney Rock quarry. Although the most intense concentration of copper minerals is in the Passaic Formation sediments just beneath the basal contact of the Orange Mountain Basalt this reflects the difference in the depositional process between the copper minerals and the other secondary minerals. Copper minerals are found sporadically throughout the quarry and are an integral part of the calcite-prehnite-zeolite mineral assemblage that is typical of the Watchung Basalts. The only extraordinary thing about the secondary mineral assemblages in the Chimney Rock Quarry is the increased variety and abundance of copper minerals.

The spatial distributions of several secondary minerals and groups of minerals in the quarry all indicate a general upward flow of hydrothermal fluid out of the underlying Passaic Formation and through the basalt. In general the mineral assemblages that crystallized in sites with more direct hydraulic connection to the Passaic Formation sediments are those that contain chemical components that are likely to have been introduced into the basalts from the sediments. At sites more remote from the Passaic sediments minerals containing only basalt derived components are predominant.

At present, only the outline of the processes and effects of the hydrothermal event in the Newark Basin is discernable. Further resolution will require studies that go beyond those based largely on sample collecting and mapping to a more quantitative approach such as has already been applied to the petrogenesis of the igneous rocks of the basin.

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THE AMERICAN MINE COPPER DEPOSIT OF NEW JERSEY

Cattafi, P.P; Mahon, J.C.; Shaw, M.F.; Stefanik A.; Syred, T.A.; Villacis, J.P.; and
Puffer, J.H.
Department of Geological Sciences
Rutgers University
Newark, NJ 07902

ABSTRACT

The American Mine (also known as the Bridgewater Mine and Van Horne's mine) is one of 52 historic copper deposits mapped by Lewis (1907). The American Mine was the most productive mines in New Jersey and was active during several intervals from pre Revolutionary War time until it was finaly closed in 1909. The ore is confined to a one m layer of Passaic Siltstone located directly beneath and conformable to the early Jurassic Orange Mountain Basalt and to a chloritized amygduloidal basalt layer at the base of the flow. The ore consists of disseminated native copper, cuprite, and chalcocite with variable malachite and chrysocolla. Chemical analyses of 8 new samples collected from the deposit indicate copper concentrations up to 5.6 percent. The copper concentrations correlate negatively with potassium and iron content but positively with and magnesum (chlorite) content and with sodium suggesting precipitation at elevated temperatures.

MINE DEVELOPMENT

Before the Revolutionary War several small drifts were driven into the base of the Orange Mountain Basalt near Bridgewater, New Jersey some of which extended about100 feet. Before 1754 as much as 1900 pounds of native copper was discovered including one nugget weighing 128 pounds (Woodward, 1944)

During the Revolutionary War (1790-1800) it is widely reported (Woodward, 1944) that when the Continental army was camped near the American Mine enough native copper was found to make a brass cannon although this report may not be factual.

After the War (during 1821) Augustus Camman bought three tracts of land near Bridgewater including the American Mine site and organized the Bridgewater Copper Company. During 1824 he erected smelters at Chimney Rock and at the American Mine site that was then named the Bridgewater Mine. Mining at the Bridgewater Mine, however was unsucessful and the mine was closed in 1830. The activity there during the 1820s occurred during the beginning of the period of greatest copper mining activity in New Jersey, from 1825 to 1850 (Weed, 1902).

The mine remained abandoned until 1880 when the American Copper Company was organized by A.H. Hovey who reopened the mine. Kummel's (1900) report on the progress of the American Mine describes the renewed work by A.H. Hovey in 1881 when a new tunnel was driven into the hillside for a distance of 228 feet with side-drifts of 240 feet. The ore was mined like coal with no timber but with ore pillers holding up the roof of the mine. The average copper content of the high grade ore was reported to be 19 percent with 6 ounces of silver per ton (probably an inflated value) but not enough new ore was found to justify furthur development and the mine was closed again in 1883.

The mine was abandoned until about 1897 when work resumed once again. Considerable activity occurred at the American Mine in 1901. The main tunnel was extended an additional 655 feet to a length of 1112 feet down the dip of the Passaic Formation at the base of the Orange Mountain Basalt to a depth of 600 feet (the deepest copper mine in New Jersey). A secont tunnel (the Spencer slope) was lengthended 160 feet, and 740 feet of side-drift work was done for a total of 1270 feet of slope and 1800 feet of side drifts. The drifts were driven 30 feet apart. Also in 1901 president J. C. Reiff and general manager Josiah Bond, of the American Copper Company, installed a 20-ton brick and steel-jacketed smelter designed for testing" (Reiff and Bond, 1902). As of 1901 the equipment at the American Mine consisted of a 5-drill Rand Compressor plant with a 80 horsepower boiler, a hoisting plant with a 12-horsepower Lidgerwood engine, a mill with a 60-horsepower boiler and engine, a crusher, two sets of roughing rolls, drier, screen, sizers, and two Wilfrey tables for a daily capaacity of 50 tons of ore.

Mining at the American Mine was conducted using small hand drills, three quarters of an inch in diameter. Small "Gleason" pumps consisting of a tin tube with a wooden piston, a discharge pipe an inch in diameter, and a four-foot wooden lever for one man to operate, were inadequate to cope with the water obstacle which always drove the minor out of his diggings (Weiss and Weiss, 1963). Dynamite was not used during the greater part of the mining. Instead, small and usually shallow holes were fired by pouring in coarse, black powder, tamping it lightly and inserting a rye straw filled with fine powder to which was attached a cotton string that had previously been dipped in melted sulfur. The miner lit the string and ran (Weiss and Weiss, 1963).

The surface equipment was later enlarged and several thousand tons of crude ore were mined and several hundred tons of high grade were run through the crusher and were smelted with good results. Everything looked hopeful, but the mining operations in succeeding years quickly slowed down. In 1904 the mine was closed, and a little later the company was out of business (Weiss and Weiss, 1963). As of 1906 the American mine consisted of 2040 feet of side drifts into the top of the Passaic Formation.

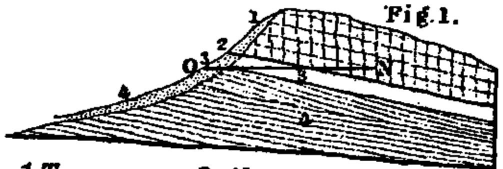
The American Mine was oppened one last time in 1907 by the Alpha Copper Company but production lasted only until 1909 when it was finally closed (Woodward, 1944).

ORE DESCRIPTION

The American Mine copper ore is hosted largely by the Passaic Formation which consists of Mesozoic red-bed siltstones described by Olsen (1980) and Olsen and others (1996) but some ore is also found along the base of overlying Orange Mountain Basalt (Figure 1). The abandoned historic mine site is located along the base of a basalt ridge in

Geol. Section, Bridgewater Mountain
Somerville N.J.

Fig. 1.



1 Trap.
2 Copper Ore.
3 Altered Rock.
4 Red Sandstone.
5 Debris & Drift.

Fig. 2.

Section along A.B. on the Map.

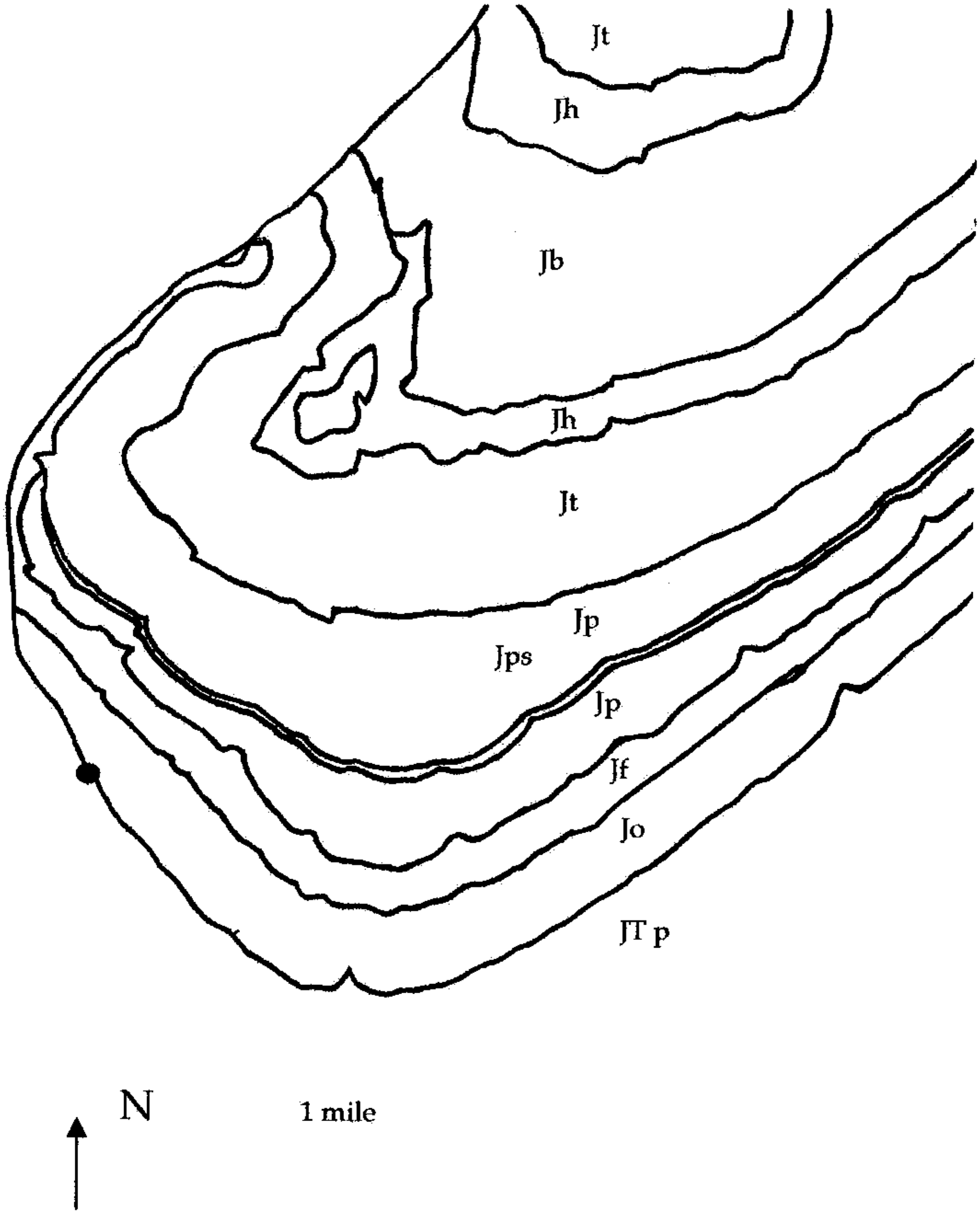
Dip of the Strata 6° 40'

Explanation of letters.

a. Trap Rock
b " " altered & soft
c Copper Ore
d Shale, much altered by the Trap.
e Red Shale.

Figure 1. Section through "Bridgewater Mountain" at the American mine from "Act of Incorporation and By-Laws of the Washington Mining Company, New Jersey" Boston, 1846. The "trap" is Orange Mountain Basalt; the "red sandstone" is Passaic Formation.

Fig 2



Legend

JT p – Passaic Formation
Jo – Orange Mt. Basalt
Jf – Feltville Formation
Jp – Preakness Basalt
Jps – Preakness Basalt
Jt – Towaco Formation
Jh – Hook Mt. Basalt
Jb – Boonton Formation
● - Study Area

Figure 2. Geologic map of Mesozoic formations and location of the American Mine study area at the base of the Orange Mountain Basalt.

a residental neighborhood (Figure 2) that does not lend itself to field trip access extept for small groups at the permission of local home owners.

The age of the siltstones ranges from upper Triassic to early Jurassic, although the high grade copper ore is confined to the uppermost or early Jurassic portion of the formation. Portions of the Passaic Formation are intruded by the Palisades Sill (an early Jurassic 400 m thick diabase) beneath each of the copper deposits at the base of the Orange Mountain basalt. The dip of the contact (and mine workings) was 10 degrees to the NE into the Passaic Formation at the base of the Orange Mountain Basalt (Figure 3).

The ore at the American Mine is concentrated in the uppermost Passaic siltstone at the base of the Orange Mountain Basalt. The ore zone is 12 cm to 90 cm thick and consists of dark purple hornfels in contrast to the red siltstone below the ore zone. The richest copper concentrations are found in dark green irregular amiboid shaped bodies surrounded by bleached white spots about 3 to 30 cm across with most of the copper mineralization located near the center of the spots (Figure 4).

Eight new rock samples were collected along a traverce perpendicular to strike through the ore zone at the American Mine (Figure 3) and were chemically and petrographically analyzed.

Brief descriptions of the eight samples:

1. Passaic mudstone - brick red, fine grained, very friable mudstone containing mica flakes, with well developed laminations typical of Passaic Formation

2. Passaic sandstone - brick red, medium grained sand facies from a 4 cm thick bed containing common mica flakes, with well developed bedding.

3. Passaic hornfels - purple meta-siltstone, hard and compact, with poorly developed to absent bedding and no evidence of any organic content.

4. Passaic hornfels copper ore -
    - 4a. dark purple meta siltstone, hard and compact, with small open vugs resembling vessicules, with no apparent bedding or laminations (Figure 4).
    - 4b. dark gray spot rimmed with white containing 1 percent native copper and 2 percent cuprite (Figure 4).

5. Passaic hornfels copper ore -
    - 5a. bleached zone, almost white (carbonate enriched) rim around dark green high grade ore within meta-siltstone.
    - 5b. dark green spot enriched in chlorite, cuprite, and native copper.

6. Passaic vein filling from a joint surface composed largely of secondary malachite, chrysocolla, limonite, chlorite, and fine grain pelitic detritus.

7. Orange Mountain basalt - dark green, chloritized and vuggy basalt.

Figure 3. Cross section through the American Mine, with location of analyzed samples.

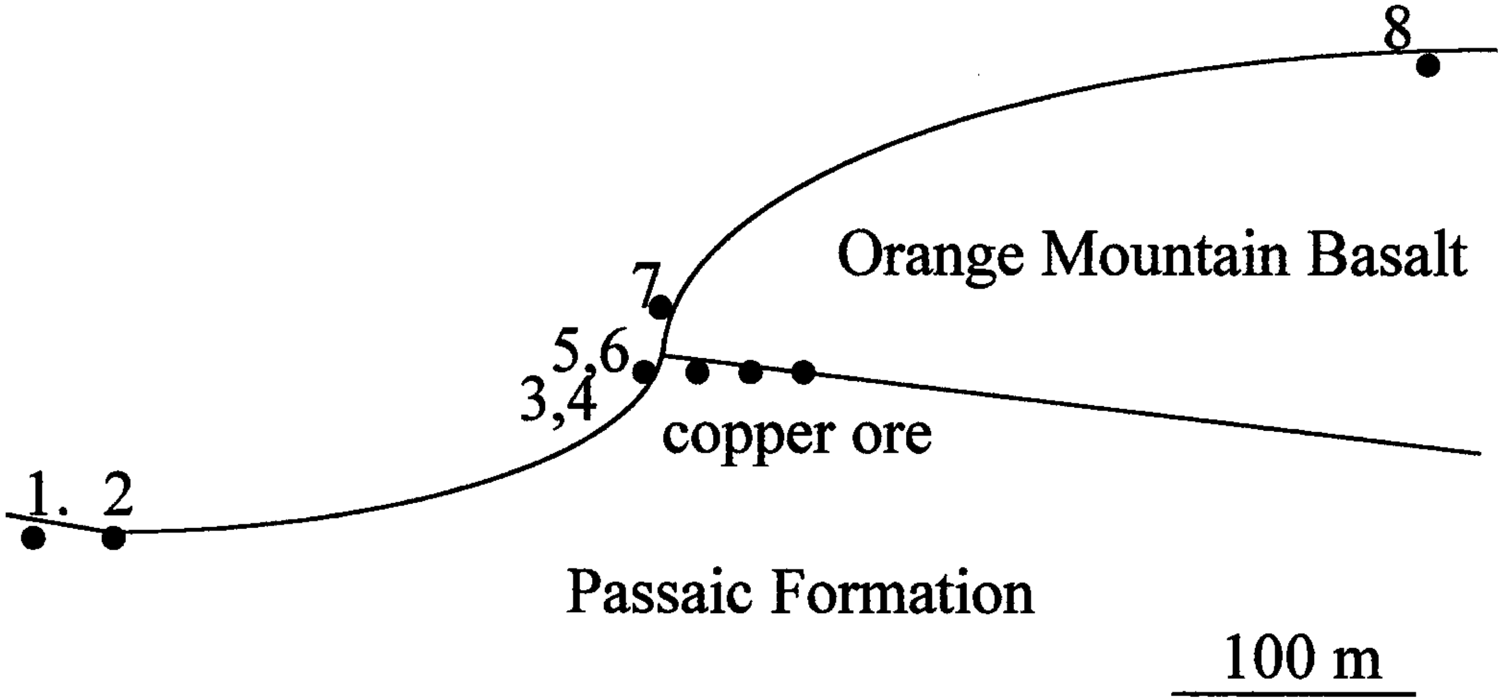


Table 1

American Copper Mine, New Jersey

sample	1	2	3	4a	4b	5a	5b	6	7	8
rock	red-bed	red-bed	hornfels	hornfels	hornfels	ore	ore	ore	basalt	basalt
color	red	red	purple	purple	gray	white	dk green	lt green	gray	glack
Weight percent										
SiO2	55.45	61.23	56.34	52.56	49.97	43.2	37.42	49.37	50.67	51.87
TiO2	1.05	0.97	0.89	1.02	0.75	0.74	0.73	1.89	1.15	1.09
Al2O3	19.7	18.1	23.65	15.49	19.86	20.05	8.31	12.23	13.65	14.12
FeO	8.57	6.11	7.32	11.36	5.65	6.41	3.45	3.83	9.9	10.1
MgO	4.12	3.59	5.23	8.14	6.39	7.32	4.86	3.92	8.57	7.71
CaO	0.3	0.29	0.42	0.38	1.98	5.96	0.56	0.72	10.68	10.68
Na2O	0.96	1.57	2.49	7.1	5.65	4.32	3.68	5.89	2.24	2.41
K2O	4.05	2.66	0.86	0.22	0.31	0.29	0.13	0.11	0.46	0.39
P2O5	0.06	0.05	0.11	0.16	0.18	0.17	0.17	0.19	0.16	0.14
LOI	5.04	5.12	3	2.67	6	6.98	32.3	16.35	1.85	1.29
Cu	0.01	0.01	0.09	0.08	2.45	2.83	6.85	4.75	0.01	0.01
total	99.31	99.7	100.4	99.18	99.19	98.27	98.46	99.25	99.34	99.81
ppm										
Cu	68	62	850	839	24546	28341	68529	47522	119	125
Zn	148	141	130	150	154	119	121	nd	82	84
Sr	209	209	nd	127	nd	nd	65	87	168	190
Zr	173	259	nd	129	nd	nd	64	88	94	101
Ni	81	73	nd	94	nd	nd	nd	105	90	97

8. Orange Mountain basalt - black unaltered, massive basalt.

Passaic red bed samples were collected from a stream bank located less than 1 km west of the mine sice. The baren hornfels and copper bearing hornfels samples were collected within 2 m of the base of the basalt flow and the altered basalt was collected within 1 m above the base of the flow. The hornfels is characterized by a relatively tough and dense property and by much lower porosity and permeability than the unmetamorphosed Passaic red-beds.

Although published reports of the average copper content of the ore varies considerably a serious attempt to calculate an accurate average was published by Woodward (1944) based on 273 measured sections across the orebed on the main slope and in side drifts and chambers . The results indicate:

Percent copper	Number of samples
<1	52
1-2	94
2-3	64
3-4	43
6-7	5
7-8	7

An average of 2.101 percent copper was determined.

ORE MINERALOGY

Most of the copper concentrated in the white spots that we examined occurs as cuprite (Cu_2O) and native copper with variable amounts of chrysocolla $CuSiO_3.2H_2O$, malachite $Cu_2(CO_3)(OH)_2$, and chalcocite(Cu_2S).

Polished sections cut from samples of high grade copper ore from the American Mine contain at least 5 copper bearing species including:

1. cuprite - ranging from trace amounts in samples 4 and 5a to 10 percent in sample 4b to absent in all other samples. The cuprite occurs 0.5 to 1.5 mm mm grains shaped like small irregular grains with feathery grain boundaries. Most of the cuprite seems to be an alteration product of native copper and desplays replacement textures around residual grains of native copper (Figure 5).

2. native copper - ranging from trace amounts in sample 5a to one volume percent in sample 4b, to two volume percent in sample 5b to absent in all other Passaic siltstone samples and occurring as 0.1 to 2 mm grains shaped like lenses and irregular particles intergrone with cuprite (Figure 4). Native copper was also observed in amygdules in chloritized basalt samples at the base of the Orange Mountain flow although it is absent in all basalt found more than 1 m above the base. Most concentrations of native copper

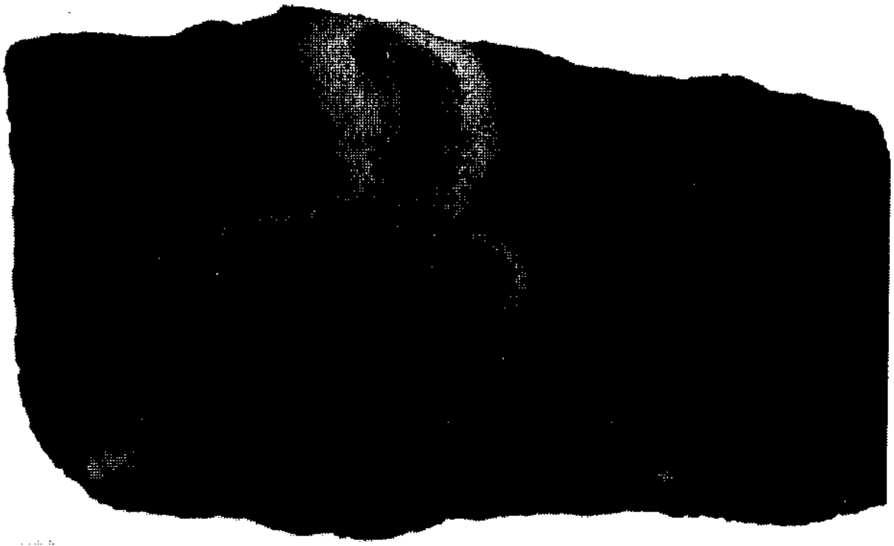


Figure 4. Typical slab of high grade copper ore sampled at the American mine within one meter of the overlying Orange Mountain Basalt. Note dark chlorite rich center of white spot (sample 4b, Table 1 and Figure 3) containing about 2 percent native copper and 2 percent cuprite. The white spot is surrounded by hard dark purple Passaic hornfels (sample 4a, Table 1 and Figure 3).

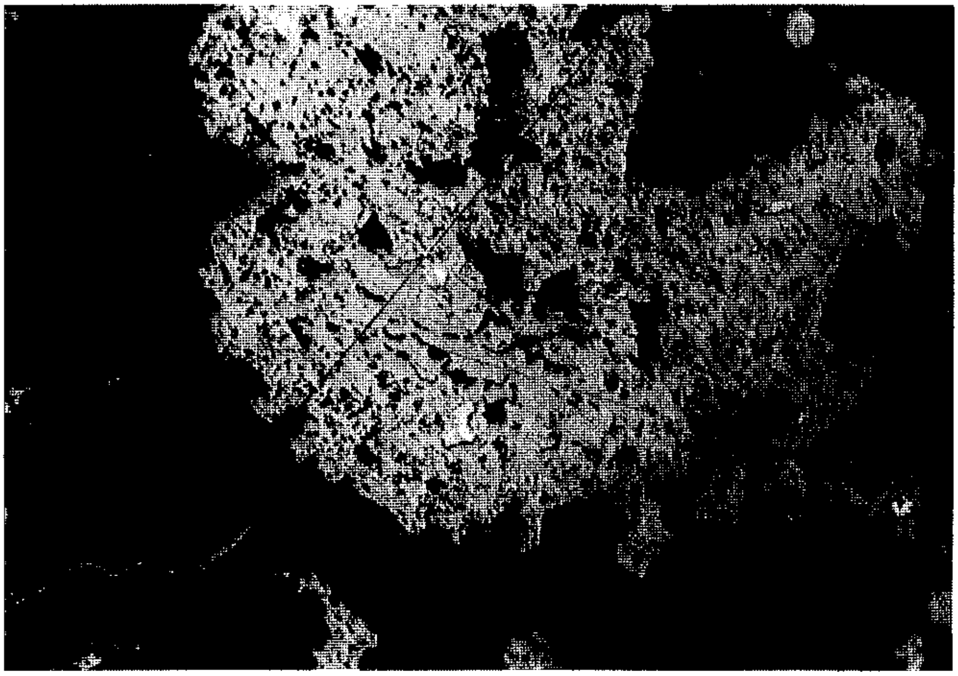


Figure 5. Polished photomicrograph of a grain of cuprite in reflected light from sample 4b (Figure 4). The cuprite grain contains about 25 volume percent unoxidized relic native copper. The field of view is 1 mm.

were found to be associated with small concentrations of dessiminated calcite surrounded by dark green chlorite in the purple hornfels.
3. chrysocolla - ranging from 2 volume percent in sample 5b to 5 percent in sample 6.
4. chalcocite - found in trace amounts in samples 5b and 6 and in a few unanalyzed samples typically occurring in veins with calcite and malachite. The chalcocite appears to be a secondary vein precipitate. Chalcocite is also reported by Woodward to occur as drusy masses and as minute specks in nodules of the bleached (white zone) hornfels.
5. chalcopyrite - small grains of chalcopyrite were found in sample 6.

In addition to the copper bearing minerals that we observed. trace amounts of bornite have also been reported by several authors.

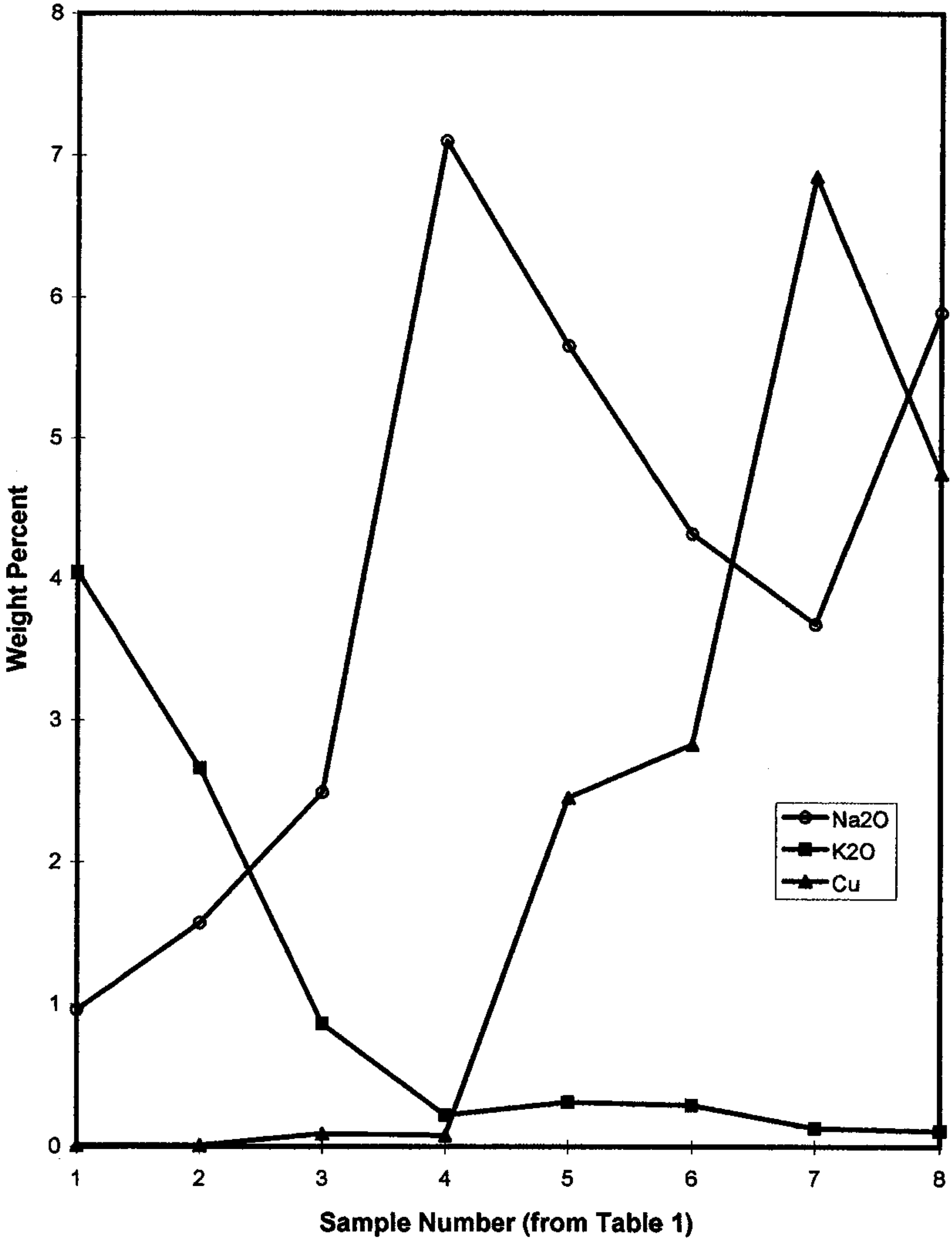
The samples that we analyzed are typical of high grade samples described by Weed (190x) , Lewis (1900) and Woodward (1944). Native copper, however was aparently the chief ore mineral, particularly below the near surface layers. Considerable variation in the mineralogy of the ore was found to be related to depth. All of the copper carbonates and silicates and most of the sulfides are confined to near surface layers persumable controled by supergene enrichment poreesses. As the base of the 600 feet level was approached the ore consisted primarely of native copper. Reiff and Bond (1902) describe masses of mineralized rock several feet in diameter consisting of 20 to 25 percent native copper.

GEOCHEMISTRY

The chemical composition of samples of American mine copper ore is compared with samples of adjacent Passaic siltstone relatively depleted in copper. The copper content of 8 unaltered samples of Orange Mountain basalt ranges from 85 to 140 and averages 127 ppm (Puffer, 1992); and the copper content of 2 samples of unaltered Passaic siltstone taken about 0.7 km stratigraphically beneath the American mine (Figure 3) is 116 and 147 ppm. In contrast the average grade of the ore at the American Mine was about 2 percent Cu.(Woodward, 1944). Examination of chemical content along our sample traverse through the American mine and perpendicular to the Orange Mountain /Passaic contact (Table 1) indicates a strong positive correlation of copper content with both sodium, magnesium, and water, a weaker positive correlation with calcium and phosphorus and a very distinct negative correlation with potassium and iron. The positive correlation with sodium content and the negative correlation of copper with potassium is particularly apparent. (Figure 6).

Each of these chemical trends are consistent with trends observed at high temperatures (>150 C°) where basalt has reacted with seawater (Thompson, 1983). Thompson found that at temperatures less than 150 C° reacted rock looses Mg and gains K but at higher temperatures the reacted rock gains H_2O, and Mg and looses K in agreement with our data. Country rock close to high temperature hydrothermal veins are also typically leached in large ion low charge ions such as K and Sr. Weathering reachion, however, result in the opposite results and are characterized by leaching of Mg and Ca with an addition of K and P. Our data therefore suggest that high temperature

Figure 6. Sodium, Potassium and Copper content of Passaic Red-Beds and Copper Ore at the American Mine



alteration processes controlled the final composition of the copper ore at the American Mine.

ACKNOWLEDGMENTS

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ORIGIN OF THE MESOZOIC RED-BED COPPER DEPOSITS OF NEW JERSEY

John H. Puffer
Department of Geological Sciences
Rutgers University
Newark, NJ 07102

ABSTRACT

The proposed origin presented in this report is unlike any of several previous published proposals and is consistent with each of the principal characteristics of the Mesozoic red-bed copper deposits of New Jersey. With rare exceptions each deposit is located at the base of the Orange Mountain flood basalt or near the margins of co-magmatic intrusive diabase. Most copper is concentrated in dense, black to dark purple sodic hornfels within a meter of igneous contacts and in amygdules and veinlets in the basalt. A few minor concentrations may not be located within close proximity to igneous rocks and are concentrated in gray strata that may have been enriched in organic content, although an igneous rock association can not be ruled out for any of the deposits on the basis of current mapping. I propose that saline brines leached copper from hot but cooling early Jurassic igneous rocks according to the mechanism commonly invoked for volcanogenic black smoker deposits. However, instead of marine water circulation as in the case of black smokers, brackish pond water and groundwater contained within thick layers of Triassic red beds circulated through hot diabasic rock. Instead of copper deposition near submarine vents, deposition of the New Jersey deposits occurred at the surface in solfatara muds near fumarole vents above thick active intrusions or close to thin copper enriched hypabysal sills. Most copper was concentrated in hot sodic muds at the surface where precipitation was controlled by the drop in the temperature and pressure of circulating brine. Some copper may also have been precipitated at depth wherever organic enriched strata were encountered. The copper enriched surface muds were then baked into a dense sodic hornfels by the extrusion of the first thick (70 m) Orange Mountain flood basalt extrusion. Copper enrichment at the base of overlying flows is absent to rare because of the absence of a similar sediment, brine, and intrusive sill configuration and because of previous dehydration of red bed sediments.

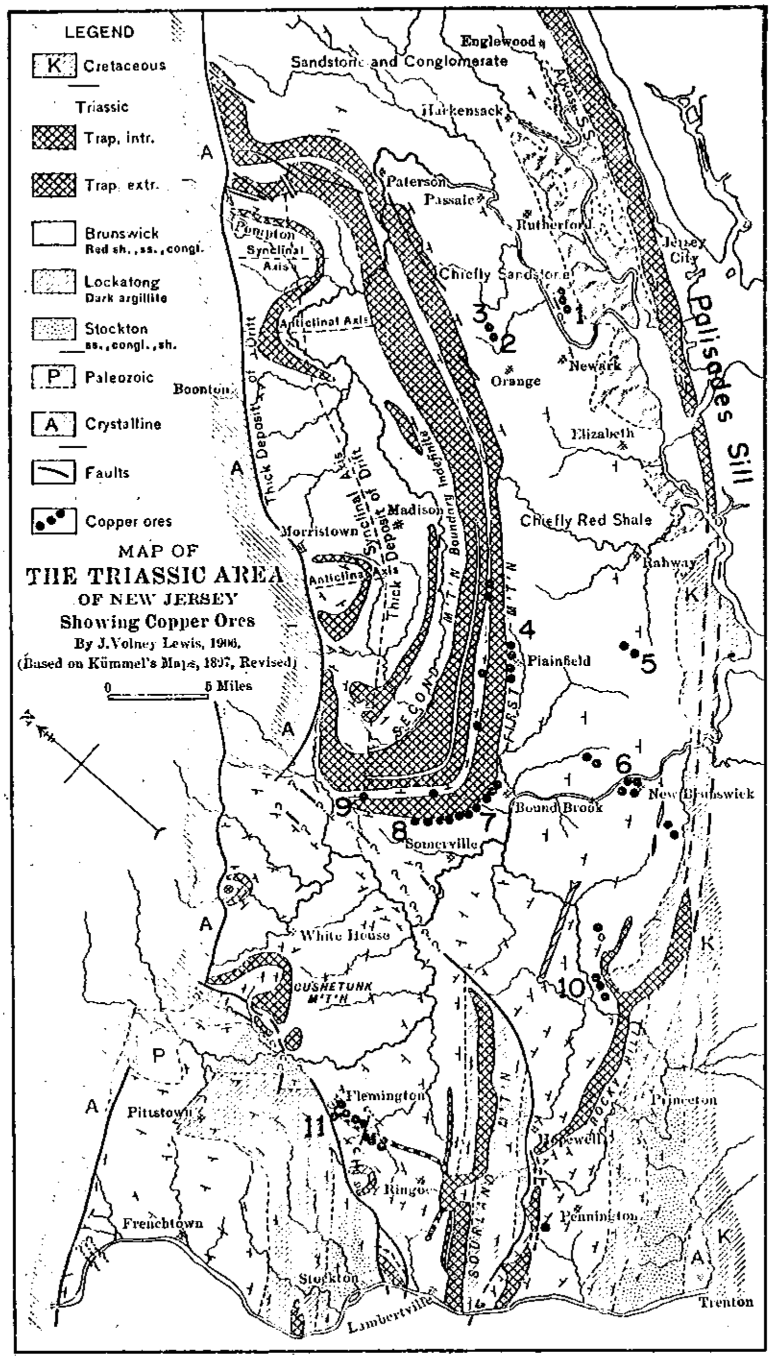


Figure 1. Copper deposits of the Newark Basin (after Lewis, 1907) with major deposits numbered and listed on following page.

Major Copper Deposits of the Newark Basin

1. The Schuyler mine, also called the Belleville, Arlington, and Victoria mine. Most of the ore occurs in Passaic meta-siltstone lenses adjacent to thin branching diabase dikes and sills.
2. The Dod mine; a small deposit in Passaic siltstone first mined in the 1720's.
3. The Glen Ridge mine; another small deposit in Passaic siltstone at the same stratigraphic position as the Dod mine.
4. The Stony Brook mine, also called the Green Valley prospect in Passaic meta-siltstone and adjacent Orange Mt. Basalt.
5. The Menlo Park mine, also called the Edison mine first mined in 1784 in Passaic siltstone.
6. The New Brunswick mine, also called the French mine was an open pit in Passaic siltstone located near a farm where Morse (1812) reported that prospectors found nuggets of native copper from five to thirty pounds in the soil.
7. The Chimney Rock mine in Passaic meta-siltstone and adjacent Orange Mt. Basalt; where one native copper nugget weighing 76 pounds was found in 1827 when it jammed the crusher. The nugget is in the Rutgers University mineral collection.
8. The American mine, also called the Bridgewater mine in Passaic meta-siltstone and adjacent Orange Mt. Basalt was the most productive copper mine in New Jersey.
9. The Hoffman mine, in scoreacous flow top of Orange Mt. Basalt .
10. The Griggstown mine, also called the Franklin mine, in Passaic meta-siltstone adjacent to a diabase sill, is one of the first copper mines in New Jersey with production preceding 1699.
11. The Flemington mine in Passaic meta-siltstone near an outlier of Watchung Basalt.

GEOLOGIC SETTING

At least 52 historic copper deposits of Mesozoic age occur in the red-beds of the Passaic Formation as mapped by Lewis (1907), (Figure 1). The ore varies from mine to mine but typically consists of disseminated native copper, chalcocite, and cuprite in upper Passaic Formation metasediments with less common native copper, and chalcocite in amygdules, joints, and fault plains along the base of the overlying Orange Mountain Basalt Minor quantities of malachite and crysocola concentrated along joint and bedding plains are found near the surface presumably as secondary supergene mineralization. Most copper ore found in the upper Passaic Formation is confined to a gray hornfels layer within one meter of the flow contact as typified by the American Mine (Cattafi and others, 1998, this guidebook). A few deposits, however, are found at deeper statigraphic levels, intermediate between the Orange Mountain Basalt and the underlying and co-magmatic Palisades sill. Most if not all of the mid-Passaic deposits are located within a few meters from a dike or sill of Palisades/Orange Mountain composition.

The upper Passaic Formation that is the host rock of most copper ore was deposited as lacustrian and fluvial sediment characterized by the effects of alternating Melankovich forced climatic cycles (Olsen, 1996) that resulted in expansion and contraction of lakes across alluvial plains. In general, the water level of the lakes and depositional rates decreased during Passaic sedimentation then rapidly increased at the onset of volcanic activity (Olsen and others, 1996). Calcium sulfate precipitation in the Passaic sediments and in amygdules in pillowed Orange Mountain Basalt indicate that the water was brackish.

The metamoprphic effect of the extrusion of the first flow of Orange Mountain flood basalt onto the Passaic sediments is highly variable. Although the flow was 70 m thick only 5 to 10 cm of gray hornfels was typically generated under the base of the flow. However, wherever copper mineralization is concentrated, the thickness of the hornfels increases to about one to two meters and local salt fluxing has resulted in a few occurrences of sediment fusion (Puffer and others, 1993).

PREVIOUS PROPOSALS

Several alternative enrichment mechanisms were considered including those proposed by Weed (1902), Lewis (1907), Woodward (1944), Robinson (1987), Robinson and Sears (1987), Robinson and Woodriff (1987), Smoot and Robinson (1987) and Puffer and Proctor (1992, 1994) for Jurassic New Jersey deposits and by Stolpert and Davidson (1959), Berger and Silberman (1985), Hedenquist and Lowenstern (1994) and Gray (1994) for deposits outside New Jersey but concentrated in geologic settings similar to the Summerville deposit. Most of these previous published interpretations of New Jersey Jurassic copper ore petrogenesis fall into three groups: 1) Deuteric release of copper from an Orange Mountain basalt source; 2) Copper precipitated out of groundwater into organic enriched Passaic sediments and 3) Hydrothermal fluids generated from intrusive sheets.

1) An Orange Mountain Basalt Source - Weed (1902) proposed that the New Jersey copper deposits were precipitated out of descending solutions that leached copper from basalt and transported it to the base of the flows and to the red beds below. Weeds's proposal recognizes the close relationship between most of the New Jersey copper occurrences and the lower contact of the Orange Mountain Basalt (Figures 1 and 2a). Weed (1902) also recognizes similarities between the native copper dominated mineral assemblage of the New Jersey occurrences and the copper deposits of the Keweenawan Basalt. The Keweenawan copper deposits of the upper peninsula of Michigan are also widely thought to have been derived from solutions that precipitated copper in vesicles at the top of thick flood-basalt flows, although most New Jersey deposits are found in metasedimentary hornfels at the base.

2) Organic Stratabound Precipitation - Robinson and Sears (1988) classify the American Mine (Bridgewater Mine) and most New Jersey Mesozoic copper deposits as a "stratabound/replacement" type. They describe this type of mine as associated with organic debris, black-mudstone-hosted deposits that are in general stratabound disseminated deposits or stratabound discordant veinlets and replacements. They conclude that such occurrences are "... associated with the migration of brines within the basins, apparently unrelated to igneous intrusion.". Smoot and Robinson (1988) agree with this classification and propose that the copper enriched sediments were fluvial deposits with copper enrichments controlled by strata containing organic material. They suggest that organic-matter-rich mudstone-siltstone lenses overlying trough cross-bed scours provided favorable reducing conditions for preservation of organic material long enough for it to be mineralized The sandstones acted as permeable conduits for copper bearing fluids and the organics precipitated the metals by providing reducing conditions (Figure 2b).

Support for their proposal is offered by Gray (1988) who proposed that copper mineralizing fluids associated with some Mesozoic copper deposits in the Hartford Basin of Connecticut were sedimentary pour or formation waters and that the copper was released from detrital ilmenite and magnetite at an early stage of diagenesis. Gray (1988) suggests that the thermal effects of early Jurassic intrusions may have helped drive formation water out of the sediments. The copper was then deposited at local organic enriched reducing sites in a shallow sub-surface environment. There is however, a notable absence of any evidence of organic deposition in the metasediments of the American mine (Catttafi and others, this volume); an observation also made by Lewis (1906).

Rose and others (1986) propose a similar syngenitic mechanism is responsible for the concentrations of copper in the red-beds of the Devonian Catskill Formation of Pennsylvania. They find that copper has been depleted from the red (oxidized) sediments but is concentrated in the green and gray (reduced) sediments. They propose that copper was mobilized by chloride-bearing pore fluids followed by flow through relatively

Figure 2a. An Orange Mountain Basalt copper source with precipitation at the base of the flow as proposed by Weed (1902).

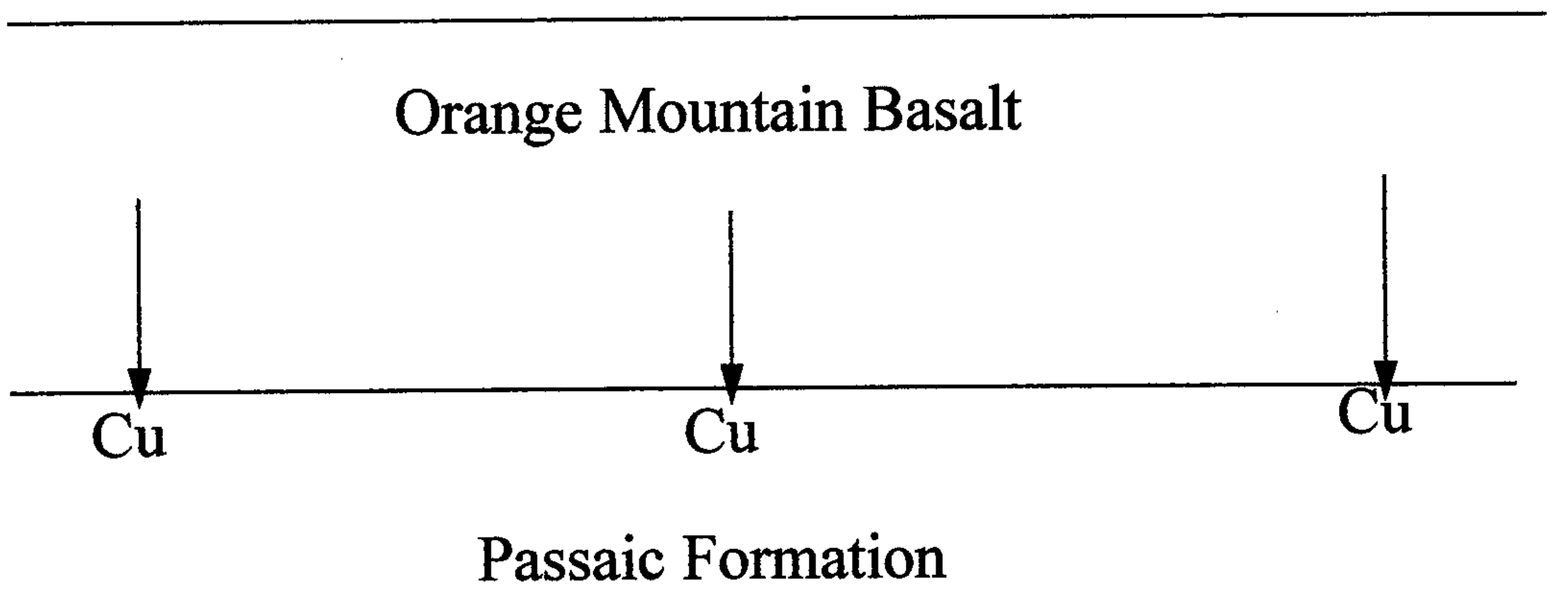


Figure 2b. Precipitation of copper out of groundwater into organic enriched layers within Passaic Formation as proposed by Smoot and Robinson (1987).

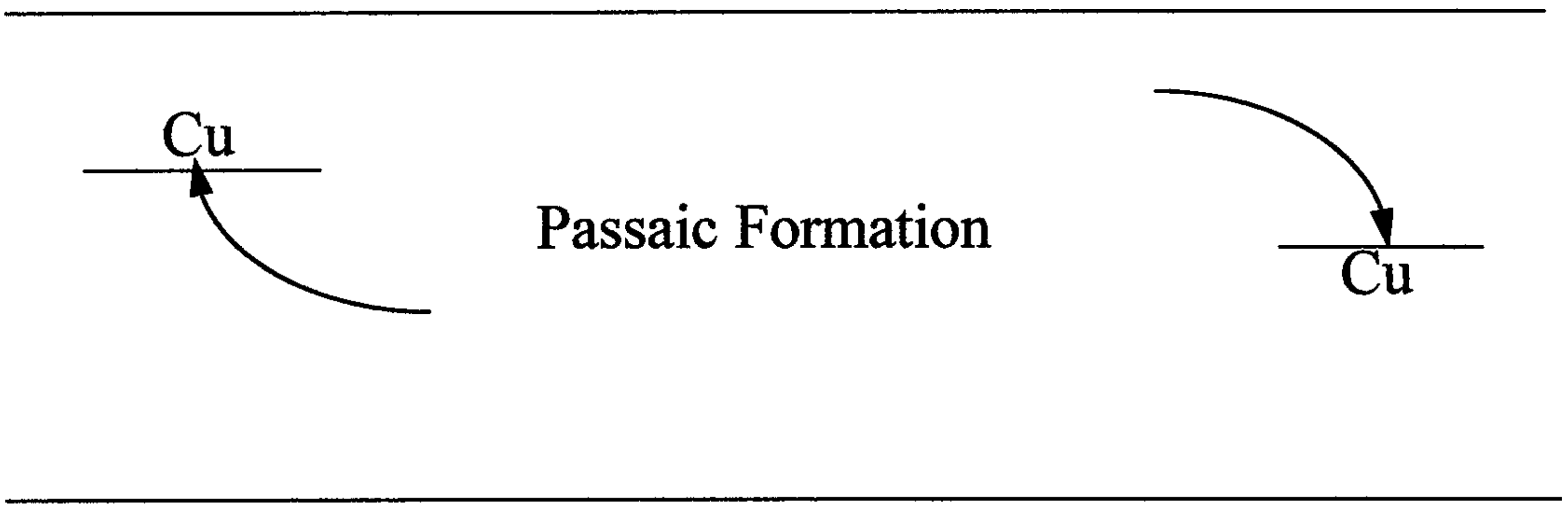
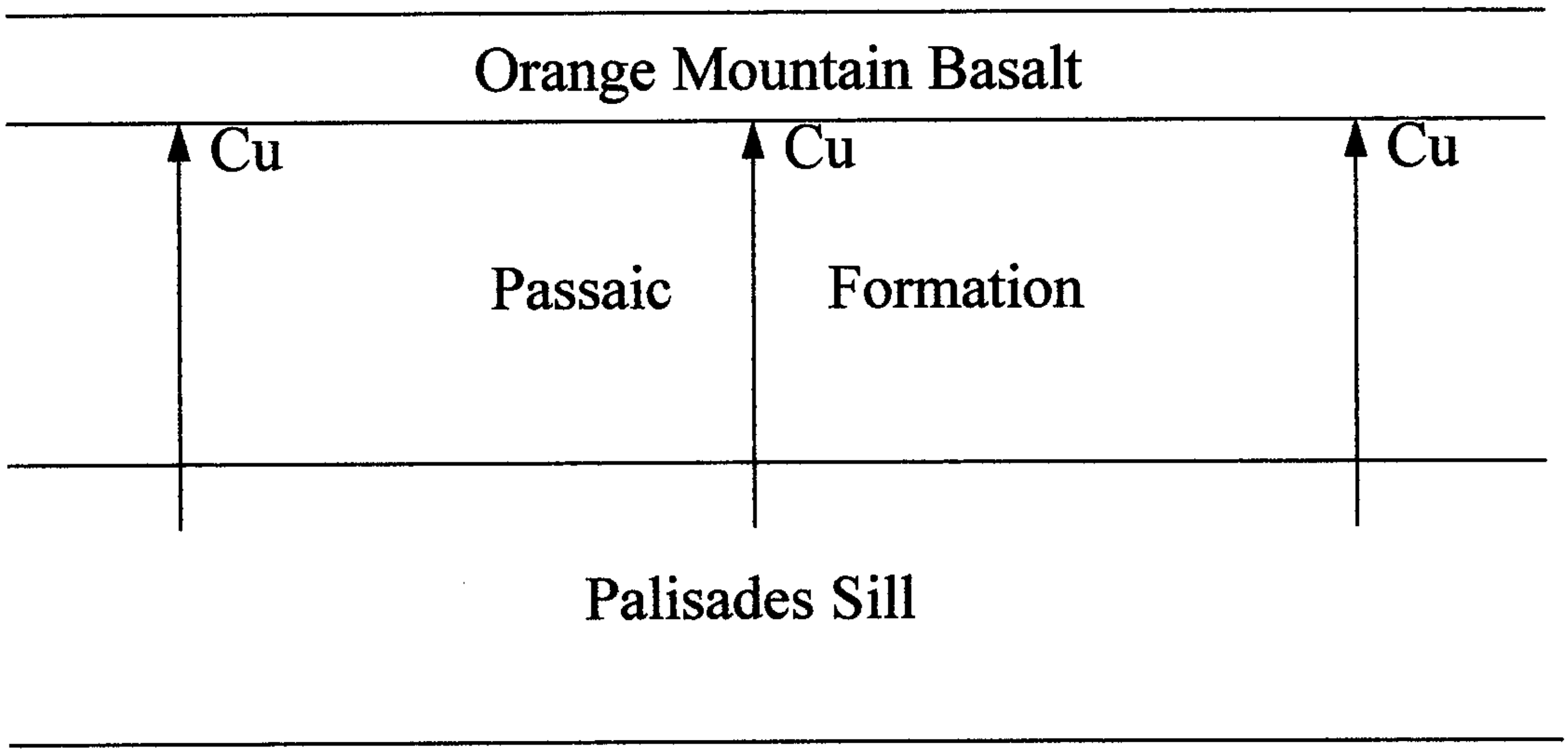


Figure 2c. A Palisades Sill derived hydrothermal fluid source as proposed by Lewis (1907).



permeable beds until organic ruductants were encountered that forced copper precipitation..

3) Intrusive diabase generated hydrothermal fluids - Lewis (1906) proposed that copper enriched hydrothermal fluids were released from the Palisades Sill that underlies the New Jersey deposits (Figure 2c) and carried copper upward through faults and other structures to favorable sites of precipitation, particularly calcite concentrations, at the base of the Orange Mountain Basalt. However, the faults, veins and organic enriched layers in the Passaic Formation overlying the Palisades Sill are rarely mineralized with copper except for those near the stratigratigraphic layer representing the surface at the time of the Palisades intrusion.

Woodward (1944) also suggests that most of the copper ore was accumulated where ascending hydrothermal solutions were dammed and spread laterally along the base of the Orange Mountain flow. However, unlike Lewis, he suggests that most of the copper ore was introduced into the ore-bed long after the contact-metamorphic minerals had been produced based on his observation that some of the copper minerals surround or replace contact-metamorphic minerals.

Copper deposits associated with diabase intrusions in the Newark, Gettysburg, and Culpeper basins were also described by Robinson (1988). A type described as a "hornfel copper deposit" and another described as "diabase-hosted vein and segregation deposit" was found to be common throughout the Mesozoic basins and was attributed to hydrothermal activity associated with late-stage diabase differentiates perhaps a chlorine-rich fluid capable of transporting Cu. However, Robinson (1988) does not consider any of the New Jersey Copper mines to be members of this type.

ORE CHARACTERISTICS RELATED TO COPPER ENRICHMENT

Facts that must be consistent with any proposed concentration mechanism include:

1. Most New Jersey copper ore, including the American Mine (Cattafi and others, this volume) and the Chimney Rock deposit (Cummings, this volume) is confined to a zone within 1 m of the lower contact of the Orange Mountain Basalt. The few New Jersey copper deposits that are not located along the base of the Orange Mountain flow are found near the contacts of co-magmatic Palisades type intrusive sills (for example the Schuyler Mine and the Grigstown Mine) or consist of small poorly described prospects with undefined stratigraphic relationships.

2. At most New Jersey copper mines some of the copper ore mineralization was precipitated in amygdules and joints within the Orange Mountain Basalt near the base of the flow. This fact discounts the importance of organic controls on copper precipitation.

Table 1

Chemical Composition of typical Passaic red-bed, ore samples, and associated igneous rocks at New Jersey copper mines.

Formation				Passaic Formation					Orange	Mountain	Basalt
Mine	American	Chimney	Schuyler	American	Chimney	Schuyler	aver. 9	American	Chimney	Schuyler	Chimney
sample #	1	2	3	4	5	6	7	8	10	11	12
rock	red-bed	red-bed	red-bed	Cu ore	Cu ore	Cu ore	Cu ore	alt basalt	alt basalt	alt basalt	basalt
color	red	red	red	gray	gray	gray	gray	gray	lt green	lt green	black
Weight percent											
SiO2	55.45	61.14	66.51	49.97	55.97	50.09	53.21	50.67	46.03	47.26	51.25
TiO2	1.05	1.15	0.9	0.75	0.64	1.81	0.91	1.15	1.36	1.73	1.18
Al2O3	19.7	13.79	15.32	19.86	12.25	14.43	16.3	13.65	11.7	13.77	14.23
FeO	8.57	5.55	5.73	5.65	4.66	9.42	5	9.9	13.02	12.48	10.21
MgO	4.12	3.17	3.92	6.39	5.13	6.77	6.33	8.57	16.1	8.29	8.6
CaO	0.3	5.48	0.61	1.98	5.83	0.41	3.24	10.68	5.03	4.75	11.25
Na2O	0.96	2.67	3.19	5.65	7.07	6.2	5.85	2.24	3.43	5.19	2.23
K2O	4.05	2.09	1.9	0.31	0.03	0.02	0.24	0.46	0.04	0.03	0.42
P2O5	0.06	0.05	0.11	0.18	0.18	0.21	0.17	0.16	0.16	0.18	0.19
LOI	5.04	5.12	2.97	6.32	5.84	6.98	6.35	1.85	2.28	3.79	0.98
Cu	0.01	0.01	0.09	2.45	3.06	3.05	1.97	0.01	0.02	1.53	0.01
total	99.31	100.22	101.25	99.51	100.66	99.39	99.57	99.18	99.17	99	100.55
ppm											
Cu	68	85	850	24546	30642	28341	19741	119	245	15320	101
Zn	148	141	130	154		119	121	82	82	487	
Sr	209	82				139				138	168
Ba				54							
Zr	173					111				104	
Cr		94			310	500			600	500	333
Ni	81	38			52	139			122	137	88

3. At virtually all New Jersey copper mines the richest ore occurs within a hornfels that is characterized by its toughness and its relatively low porosity and permeability. This is a fact that is not supportive of the theory that the copper was introduced by circulating aqueous solutions after the hornfels was developed .

4. At most New Jersey copper occurrences mineralization is found disseminated within ameboid chloritized zones (green spots) or bleached calcite enriched white spots. With rare exceptions there is little if any evidence of organic accumulation in the ore. The dark coloration of the copper ore is due to metamorphic reduction and chlorite precipitation rather than organic content Most copper enriched hornfels are unbedded and unlaminated meta-mudstones.

5. Chemical data (Table 1) indicates that New Jersey Mesozoic copper ore is characterized by a distinct potassium depletion and sodium enrichment compared with Passaic sediment that is not enriched in copper.

A VOLCANOGENIC INTERPRETATION

I propose that most of the Mesozoic copper found in New Jersey red-beds was introduced into Passaic Formation sediments (muds) at the surface, perhaps into boiling mudpots and solfatara near fumarole vents. These copper enriched solutions were heated by active magmatism involving the shallow movement of magma through the Palisades sill under and through the Passaic sediments as it was flowing to the surface and extruding as Orange Mountain Basalt (Figure 3). My proposed mechanism is similar to the classical volcanogenic black smoker concept but instead of marine water circulation through hot basaltic rock I propose brackish groundwater circulation contained within the Passaic Formation. Instead of copper deposition near a submarine vent, deposition of the New Jersey deposits occurred at the surface near fumaroles. High temperature and high pressure aqueous vapors escaped to the surface where steam evaporation would have concentrated any copper content. Some precipitation may have occurred in organic enriched beds at depth, but evaporation and the decrease in solubility caused by the drop in pressure and temperature at the surface were probably the chief concentration mechanisms.

The source of most copper, therefore, was intrusive Palisades diabase that intruded into the Triassic sediments just before and during the extrusion of the Orange Mountain Basalt. Some of the shallow fractionated diabase offshoots above the main sill may have been particularly enriched in copper. Hot saline water is a very effective copper solvent. Seyfried and Mottl (1982) have shown that copper is almost completely leached out of basalt by heated seawater. Rapid transmission of copper to the surface may have been forced by the shallow emplacement of the thick Palisades sill into the subtropical brine saturated lacustrian and fluvial Triassic sediments (Oshchudlak and Hubert, 1988)

The composition of hot-spring brines is highly variable due to variations in tectonic setting and igneous compositions. The tectonic setting of the Newark Basin was that of a new spreading center opened by massive continental flood basalt magmatism with a release of huge amounts of sulfurous vapor (McHone and Puffer, in press). The tectonic setting resembles, in several respects, the East Pacific Rise where copper enriched solutions at black-smokers have been analyzed by Edmond and others (1982).

Additional copper may have been leached out of the Orange Mountain Basalt during extrusive cooling as any remaining brine circulated through the Orange Mountain flood basalts at supercritical temperatures. However, copper concentration through evaporation, and a drop in pressure and temperature would be less effective under a very thick basalt flow. The chief effect of the basalt flow onto the copper enriched mud would have been thermal metasomatism, although presumably considerable sulfur and chlorine gas was also driven off at this point. Some copper that was precipitated in the surface muds may have been remobilized during thermal metamorphism and reprecipitated in basalt vesicles, but most copper was sealed into the impermeable hornfels effectively preventing further movement.

The copper and salt enriched surface muds were, therefore, baked into a dense sodic hornfels (Figure 4) by the extrusion of the first thick (70 m) flood basalt extrusion that, together with two additional flows, make up the approximately 200 m thick Orange Mountain basalt. Although contact metamorphism is typically poorly developed under basaltic flows, the hornfels under the Orange Mountain Basalt is unusually well defined and even underwent local fusion (Puffer and others, 1993) because of the extreme thickness of the flow and the saline content of the sediment. Copper and sodic enrichment at the base of overlying Watchung flows is absent to rare because of the absence of a similar sediment, brine, and intrusive sill configuration and because of the dehydration of red bed sediments. Once the solutions that transmitted the copper from the diabase to the surface were removed they were no longer available for recirculation by subsequent magmatism. Subsequent red-beds including the Feltville and Towaco Formation presumably contained saline groundwater and are both overlain by flood basalts but both of these formations are much thinner than the Passaic and are not intruded by diabase sills.

An important aspect of my proposal is the enrichment of copper in salty surface muds (solfatara) or shallow pond sediments before they were baked into dense hard low porosity sodic hornfels. There were, therefore, two stages of chemical alteration: 1) low temperature red-bed alteration caused by reaction with diabase derived hydrothermal vent water and 2) high temperature red-bed alteration caused by thermal metasomatism of copper enriched muds at the base of the Orange Mountain Basalt. Thompson (1983) has summarized observed chemical gains and losses from rock during salt-water reactions at different temperatures and has found that at less than 100 C° reacted rock gains potassium, copper and some other heavy metals but looses silica, calcium, and magnesium The surface temperature of the upper Passaic muds was probably low enough to force any copper solutions to precipitate. Apparently precipitation of copper out of diabase derived hydrothermal leachate does not occur at elevated temperatures.

In contrast, Thompson (1983) reports that at temperatures above 150 C° reacted rock consistently gains magnesium but looses potassium, silica, and calcium. Other

Figure 3. Volcanogenic origin of New Jersey copper deposits involving leaching of copper into saline solutions as they circulate through hot Palisades sill or shallow offshoots and precipitation in surface muds near fumarole vents and solfataras or in hornfels near offshoots during active magmatism

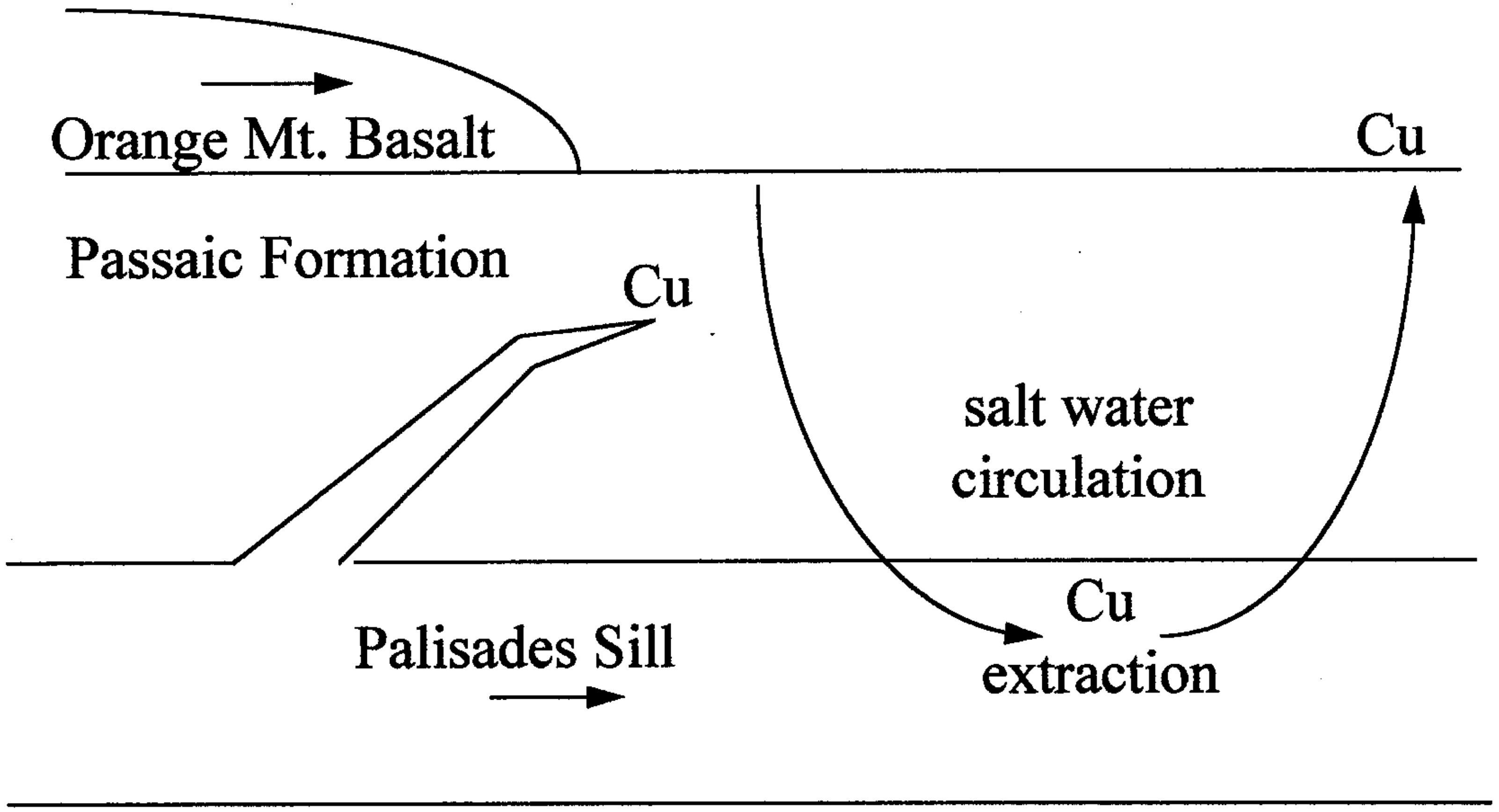
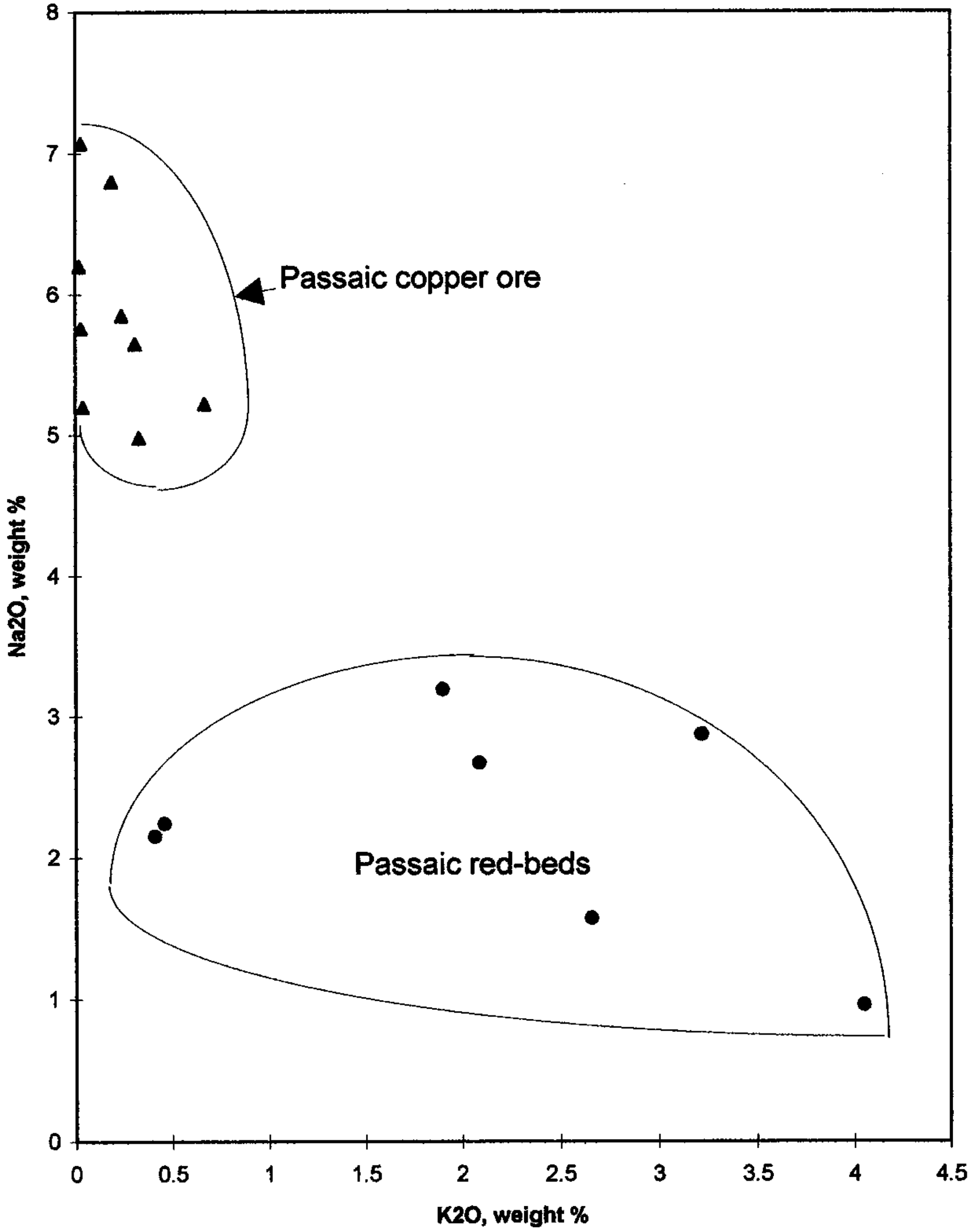


Figure 4. Potassium and Sodium Content of Typical Mesozoic Passaic Formation Red-bed Ore Samples from New Jersey



metals generally behave ambiguously. The highly variable concentrations of silica and calcium, in the ore zone (Table 1) is, therefore, probably due to low temperature depletion in the surface muds followed by local high temperature metasomatic enrichment during the extrusion of the Orange Mountain Basalt. The variable although generally enriched magnesium (Table 1) is probably due to high temperature enrichment particularly as chlorite; and the distinct decrease in potassium that characterizes the red-bed copper ore of New Jersey (Figure 4 and Table 1) was probably caused by high temperature metasomatic depletion. Thompson (1983) reports that iron does not respond to temperature changes with any consistency although most red-bed ore is depleted in iron (Table 1). The depletion of iron is probably due to reactions described by Sclar and Moses (1995). They find that the reaction:

$$4Cu^{+} + 2Fe_2O_3 + HS^{-} + 3H^{+} \dashrightarrow 4Cu + 4Fe^{++} + SO_4^{-2} + 2H_2O$$

maximizes copper precipitation on the basis of thermodynamic calculations. Copper precipitation increases according to their data as fluid temperatures cool below 220 C° as would be the case of hot brines venting through solfatara near fumaroles.

OTHER DEPOSITS OF SIMILAR ORIGIN

The origin proposed for the Mesozoic red-bed copper deposits of New Jersey draws from processes associated with 1) deposits that are described by Gilbert and Park (1985) as "related to subaerial volcanism" 2) black smoker venting at sea -floor spreading centers, and 3) hot-spring and solfatara deposits.

One of the few copper deposits related to subaerial volcanism is the Keweenawan basalt province. The ores of the Keweenawan and Orange Mountain basalts are both dominated by native copper with only minor sulfur mineralization. Unlike the New Jersey deposits, however, the Michigan deposits are concentrated in amygduloidal flow-tops. Stoiber and Davidson (1959) suggest that the absence of basalt alteration supports precipitation out of low temperature burial metamorphic derived solutions. Woodward (1944) has suggested a similar origin for the New Jersey deposits although the highly permeable flow-tops of the Keweenawan Basalt contrast considerably with the impermeable hornfels of most New Jersey ore.

The New Jersey deposits are particularly similar in many respects to some of the native copper and chalcocite deposits associated with andesites in Chile and Bolivia. The South American volcanic flows are interbedded with copper enriched lagoonal and lacustrian sediments that Sillitoe (1977) suggests accumulated in an environment similar to the Valley of Ten Thousand Smokes. However, unlike the rift related flood basalts of New Jersey, the andesites of South America are tectonically compressional, and as proposed by Gilbert and Park (1985) may be I-type extrusive equivalents of porphyry copper ore.

The tectonic setting of the New Jersey deposits more closely resembles a spreading center such as the East Pacific Rise where copper enriched precipitates are currently accumulating. The chalcopyrite rich chimneys actively growing in the East Pacific Rise have been described by several authors including Hekinian and others (1983). Sediments associated with Mesozoic continental rift volcanism of the Tethyan area are also locally enriched in copper wherever the shallow marine sediments were mixed with copper rich brines leached from rift related basalts. Robertson and Boyle (1983) describe some interstitial sediment associated with lava at Margi, Greece (Table 1) that resembles New Jersey ore in most respects although the abundant iron enrichment of these sediments and those typically associated with metallogenesis on rifted spreading axes is absent from the New Jersey ore. The relatively low iron content of New Jersey ore may be due to in part to precipitation of hematite cement in the red-beds of the Passaic formation beneath the ore beds as the heated volcanogenic brines circulated through. Oshchudlak and Hubert (1988) describe abundant secondary "late" hematite in the siltstones of New Jersey that they interpret as precipitates form intrastratal solutions.

Some geothermal brines and hot spring waters are also enriched in copper including the geothermal brine of the Salton Sea that carries 8 ppm Cu in solution (Barnes and Czamanske, 1967). However the wide range in published analyses of hot-spring, geothermal brine, and black smoker vent waters (Berger and Silberman, 1985; Schmitt, 1950), is presumably controlled by a wide range of temperature and water supply conditions, sediment thickness, and sediment and volcanic rock chemistries. The combination of these and other variables during the Mesozoic of New Jersey may have been unique or at least rare which may, therefore, explain some of the rare or perhaps unique aspects of the New Jersey copper ore.

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The Bog Iron Industry in the New Jersey Coastal Plain

R. Bruce Archer
French & Parrello Associates
670 N. Beers St., Holmdel, NJ 07733

Introduction

In 1674 the first iron furnace in New Jersey was built along Pine Brook in what is now the town of Tinton Falls, Monmouth County. This was the humble beginning of an industry which lasted for over 150 years, helped to form a new nation, and win two wars. The industry was the mining, smelting and forging of bog iron.

Towns with names like Batsto, Martha, Etna, Atsion and Allaire were hewn out of the pines and flourished until the entire industry collapsed about 1850. Many of these towns vanished leaving only piles of smelting slag or depressions of old foundations to indicate where they once stood. Through the years, as the pines reclaimed the land, towns such as Speedwell even had their names removed from maps. Yet these towns not only affected the economy of the county in which they were located but also state, national and world economies and affairs. Many made munitions, which helped to mold a new nation, and helped to win the War of 1812.

In 1709 an English ironmaster helped to seal the fate of the bog iron industry when he used coked anthracite coal for the first time in smelting iron. By the late 18th century coke was commonly used by the English to smelt iron. Coked anthracite was easier to produce, fired longer and hotter, and led to a better quality iron pig. With the discovery of the anthracite coalfields of Pennsylvania's eastern coal region, the discovery of iron ore and the development railroads to transport the raw materials and finished iron, the New Jersey industry could not compete. The older furnaces did not last long. Batsto with its newer technology lasted the longest, but it too finally succumbed to the Pennsylvania industry. By 1855, all of the furnaces were cold.

Today only two of these bog iron towns remain, Batsto and Allaire. Both are state parks today and are undergoing restoration. At Allaire the furnace remains, with just the stack standing. Many of the old towns are now just a crossroads with some slag piles and possibly a few ruins.

The smelting industry is still present in New Jersey. The New Jersey Steel plants in Sayreville and South Amboy still smelt iron as steel, using electricity instead of charcoal and scrap iron and steel as the "ore".

Geology and the Source of the Iron

Geomorphology

New Jersey can be divided into four geomorphic provinces; the Valley and Ridge, the New Jersey Highlands or New England, the Piedmont, and the Coastal Plain (Huguley 1975). The first three provinces listed are beyond the scope of this article. Please refer to previous GANJ Guide Books for further information on these provinces. The Coastal Plain can be divided into two smaller areas. The first is the Inner Coastal Plain, and the second is the Outer Coastal Plain. Please refer to figure 1. The boundary between the two is generally along the contact between the Cretaceous sediments and the Tertiary sediments (NJDEP, 1984). The boundary is also marked in Monmouth and

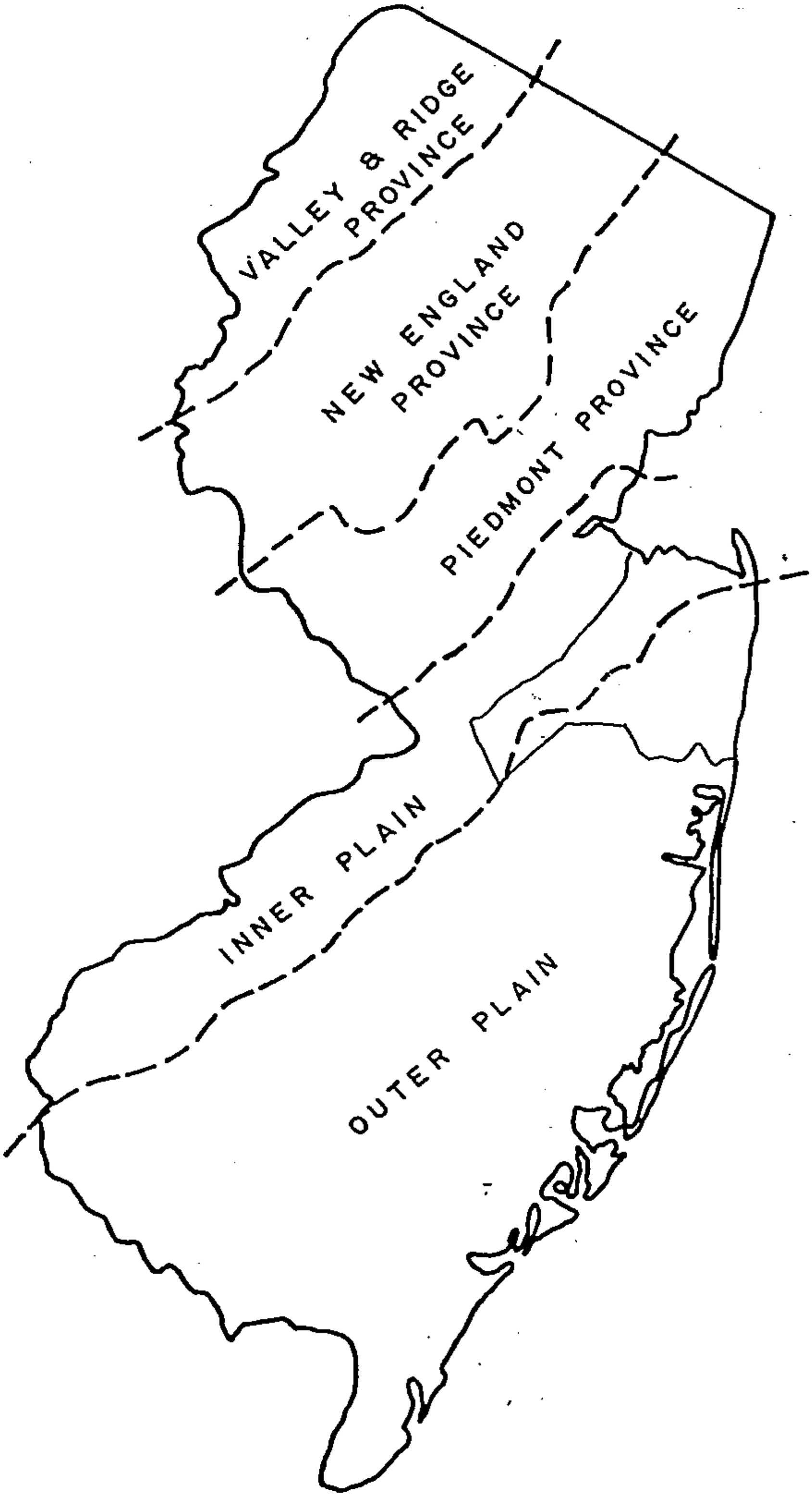

Figure 1
Geomorphic Provinces Of New Jersey

Not to Scale

Northern Ocean Counties by the Atlantic Highlands and the Mount Pleasant Hills which run through Imlaystown and into Ocean County (Huguley 1975).

Although more than half of the Coastal Plain is below 100 feet in elevation (Wolfe 1977), the central region of the Outer Coastal Plain contains considerable area which is over 200 feet in elevation.

The general lack of any significant wide variation in resistance to erosion and the gentle dip of the Coastal Plain Sediments has restricted the formation of "conspicuous asymmetrical ridges in the Coastal Plain" (Wolfe 1977).

The low relief also promoted the development of many relatively slow moving, meandering streams. Drainage patterns are dendritic, with numerous drainage basins. Along the coast tidal marshes, bays and estuaries are common.

Stratigraphy

The statigraphy of the coastal plain has been described by others (Owens and Minard 1960, Olsson 1963, Owens and Sohl 1969, Rhodehamel 1973). The Cretaceous and Tertiary sediments dip to the southeast at a rate approximating 9.5 meters per kilometer (Crerar and others 1979). These sediments are approximately 300 meters thick in the outcrop (Olsson 1963), but thicken to an ultimate subsurface thickness of 1.2 kilometer to the southeast. Figure number 2, after Owens and Sohl is a simplified stratigraphic column whilst figure number 3 is a schematic cross section trending parallel to dip. The Coastal Plain sediments reflect deposition in the alternating transgressing and regressing seas. The rising and falling sea level led to the formation of alternating aquifers and aquicludes. These record deposition of marine, marginal marine and non-marine depositional environments

.

Iron Sources

The Coastal Plain sediments provide ample sources of iron to produce bog iron. The entire stratigraphic column from the Raritan Formation upwards to the Shark River Formation, the amount of iron bearing minerals becomes clear. Table1 shows which iron-bearing mineral is contained in which Coastal Plain formation.

Table 1

Iron Bearing Formations of the Coastal Plain

Formation	Series	Contains Glauconite?	Contains Pyrite?	Contains Siderite?	Acid Producing?
Raritan	Upper Cretaceous		Yes		Yes
Magothy	Upper Cretaceous		Yes		Yes
Merchantville	Upper Cretaceous	Yes	Yes	Yes	Yes
Woodbury	Upper		Yes	Yes	Yes

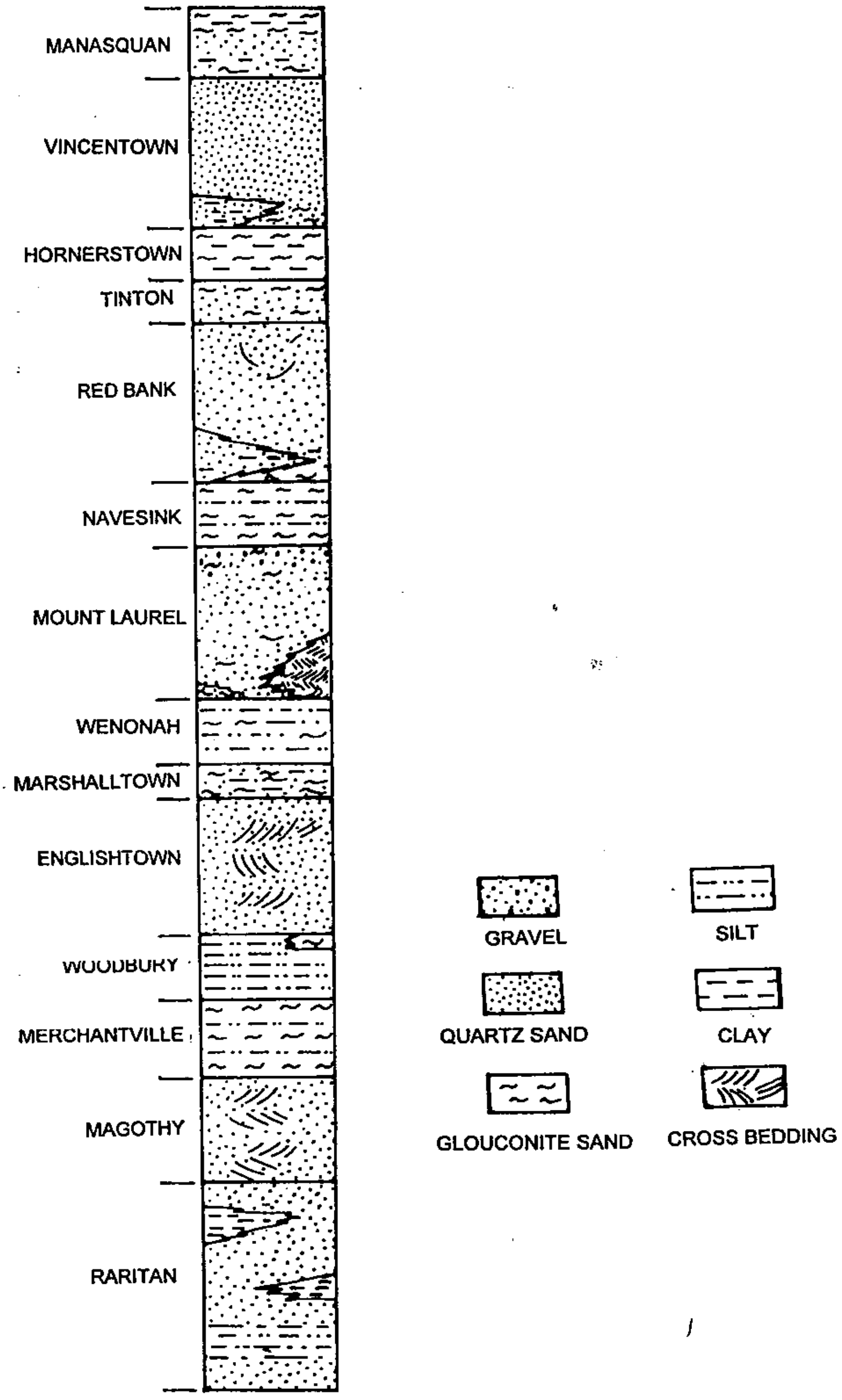

Figure 2
Simplified Stratigraphic Column

After : Owens and Sohl, 1969

Not to Scale

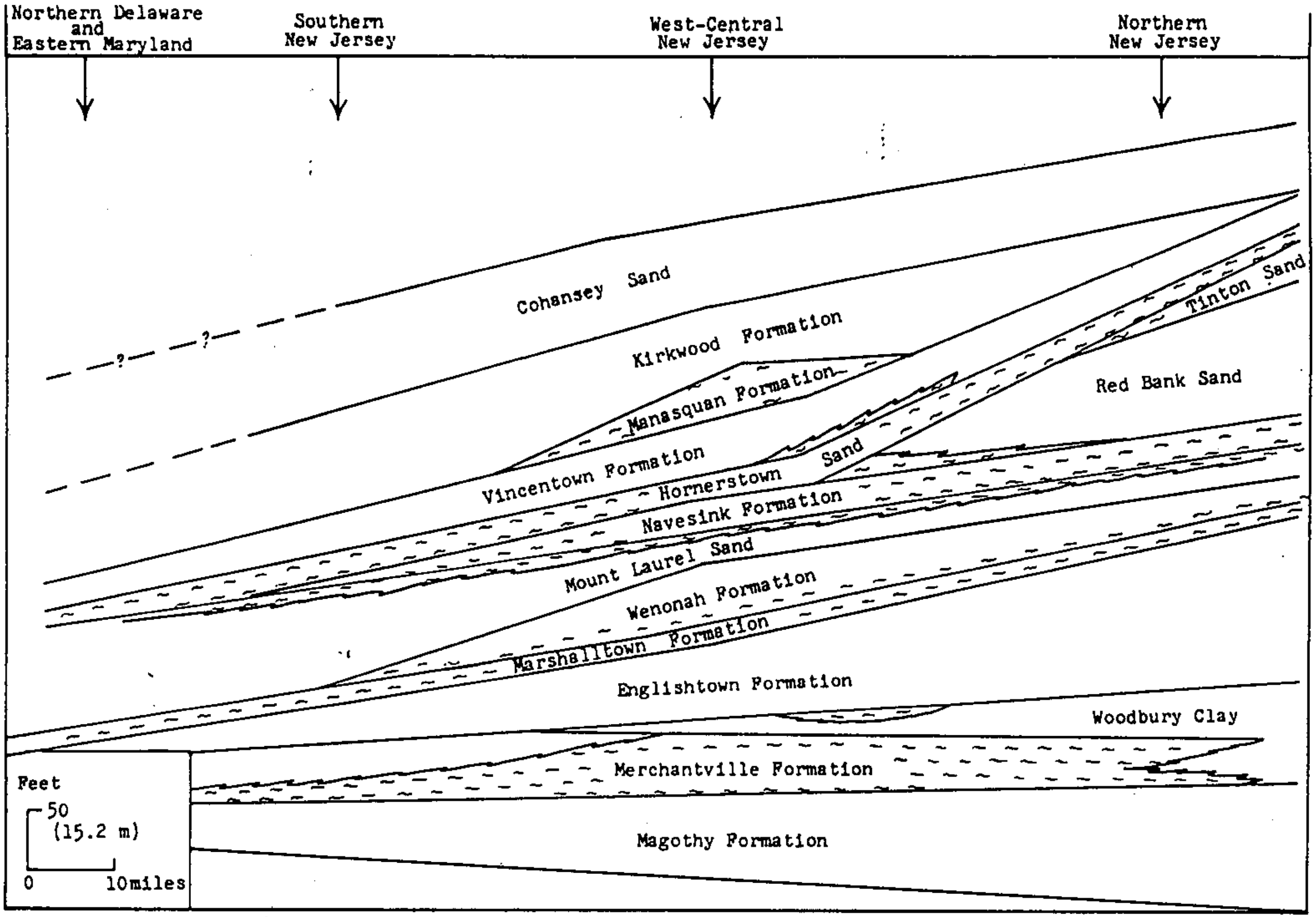

Figure 3
Simplified Geologic Cross Section

After; Owens and Sohl, 1969

Scale as Shown

Clay	Cretaceous				
Englishtown	Upper Cretaceous	Yes	Yes	Yes	Yes*
Marshalltown	Upper Cretaceous	Yes	Yes		Yes
Wenonah	Upper Cretaceous	Yes	Yes		
Mount Laurel Sand	Upper Cretaceous	Yes		Yes	
Navesink	Upper Cretaceous	Yes	Yes	Yes	Yes
Red Bank Sand	Upper Cretaceous	Yes	Yes		Yes*
Hornerstown Sand	Paleocene	Yes			
Vincentown	Paleocene	Yes			
Manasquan	Eocene	Yes		Yes	
Shark River Marl	Eocene	Yes			
Kirkwood	Miocene		Yes		Yes*

* = Only Selected Members

Glauconite

From Table 1 it is easy to see that glauconite is the predominant iron-bearing mineral found within the Coastal Plain sediments. Glauconite ($K[Fe,Mg,Al]_2[Si_4O_{10}][OH]_2$) is a green to black, granular mineral simular to muscovite, having a green streak and a hardness of 2 (Berry and Mason, 1968). Glouconite weathers to a red-brown to orange to rusty brown as the iron oxidizes. The Coastal Plain glauconites are of two types, high-alumna glauconites and low-alumna glauconites (Owens and Sohl, 1973). Higher aluminum contents correlate with shallower environments of deposition. High-alumna glauconites occur in the Woodbury Formation, Mt. Laurel Sand, Wenonah Formation, Manasquan Formation, Red Bank Formation, Marshalltown Formation, and the Vincentown Formation. Low-alumna glauconites are found in the Navesink Formation, Merchantville Formation, Englishtown Formation, and the Hornerstown Formation, which were formed in deeper environments of deposition.

The actual grains found within each formation also differ. Some formations, such as the Navesink or Hornerstown have smooth-spherical or botryoidal shapes. Others, such as the Red Bank and the Merchantville, have accordian shapes. The accordion pellets, and book type pellets are thought to be altered books of mica (Owens and Sohl, 1973). The spheroid and botryoidal pellets are the most interesting. When looked at closely, the predominately glauconite formations look heavily bioturbated, mottled and massive. Takahashi (in Boyer, 1972) suggested the idea that the spheriodal shaped pellets were actually fecal pellets (a fossil feces facies) of marine invertebrates with their own reducing environment within a mucus membrane.

Pyrite and Marcasite

Pyrite and Marcasite are dimorphous but pyrite is isometric and marcasite is orthorhombic. Their composition is FeS_2. Both have a brassy yellow colour (marcasite may be paler) and a hardness of 6-6.5 (Klein and Hurlbut, 1985). They are formed in sediment where iron and hydrogen sulfide are present. Both are often found encrusting lignatized wood in the Raritan, Wenonah, and the Englishtown Formations. Table 1 indicates which of the Coastal Plain Formations contain pyrite and marcasite.

Upon exposure to oxygen (as from the atmosphere or ground water), the pyrite and marcarsite oxidizes and produces ferrous sulfate, ferrous oxides and sulfuric acid. The Raritan Formation, Magothy Formation, Merchantville Formation, Woodbury Clay, Englishtown Formation, Marshalltown Formation, Navesink Formation, Red Bank Sand, and the Kirkwood Formation have been designated by the New Jersey Department of Enviornmental Protection to be acid producing formations. Only certain members of the Englishtown Formation, Red Bank Sand, and Kirkwood Formation contain acid producing deposits (DEP, 1988). Waters from these formations and deposits can, and do, lower the pH of many lakes and streams.

Siderite

Siderite ($FeCO_3$) is hexagonal, light to dark brown with a white streak and a hardness of 3.5 to 4. Siderite within the Coastal Plain is a minor contributor of iron. It weathers to hematite or limonite (Berry and Mason, 1968). Coastal Plain Formations that contain siderite are shown in table 1.

Vivianite

Vivianite ($Fe_3[PO_4]_2\,8H_20$) is monoclinic, colourless when fresh, and weathers to light to dark blue from oxidation. Vivianite has a white changing to blue or brown streak and has a hardness of 1.5 to 2. Vivianite is associated with bone and other organic material and as concretions in clays (Berry and Mason, 1968).

Formation of Bog Iron

Contrary to the popular belief that bog iron forms from precipitates in cycles of 20 years, the actual process is longer and more complicated. The process involves acid producing formations, decaying organic matter, bacteria, and a series of chemical reactions. The process produces three distinct types of ore. The first is "loam ore", loose precipitate with granular material, the second is "seed ore", partially lithified precipitate, and the third type of ore is "massive ore", completely lithified ore (Means and others, 1981).

The process starts with the groundwater in the coastal plain. It has been found that, though the water had a lower Eh deeper in the water column, the pH was lower higher in the water column. From this the Fe solubility ought to be higher in shallow ground water and streams than in deeper ground waters, yet it is from the shallow ground waters that the iron is precipitating (Means and others1981)!

The rivers and bogs within the Pine Barrens show seasonal trends in Eh and pH. During the winter months the Eh is higher than in the summer months. The pH was found to be higher in the spring or fall months (Means and others, 1981).

Because of this apparent paradox of solubilities and precipitation, there has to be one additional piece of the puzzle. The final piece is the participation of microbes, which act as catalysts in the precipitation of the iron. Known iron-oxidizing microbes, those positively identified, include *Thiobacillus ferrooxidans, Leptothrix ochracea, Crenothrix polyspora, Siderocapsa geminata, Metallogenium sp.,* and *Naumaniella sp.* (Means and others, 1981). Without the microbes, the iron would not precipitate at an appreciable rate. As Means and others (1981) stated " theoretical calculations based on the rate law of $Fe2^+$ oxidation suggest abiotic oxidation is too slow at pH 4.5, which is typical of Pine Barrens waters to account for quantitatively significant deposits of bog iron." Thus the formation of bog iron depends on these microbes.

For a thorough discussion of the kinematics of the formation and precipitation of bog iron please refer to the paper of Means and others (1981).

The iron precipitates out as a friable mass containing sand, clay, pebbles and organic material. A thick layer or layers of limonite cement the inclusions. The State Geological Survey report on iron mines described the bog ore: "Appearance-the bog iron ores are mixtures of limonite and other hydrated oxides of iron intermingled with clay, sand, and various organic compounds. As usually found, the ore is a brown yellowish-red, soft earthy substance, containing scattered nodules of compact limonite, casts of leaves, roots etc. composed of the same material and mixed with sand or clay, the whole forming thin layers that may or may not be porous. It occurs, also as crusts enveloping twigs, twigs, leaves, bones, and other organic remains. When dried the ore tends to fall into a brown or reddish powder." (Cottrell, 1967). When subjected to x-ray diffraction, the only mineral discernable is goethite. The remaining mass consists of amorphous iron oxyhydroxides (Means and others, 1981).

Smelting the Iron

Smelting of ore into iron requires three ingredients. The first is the ore. The ore used in the coastal plain furnaces was initially bog iron: later in their lives many furnaces used imported ores from Staten Island, Pennsylvania, and Morris County (Pierce, 1957). The second ingredient is calcium carbonate (as calcite or aragonite) to be used as a flux. The last charcoal, was used as a fuel.

Mining the Ore

The bog iron ore was mined by one of two methods depending upon where the ore was located. The first method was used when the ore was located in bogs or streams. The miners would either lift the ore from the bottom of the stream or bog, or the miners would dam off a section of the steam to recover the ore. The ore in either case was placed into boats and floated to the furnace or to a landing near the furnace. From there the ore was shipped overland to the hammer mill. When the ore was exposed at an outcrop, the miners employed the second method where by they simply extracted the ore using open pit mining techniques. The ore then was hauled overland to the hammer mill. A water driven hammer mill was utilized to pulverize the ore in preparation for firing.

Collecting the Flux

Flux is important in the production of iron. Impurities found in all ores are fixed by the flux and drawn off during smelting as slag. As there are no economically usable limestone deposits contained in the coastal plain the ironmasters developed an ingenious way to overcome this handicap. Collection teams were sent to the shore to collect great quantities of shells to use as the calcium carbonate flux. Shell collection along with the mining of the ore continued all year long, even if the furnace was not in "blast" to insure an adequate supply of materials during production. Upon arrival at the furnace the shells were also sent to the hammer mill to be prepared for use.

Producing Charcoal

The fuel for the furnaces was produced at the furnace site. Theophrastus in370 B.C. described the method used by most of the coastal plain furnaces to produce charcoal (Cottrell, 1967). This same basic method was used into the 1850s. There were several reasons why charcoal was preferred over coal in the furnaces in the coastal plain. The first was availability. Coal that was suitable to be coked was not readily available to the ironmasters in the coastal plain. There was also an apparent prejudice against coal until the English started to use coal regularly (Cottrell, 1967). Charcoal was produced by placing the cut logs into a "pit" (the term pit is actually in error, the wood was actually burned on the ground, not in a pit or depression) which had a beehive or a pyramid shape. The "collier" (the person who did the burning of the wood) would start the pit with a "fergin", a center pole. The wood to be converted to charcoal (the type of wood depended on what was locally available or what the preferences of the collier were) was then stacked around the fergin. Enough kindling was placed into the pit to start the fire. Additionally an archway was built to allow the fire to be lit. Upon the completion of stacking the wood, "floats" were then placed around the pit. These floats, usually sod dug locally, were placed around the pit with the root side out to limit the amount of oxygen entering the pit. A series of holes made with the handle of a shovel allowed the draft and a second series of holes above the first and near the top of the pit allowed the exhausting gases to escape. The amount of draft was controlled by "chipping," the placing of stone or wood chips over the draft holes to cut the flow of air, or by making more holes to increase the amount of air entering the pit. A good collier could tell when the burning was finished by the changing colour of the smoke. When burning was completed all of the draft and exhaust holes were closed and the entire pit was allowed to cool completely before the pit was opened. The cooling prevented the re-ignition of the fire when the floats were removed. This process was continued all year to provide adequate supplies of charcoal for the furnace and blacksmiths.

Refining the Ore

It was in the furnace that the ore, flux and fuel were fired into iron. Though several types of furnaces were used in the coastal plain iron industry, especially at Batsto, the "cold blast" furnace was the most popular type. The cold blast furnace ultimately helped cause the demise of the bog iron industry.

The outside of most furnaces were shaped like a pyramid with the top cut off (Pierce, 1957), while the minority were round in shape like the furnace at Allaire. All of the furnaces were lined with refractory brick. The interior of the furnace was shaped like a bottle, open at both ends. The wide part of the furnace is known as a "bosh". Under the bosh was the "tuyere", the nozzle through which the "blast" was introduced to the fire. Beneath both was a crucible in which the molten iron collected. All of the furnaces were built near a stream to harness its power. Stream power was used to run the hammer or stamping mills, and most importantly the bellows for the blast. The bellows were typically wooden cylinders and pistons with leather seals. Cammed shafts attached to a water wheel drove the bellows. The air produced was then fed by the tuyere (becoming the blast) into the fire. Most coastal plain furnaces had only one tuyere (Pierce, 1957).

If possible, the furnace was built next to a hill so the "charge" could be introduced to the fire easily. The charge was the weighted portions of ore, flux, and charcoal. After weighing the charge was loaded into the furnace over a trestle by workman known as "fillers" or "fillermen" (Pierce, 1957). When the furnace was in operation the fillers went about their work dumping alternating layers of ore, flux and charcoal 24 hours a day, 7 days a week. Often crushed slag was added to re-refine it.

Inside the bosh the blast fanned the fire to a temperature high enough to reduce the charge to a molten mass. From chemical reactions brought on by the high temperatures and the action of the flux, the iron separated and collected in the crucible in the lower part of the furnace. Put very simply the blast introduced oxygen (as air) which reacted with the carbon in the charcoal forming carbon monoxide. The carbon monoxide reacted with the iron oxides by reducing the iron in the ore forming iron and carbon dioxide. The lighter impurities bonded with the flux, floated above the iron, and were drawn off (Brown 1958). When full the crucible was tipped and the molten iron flowed into molds which were shaped like bars and were at right angles to the channels which fed them. They looked like a sow with piglets, hence the bars became known as" pigs", and the iron as "pig iron" which continues to this day (Pierce, 1957). This process produced pigs which were brittle, and full of airholes and impurities.

The forge transformed this rough brittle iron into usable malleable iron. In the forge the iron was reheated into a pasty molten mass. This mass was then hammered. The hammers were approximately 500 pounds in weight and were water driven in the same way as the furnace's bellows. Again charcoal was used as fuel, and cold blast methods were used to raise the temperature high enough to melt the pigs. The hammer forging drove off excess carbon, impurities, and air. Furnaces, which also had a forge, were known as "bloomers"(Pierce, 1957). Most forges also had screw mills (which made screws), slitting mills (which made nails), and some had rolling mills (which made a variety of products).

The furnaces were in blast from about March until December. The furnace was worked 24 hours a day, 7 days a week unless as frequently occurred there was a breakdown. The down time between December and March was often due to frozen steams. This time was put to good use relining the furnace and repairing the bellows and the furnace house.

Iron Towns of New Jersey

When the furnace in Tinton Falls was built in 1674,an industry started which eventually supported at least 33 towns over a period of 180 years. Many of these towns

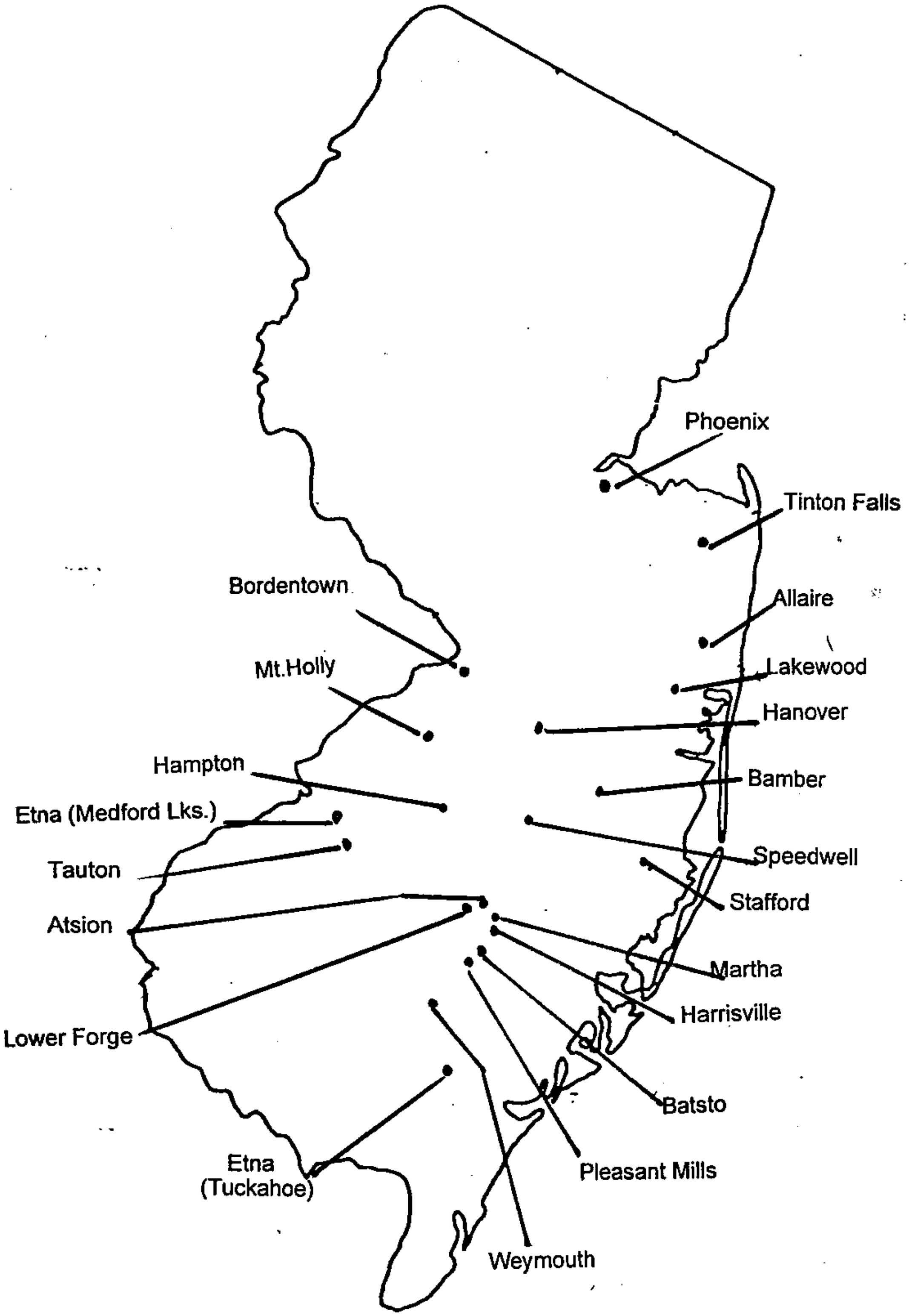

Figure 4
Coastal Plain Iron Towns

Not To Scale

have eventually totally disappeared, such as Speedwell, or have become an entirely new town such as Etna (which became Medford Lakes). The towns and furnaces or forges of Atsion, Bamber, Bergen, Retreat, Butchers, Budd's Iron Works, Bordentown, Cohansie, Etna (Tuckahoe), Etna (Medford Lakes), Federal Forge, Federal Furnace, Hampton, Hanover, Harrisville, Lisbon, Martha, Mary Ann, Mount Holly, New Mills, Phoenix, Pleasant Mills, Speedwell, Tauton, Tinton Falls, Union, Wading River, Washington, West Creek, Stafford, and Weymouth came into existence, flourished for a period as industrial centers, then failed and were abandoned (Beck, 1936; Pierce, 1957). Many towns are remembered as a named crossroads. Others survive as different towns. Only Allaire and Batsto have survived as they were in the 18th and 19th centuries as state parks. Figure 4 shows the location of some of these towns.

There are two men who had a very large impact on the bog iron industry. The first was Charles Read who built many of the furnaces, and the second was Samuel Richards who successfully ran many of these furnaces until his death.

Charles Read of Burlington, N.J. worked his way up from County Clerk to one of the most powerful political figures in 18th century New Jersey. For nearly 30 years Charles Read was the person who dispensed nearly all of the political patronage in New Jersey (Pierce, 1957). At 51 read set out to become the greatest ironmaster in NJ. Read built Atsion, Etna, Tauton, and Batsto in quick succession, and all were in operation by1768. However his scheme consumed much of his capital, more than he planned, Read soon had financial problems. Forced to sell off his assets, Read fled the state as he could not meet his obligations.

Samuel Richards' father William bought Batsto .In 1808 Samuel along with Joseph Ball acquired Weymouth Furnace, and soon purchased Martha, Atsion, and others. All of the furnaces owned by Samuel Richards prospered, including Atsion which had been practically abandoned by it previous owners. Samuel Richards passed away in 1842, just prior to the collapse of the industry.

The histories of some of these bog iron towns follow.

Atsion

Charles Read built Atsion in 1766 as part of his empire (figure 5). By 1770 the furnace had four fires and two hammer (stamping) mills. Most of Atsion's production went to Batsto's forge during Read's ownership. Assays of the ore at this time showed the ore contained a metallic iron content of 46 to 49% (Pierce, 1957). The production capacity of Atsion was improved when Henry Drinker and Abel Jones purchased the furnace. As part of the deal Drinker and Jones also purchased the machinery from the Etna (Medford Lakes) Furnace. Atsion had its ups and downs, while passing through several owners, ultimately falling into decay and abandonment by 1824. In 1824 Samuel Richards purchased Atsion. Under Richards Atsion prospered. When Richards passed away, ownership was transferred to his daughter and husband who ran Atsion until 1849 when financial troubles and the collapse of the industry occurred. After the collapse of the iron industry, Atsion was sold to several different owners. All had schemes to make money and all failed. In 1871 Maurice Raleigh bought Atsion and built a cotton mill. The mill was a success until Raleigh's death in 1882. His heirs soon ran down the company and in 1892 Joseph Wharton purchased the tract.

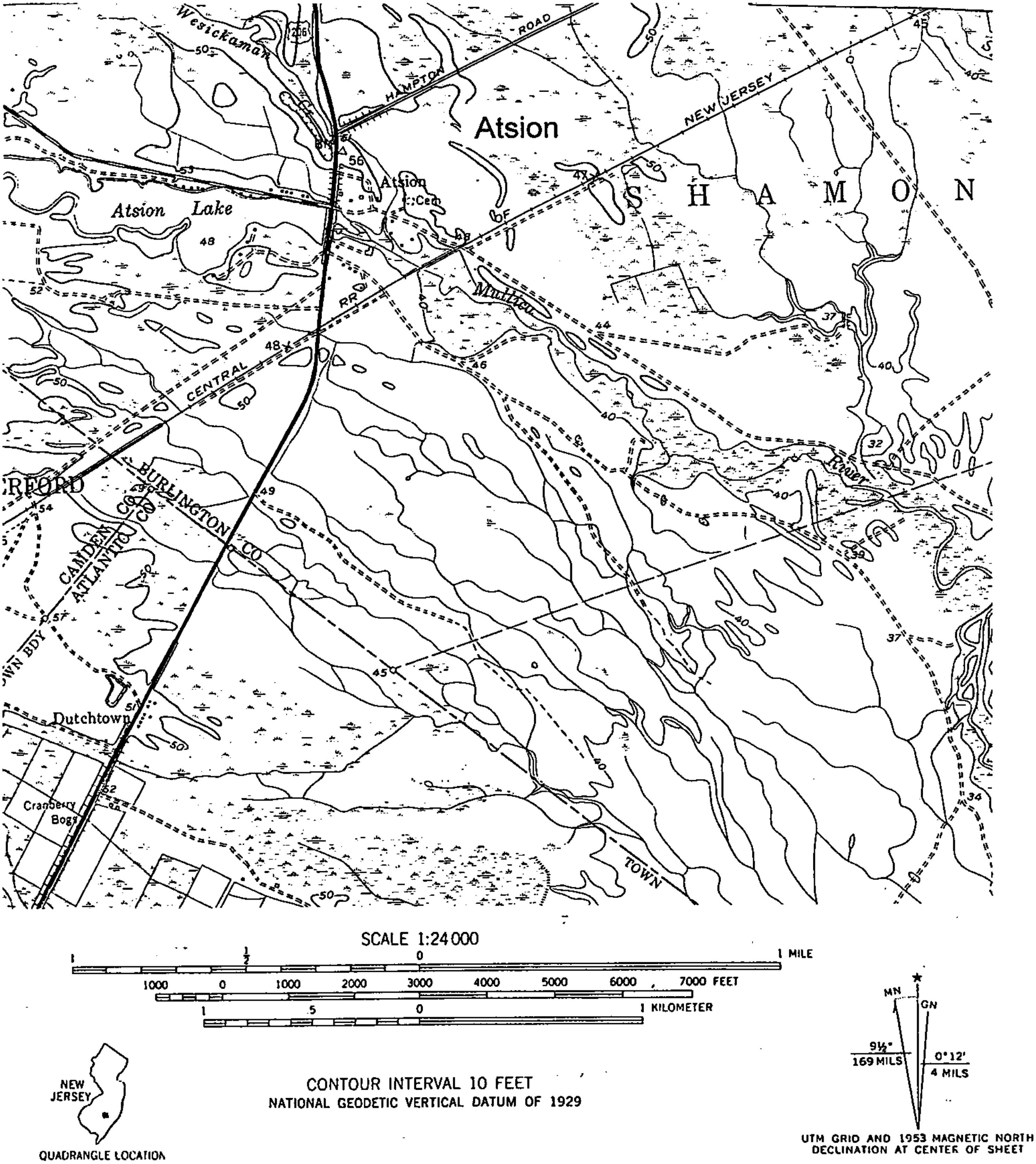

Figure 5

Atsion Location Plan

Scale as Shown

Plan taken from the USGS 7.5 minute quadrangle topographic map titled <u>Atsion</u>, photoinspected in 1977

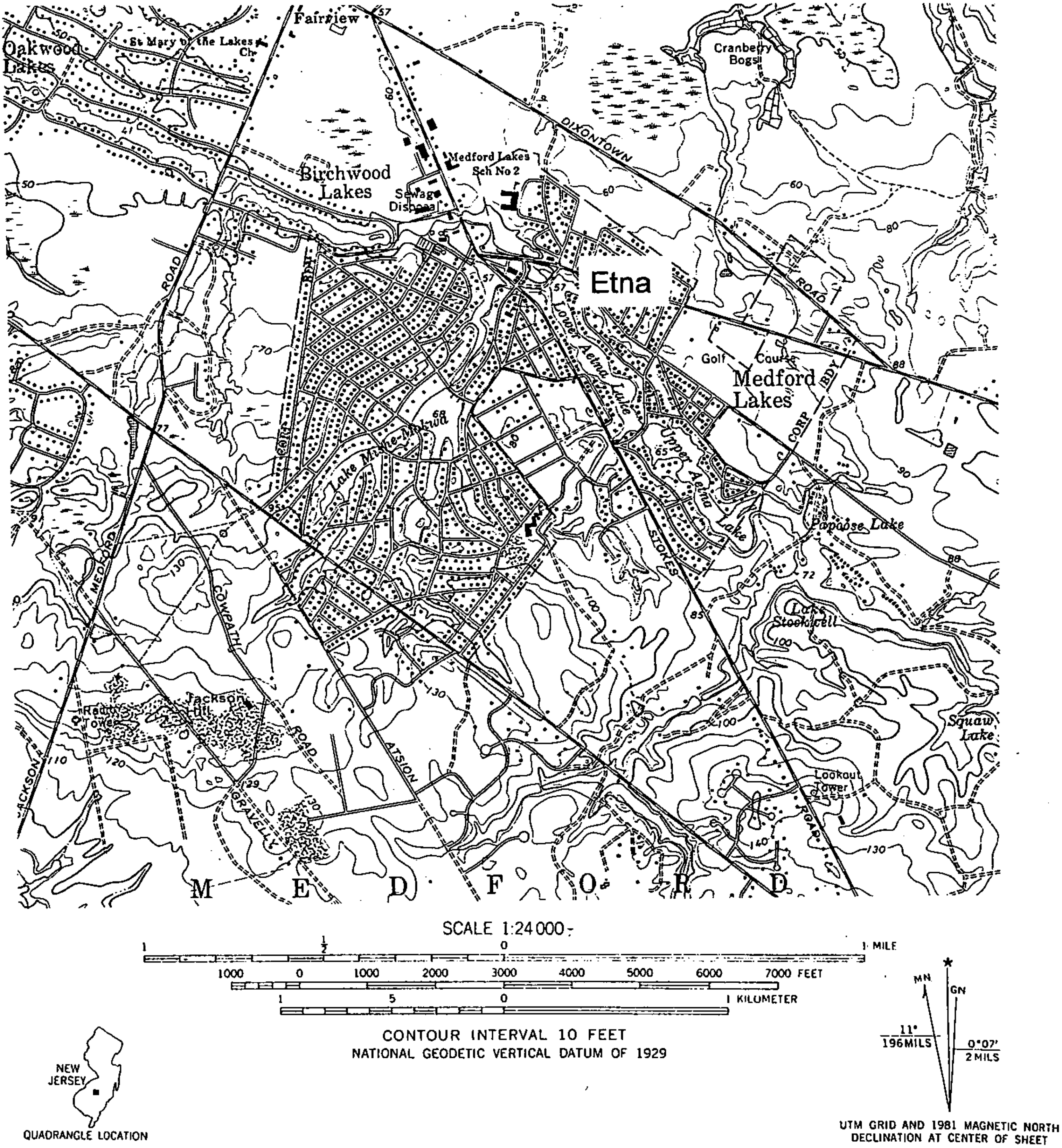

Figure 6
Etna (Medford Lakes) Location Plan

Scale as Shown

Plan taken from the USGS 7.5 minute quadrangle topographic map titled Medford Lakes, photorevised in 1981

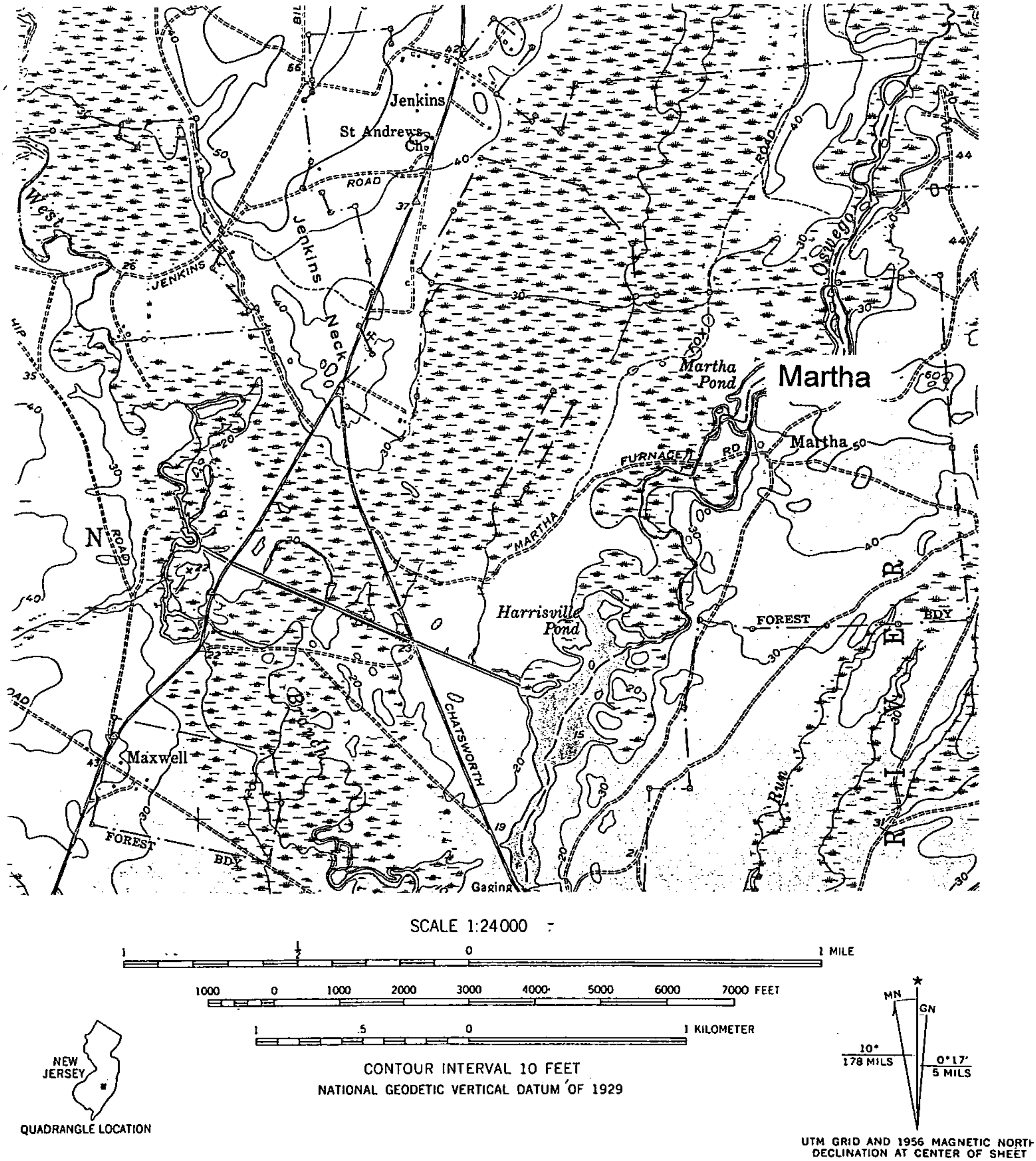

Figure 7
Martha Furnace Location Plan

Scale as Shown

Plan taken from the USGS 7.5 minute quadrangle topographic map titled Jenkins, photoinspected in 1977

Etna (Medford Lakes)

Charles Read purchased the site that included over 9,000 acres in 1766 (figure 6). Read also bought up the mineral rights to many of the properties around Etna. By 1767 the furnace was up and running. Because of Read's worsening financial situation, the furnace was put up for sale in 1770, and was still for sale when it burned in 1773. The machinery was sold and taken to Atsion in 1773. Etna returned to farmland and eventually became part of Medford Lakes.

Martha Furnace

Martha Furnace was built by Issac Potts in 1793, and was named for his wife (figure 7). The workers community was known as Calico. Initially the pigs were sent to Harrisville for forging. In 1800 the furnace was sold to four partners, who were not very successful at making iron, eventually Martha was sold to Samuel Richards and Joseph Ball. Under Richards the furnace was successful until the industry started to fail. The fires were out by 1845.

Batsto

Charles Read and partners built Batsto in 1766 (figure 8). Read also bought the mineral rights along the Atsion River almost to Atsion. John Cox (later Lt. Col.) acquired control of Batsto by 1773. During the Revolutionary War Batsto was one of the major suppliers of munitions to the Continental Army. Batsto was sold and bought several times until William Richards purchased the furnace in1784. Batsto remained in the Richards family for the next 92 years until bought by Joseph Wharton in 1876.

By 1812, during the height of the War of 1812, iron ore began to become scarce. New smelting techniques were introduced to keep the furnace going as ore started to be imported from Rancocas, Staten Island and Morris County. Hot blast smelting methods were introduced in 1838. The hot blast was similar to the cold blast except the air introduced to the fire was hot. The new cupola furnace was built in1841. In 1852 the latest style cupola furnace was built. The old furnace was shut down in 1848. By 1852 the furnace was operated only sporadically due to the lack of ore. In 1855 the furnace shut down and went out of blast for the last time.

Batsto continued operation as a glass works until a fire in 1874. Batsto was rebuilt but was foreclosed on in1876. Joseph Warton purchased Batsto in1876. Batsto was the first property in Wharton's plan for a water supply system for Philadelphia in the Pine Barrens (Pierce, 1957). These properties later became Wharton State Forest.

Allaire (Howell Works)

The first recorded iron works at Allaire State Park was the Williamsburg Forge, and the owners of the forge built the Monmouth Furnace in 1813. At the time the Monmouth Furnace was sold to William Newbold in 1821, the furnace complex consisted of the main dwelling, 15 other dwellings, the furnace, sawmill, outbuildings, ore beds and waters rights. Newbold soon sold the furnace to Benjamin Howell of Philadelphia who in turn sold the Monmouth Furnace to James P. Allaire in 1822. Allaire, at the time, owned the largest marine engine works in the United States and was a close friend of Robert Fulton. Allaire had cast in brass the air chamber for Steven's steam powered vessel

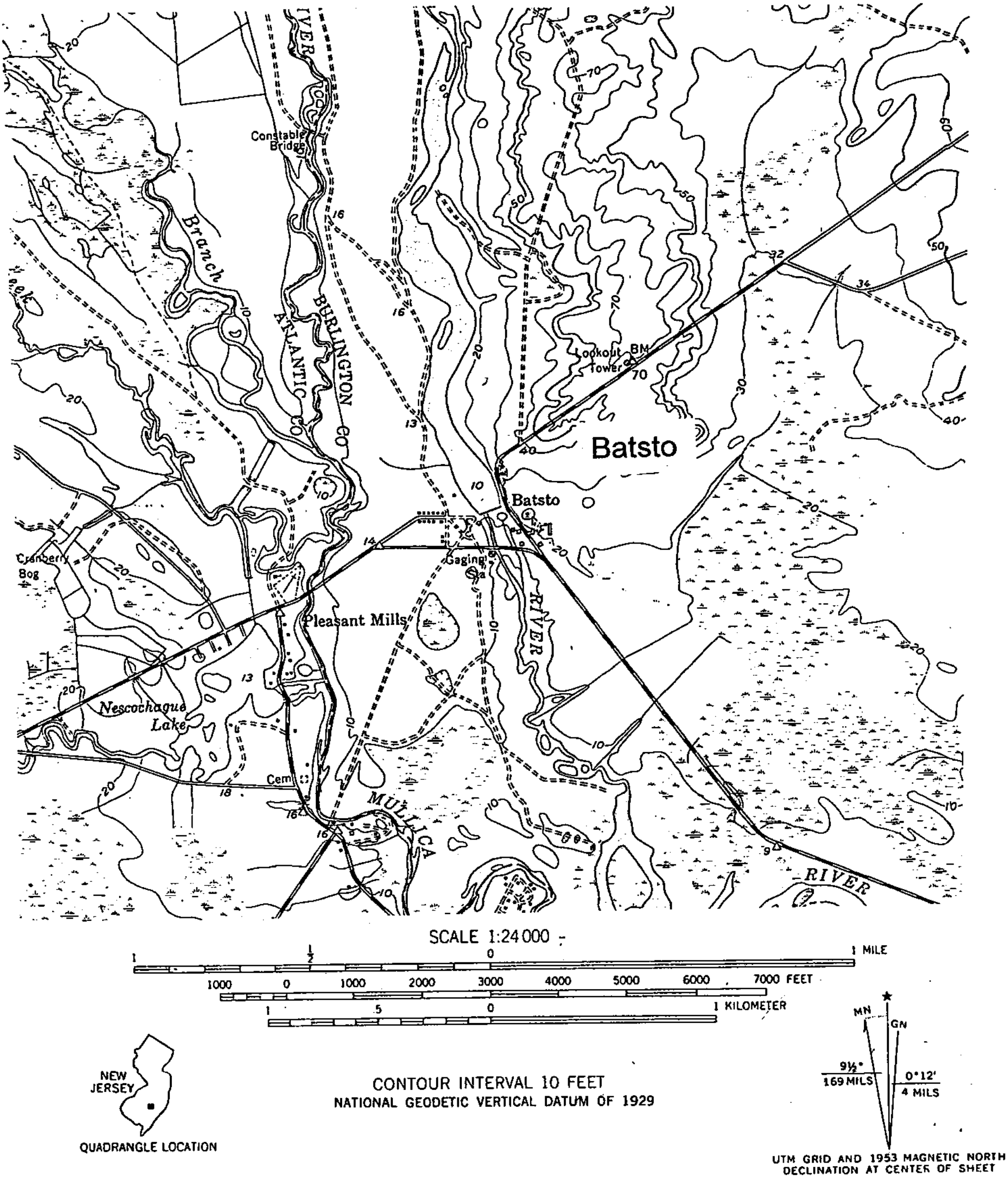

Figure 8

Batsto Location Plan

Scale as Shown

Plan taken from the USGS 7.5 minute quadrangle topographic map titled <u>Atsion</u>, photoinspected in 1977

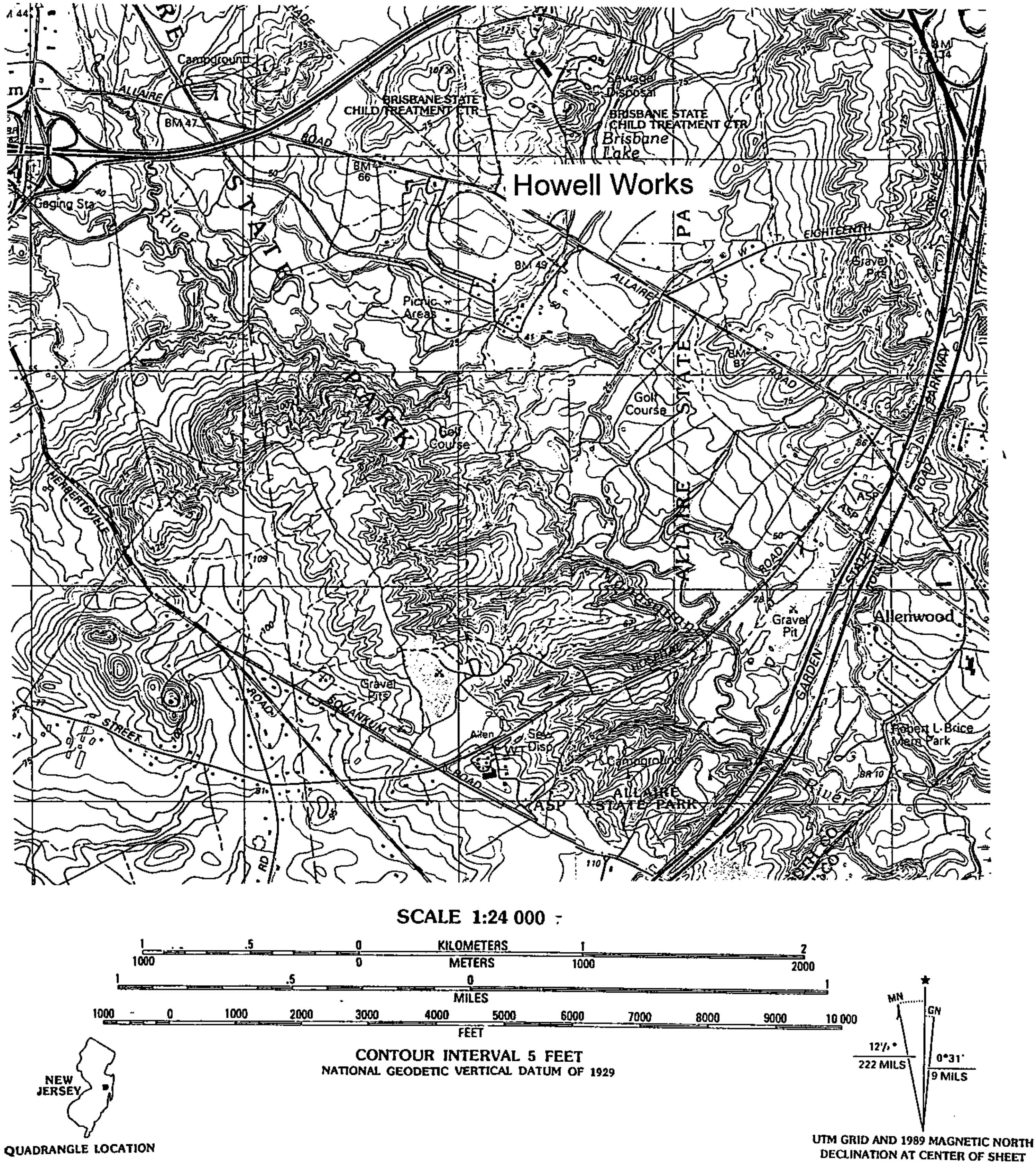

Figure 9
Allaire (Howell Works) Location Plan

Scale as Shown

Plan taken from the USGS 7.5 minute quadrangle topographic maps titled Farmingdale and Asbury Park,revised in 1989

"Clermont" and built the marine engines for many other of Fulton's steam powered vessels. Allaire saw the Monmouth Furnace as a source of pig iron for his foundry on Cherry Street in New York City. When Allaire purchased the furnace, it became known as the Howell Iron Works or the Howell Works.

The Howell Works prospered until 1846 when financial difficulties which lasted until his death in 1858 began to plague Allaire. The furnace did not operate after 1846, though the town survived for a few years as a community center.

Allaire's son Hal lived on the property until 1901 when it was sold to W.J. Harrison of Lakewood, N. J. In 1907 Arthur Brisbane bought Allaire (as it became to be known) and leased the site to the Monmouth Council of Boy Scouts. The Boy Scouts started the restoration process at Allaire. Brisbane's widow deeded the entire site to the State of New Jersey in 1941.

Starting in the 1950s a slow, continuing restoration of the village has been taking place. Today Allaire is closer to how it was in the 19th century than any other iron town in New Jersey. Many of the buildings have been restored, work is continuing on others and there are plans to restore the furnace house.

Collapse of the Industry

The bog iron industry started in New Jersey at Tinton Falls in 1674 lasted for 181 years during the formative years of this country and ended at Batsto in 1855. The bog iron industry drove the growth of the coastal plain region of New Jersey.

The precipitous decline of the bog ore industry began in the late 1840s. The five main reasons were:

1 Pennsylvania Anthracite: Pennsylvania anthracite was easier to coke, burned longer and hotter than charcoal. Once the prejudice against coal was overcome, anthracite quickly replaced charcoal.

2 Pennsylvania Iron Ores: the ores found in Pennsylvania were plentiful and of a high grade. These ores were near the sources of fuel and flux. This helped to cut down on transportation costs. Additionally, by the time these ores were discovered the bog ores were becoming scarce.

3 Technology of the New Jersey Furnaces: practically all of the Coastal Plain furnaces used the older inefficient cold blast method of smelting. Batsto late in its life used the more modern hot blast and cupola methods, but it was too late and the newer technology could not keep the furnaces running, as the ore was becoming scarce.

4 Ore Scarcity: from a combination of over mining and the impact of humans on the depositional environment the ore deposits did not renew themselves. Towards the end of the industry the local iron ore started to become scarce enough that several furnaces had to import ore to stay in blast.

5 Pennsylvania Carbonate Deposits- once the carbonate deposits were discovered and exploited, Pennsylvania could supply all of the needs for smelting iron. This along with the new railroads allowed Pennsylvania to out produce the bog iron furnaces. The iron smelted in Pennsylvania was of a higher quality because of the better ore, fuel and flux.

For these reasons the bog iron industry in New Jersey died off. It did however leave in its wake two state parks, and more importantly a nation.

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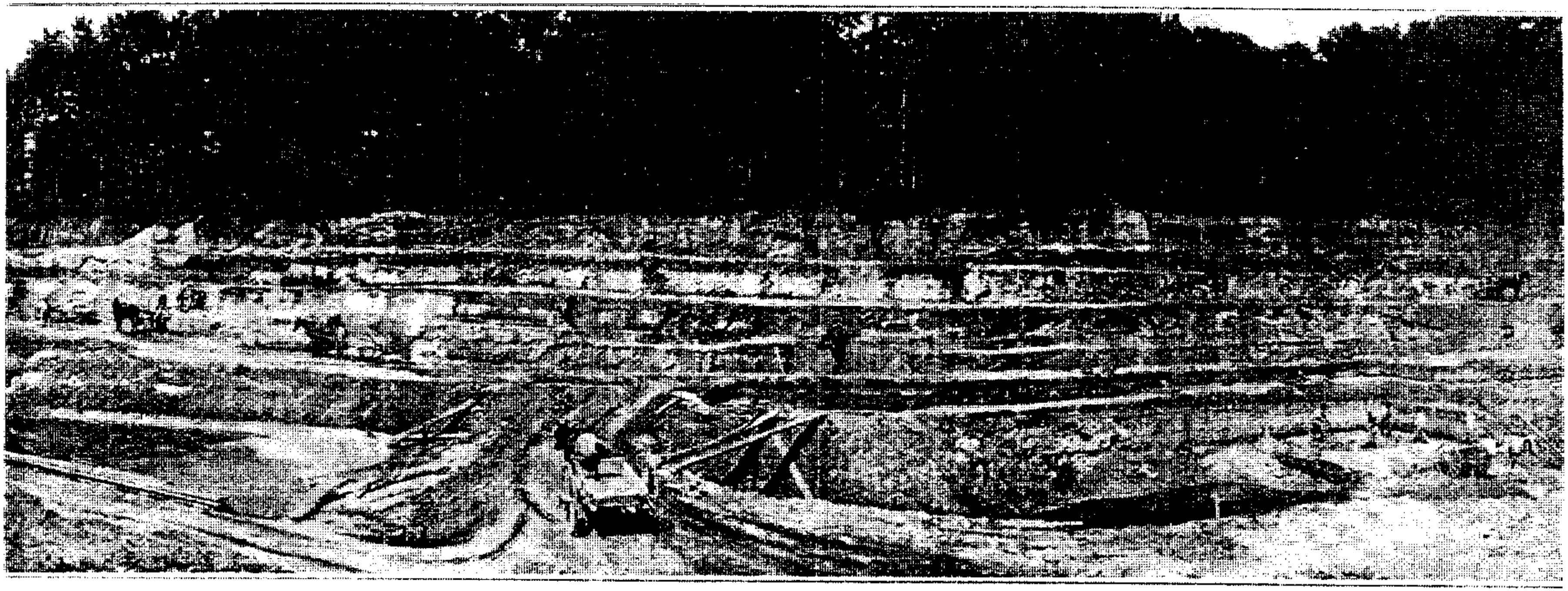

General view of W. H. Cutter's west clay bank, near Woodbridge

CLAY DEPOSITS OF THE UPPER CRETACEOUS RARITAN AND MAGOTHY FORMATIONS IN CENTRAL NEW JERSEY

Victoria C. Hover and Egon T. Weber II
Department of Geological Sciences
Rutgers/Newark
195 University Ave.
Newark, NJ 07102

ABSTRACT

The Coastal Plain province of New Jersey is underlain by a series of unconformity-bounded, shallowing-upward sedimentary sequences, which record several transgressive to regressive cycles since the early Cretaceous. Two such sequences are represented by the Upper Cretaceous Raritan and Magothy Formations. These two Formations were deposited along the up-dip margin of transgressive seas, and consist of fluvial, estuarine, delta, and pro-delta facies. Several studies have correlated these marginal marine facies with deeper-water facies in the subsurface to the south and off shore (e.g., the Bass River Formation).

Clay-rich beds in the Raritan and Magothy formations were mined in the Middlesex County area of New Jersey during the late 19th and early 20th centuries. The clay deposits were used in the manufacture of various products including common brick, fire brick, sewer pipe, earthen-ware and stoneware, porcelain, terra cotta, and paper coatings. During peak production years in the early 1900's, over 500,000 tons of clay per year were produced. However, clay production began to wane in the 1920's and 30's and was almost extinct by 1950. Today, only the exposed clay pits and some brick work foundations remain.

The economic clay beds mined from the Woodbridge Clay member of the Raritan Formation consist primarily of dark gray to black, laminated silty clays containing pyritized lignite fragments and siderite-cemented concretions. The Clay is up to 15 m thick. Overlying sand units often fill erosional surfaces in the underlying clay, and commonly contain blocky clay rip-up clasts at the base. The base of the sand horizon, at the contact with the underlying clay, commonly contains oxidized iron-nodule beds. The clay horizons were deposited in prodelta or inner neritic shelf environments or in a near-shore mangrove swamp environment. The Woodbridge clay was mined primarily for the manufacture of common brick.

Better grades of fire clay were mined from the South Amboy Fire Clay member of the Magothy Formation. These clay horizons consist of laminated to massive horizons of variegated colored clays, commonly olive gray, pyritic and lignitic, oxidized to white or red, and ranging from 0-8 m thick. The clay beds are less continuous than the Woodbridge Clay, and are commonly adjacent to cross-bedded sandy units at the same stratigraphic position. The rapid alternation of clay beds with sandy bed suggests deposition of the clays in abandoned meander channels adjacent to active stream channels in a fluvial flood- or delta-plain environment.

The clay horizons deposited in marine coastal, delta, or pro-delta environments contain a mixed clay fraction assemblage, which includes kaolinite, illite/muscovite, chlorite and trace smectite. Clay horizons deposited in fluvial environments contain a more restricted clay fraction assemblage dominated by kaolinite and illite/muscovite with only traces of chlorite and smectite. The kaolinite in the Raritan and Magothy Formations is the result of transport from eroded soils produced in a wet, tropical climate on deeply weathered felsic source rocks containing abundant feldspar and mica. Such source material was probably available in the New Jersey Highlands.

INTRODUCTION

During the 19th and 20th centuries, economic accumulations of clay were mined for a variety of applications in the central part of Middlesex counties north and south of the Raritan River from unconsolidated Cretaceous-age sediments of the Raritan, and Magothy Formations, (e.g., Cook and Smock, 1878, Ries et al., 1904). The overlying Merchantville and Woodbury Formations were also mined in portions of Monmouth County. The clay mining and manufacturing industry so dominated this area that early reports to the state Geologist refer to the area as the New Jersey "Clay District". The clay deposits along with associated sand and sandy clay beds were mined in numerous shallow pits or "banks" throughout the area to provide the raw materials for common brick, fire brick, earthen- and stone-ware, porcelain-ware and terra cotta. Much of the production of the finished products was also done in the area, commonly adjacent to the pits. These deposits were economic due to 1) the relatively shallow depth of burial beneath a thin veneer of Tertiary or Quaternary unconsolidated sediment, which permitted easy removal by hand or steam shovel, and 2) the close proximity of the deposits to the Raritan and South rivers, which provided easy access to transportation of finished products or raw materials to the entire eastern seaboard. In 1901, when clay production was at its peak, approximately 500,000 tons of raw clay was mined annually (~ 36% of entire U. S. production) (Ries et al., 1994).

By 1950's, the deposits were nearly exhausted, and no clay is being mined today (Musser, 1988), although some pits still provide sand and gravel from overlying Tertiary and Pleistocene deposits. Rapid development in Middlesex County over the past three decades has converted most of the former clay pits to housing developments and shopping centers. Most of the best exposures of the once thriving clay industry are now covered, and the few remaining open pits, are privately owned and slated for development, making accessibility difficult.

Besides providing clay for the brick-making industry, the clay members of the Raritan and Magothy Formations are also important confining layers in the Potomac-Raritan-Magothy aquifer system (e.g., Pucci et al., 1994). Sandy units within the Raritan and Magothy confined by the clay layers in the subsurface have been important aquifers since the late 1800's and currently provide up to 95% of the potable groundwater used in Middlesex County (Pucci, et al., 1994). Continued development of the area where these units crop out also has serious implications for the ability of these aquifer units to recharge in the future.

The clay deposits in the Raritan and Magothy Formations are also important to sequence stratigraphic interpretations of the Atlantic coastal plain sedimentation and relationship to global climate change, regional tectonics, and changes in eustatic sea level. The coastal plain sediments in New Jersey record several major unconformity-bounded shallowing-upward transgressive to regressive cycles, which define major sequence boundaries, (e.g., Owens and Gohn, 1985; Olsson, 1987; Olsson et al., 1988, Sugarman et al., 1993). These sequences are primarily the result of changes in eustasy (Vail et al., 1977; Olsson, 1988).

In an effort to establish the sequence stratigraphic relationships in Cretaceous and younger New Jersey Coastal Plain sediments, a series of on shore wells have been drilled as part of the New Jersey Coastal Plain Drilling Project (Fig. 1). Recently, the Ocean Drilling Program (ODP) and New Jersey Geological Survey (NJGS) completed drilling middle Miocene and older sediments, including the Upper Cretaceous down-dip marine equivalents of the Raritan and Magothy Formations at the onshore Bass River Site (Leg 174AX, Miller et al., 1998). This site is the fourth onshore ODP well drilled through coastal plain sediments, which began with the

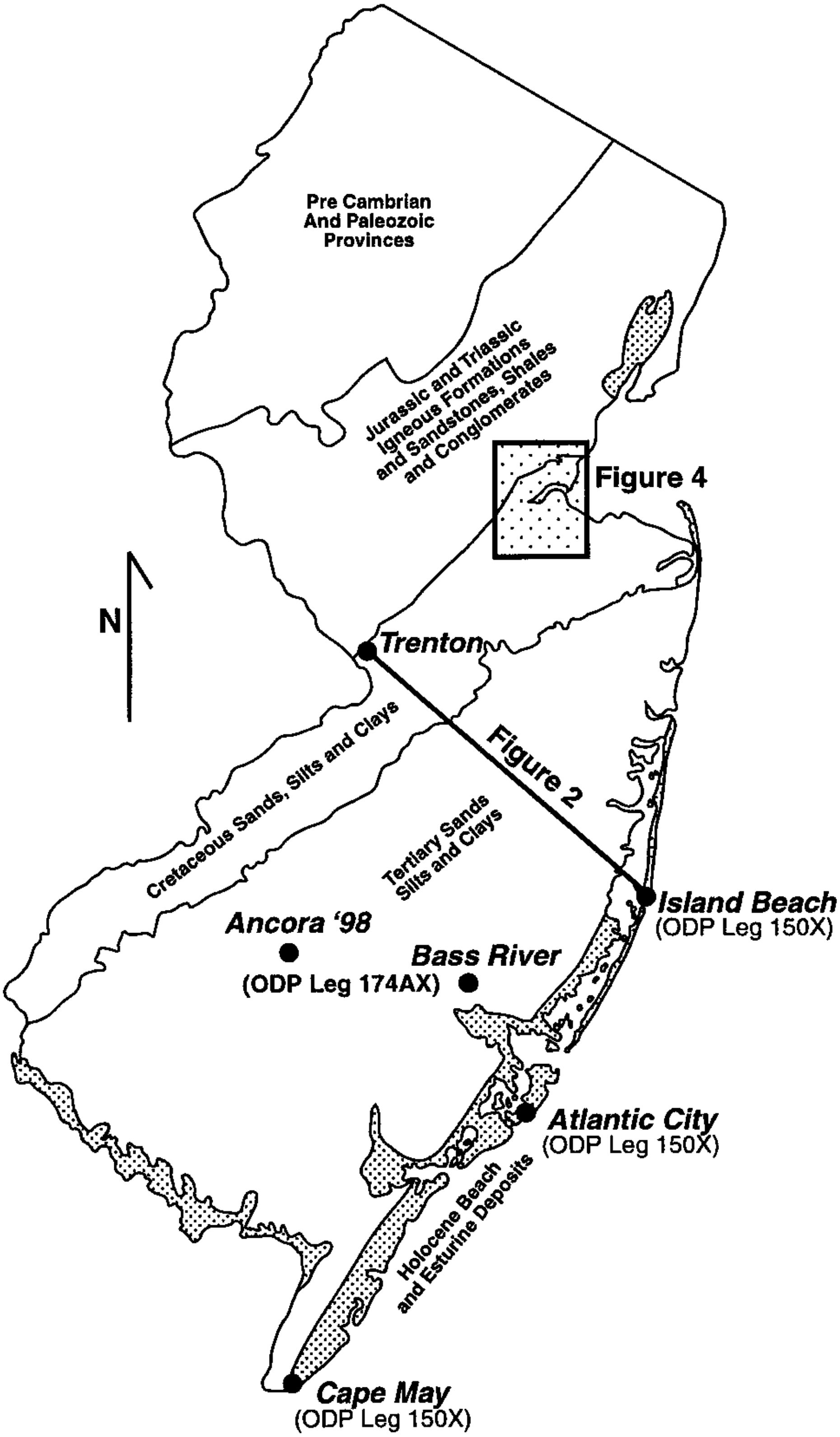

Figure 1. Generalized geologic map of New Jersey. Sequences discussed in this paper lie within the sedimenatry packages deposited on the Atlantic coast during the late Cretaceous. The cross section presented in Figure 2 is located for reference and includes a transect across the whole post late Cretaceous sedimentary package. Locations of drill sites from Ocean Drilling Program (ODP) Legs 150X, and 174AX are included for reference (Miller et al. 1998).

ODP Leg 150X sites at Island Beach, Atlantic City and Cape May (Fig. 1) (Miller et al., 1994a, 1994b, 1996). Other marine ODP sites have drilled the coastal plain section along the continental slope (Leg 150; Mountain et al., 1994, 1996), and continental shelf (Leg 174A; Austin et al., 1998).

The scope of this paper is to 1) describe the lithostratigraphic units that contain the economic clay deposits of central Middlesex County and relate them to down dip units within a sequence stratigraphic context, 2) provide a brief history of the clay industry in the area with reference to specific units mined in various clay pits, 3) describe the mineralogy of selected clay units.

LITHOSTRATIGRAPHIC DESCRIPTION AND CLAY OCCURRENCE

The Cretaceous coastal plain sediments in New Jersey crop out in a relative narrow belt from Raritan Bay toward the northeast and trending southwest along the western margin of the state (Fig. 1). The clay deposits occur within the wedge of Cretaceous to Holocene unconsolidated and semi-consolidated sediments of clay, silt, sand and gravel, which were deposited on the northern Atlantic coastal plain adjacent to the Baltimore Canyon Trough (e.g., Olsson et al., 1988 and references therein). The Cretaceous sediments unconformably overly Triassic and Jurassic sedimentary and igneous rocks in the central New Jersey area, but overly Precambrian basement towards the south (Olsson et al., 1988). The coastal plain sediments generally thicken to the southeast (Fig. 2). The regional dip of beds is generally less than 1° to the southeast (e.g., Ries et al., 1904).

The clay deposits of economic importance in the Middlesex County "Clay District" occur within the Upper Cretaceous Raritan and Magothy Formations and crop out in the central portion Middlesex County and the northern portion of Monmouth County adjacent to the Raritan River in the vicinity of Woodbridge, Perth Amboy, South Amboy, and Sayreville (Fig. 3). The Raritan and Magothy Formations in the outcrop belt are composed mainly of fluvial to marginal marine sediments deposited at the up-dip margin of transgressive seas, and are correlative to deeper water deposits in the subsurface to the southwest (Fig. 4).

The general depositional and sequence stratigraphic model for the New Jersey Coastal, as described by Olsson (1988), modified from Owens and Gohn (1985), is an unconformity-bounded sequence with a transgressive unit at the base, which shallows upward to a regressive unit at the top (Owens and Gohn, 1985; Olsson et al., 1988; Sugarman et al., 1993). A sequence records a cycle of sea-level rise (Fig. 4). Sediments typical of coastal deposition include fluvial, beach, lagoon, marsh/estuary and related deposits (Olsson et al., 1988). Inner shelf deposits include shore-face sands and related delta-front deposits of micaceous clay and slit and thinly bedded fine sand. Mid and outer shelf deposits include clayey glauconitic sands and glauconite clay, and slope deposits consist of calcareous clays (Olsson et al., 1988). Transgressive units correspond to middle and outer shelf depositional environments and regressive units to inner shelf, shoreface, and delta environments (Olsson, 1987).

The Lower and Upper Cretaceous lithostratigraphic units in the central New Jersey area and their down-dip equivalents will be described below within a sequence stratigraphic and chronostratigraphic context. The important clay units mined in the Middlesex county Clay District are the Raritan and Magothy Formations (Fig. 3). The lithologic descriptions are compiled from several previously published papers and field trip guides (e.g., e.g., Cook and

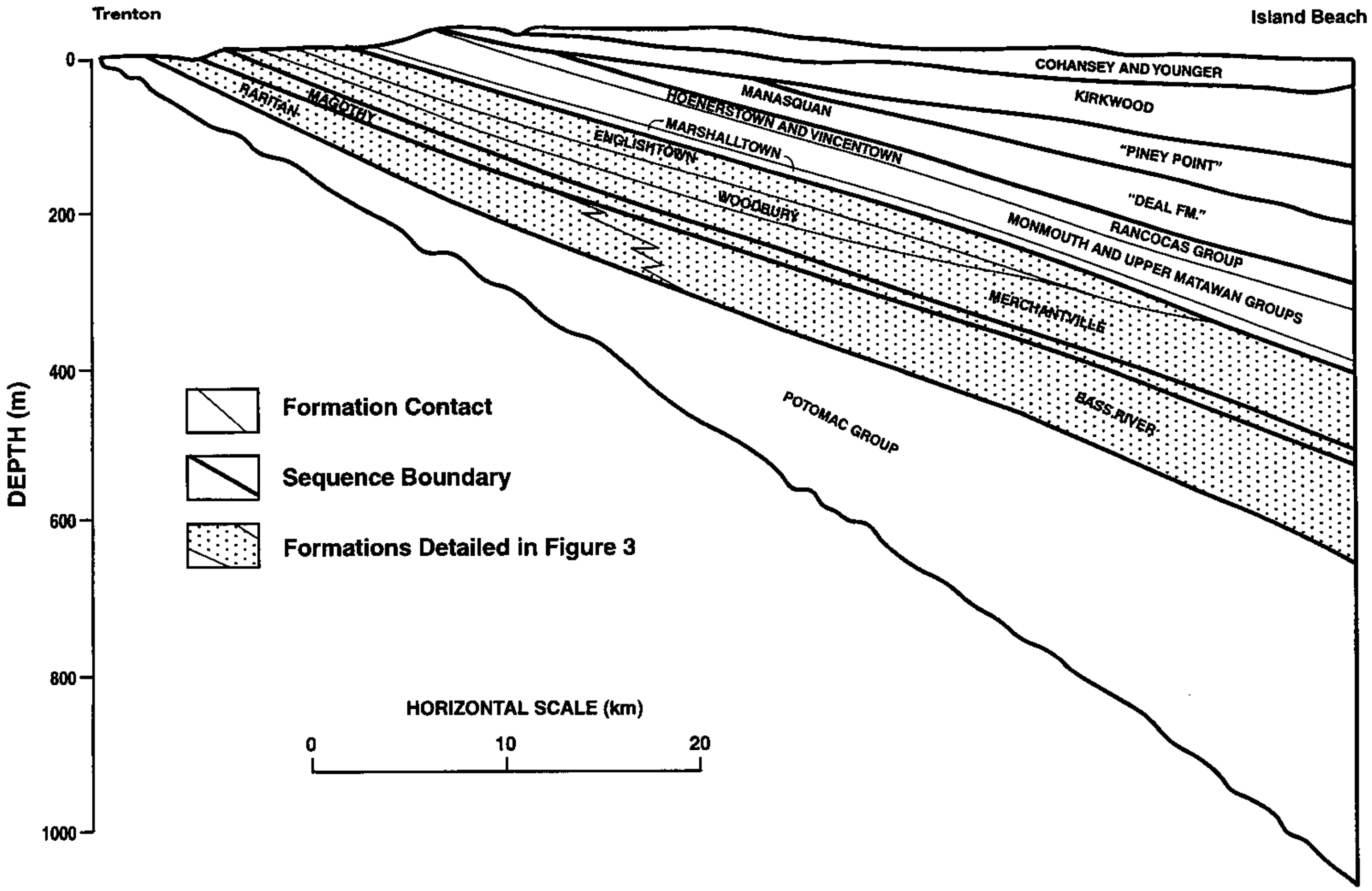

Figure 2. Generalized post-Triassic sedimentary package present on the New Jersey coastal plain. Chronostratigraphic relations present in formations is detailed in Figure 4. Formation present throughout the clay district are highlighted in stippled pattern. Modified after Olsson et al. (1988).

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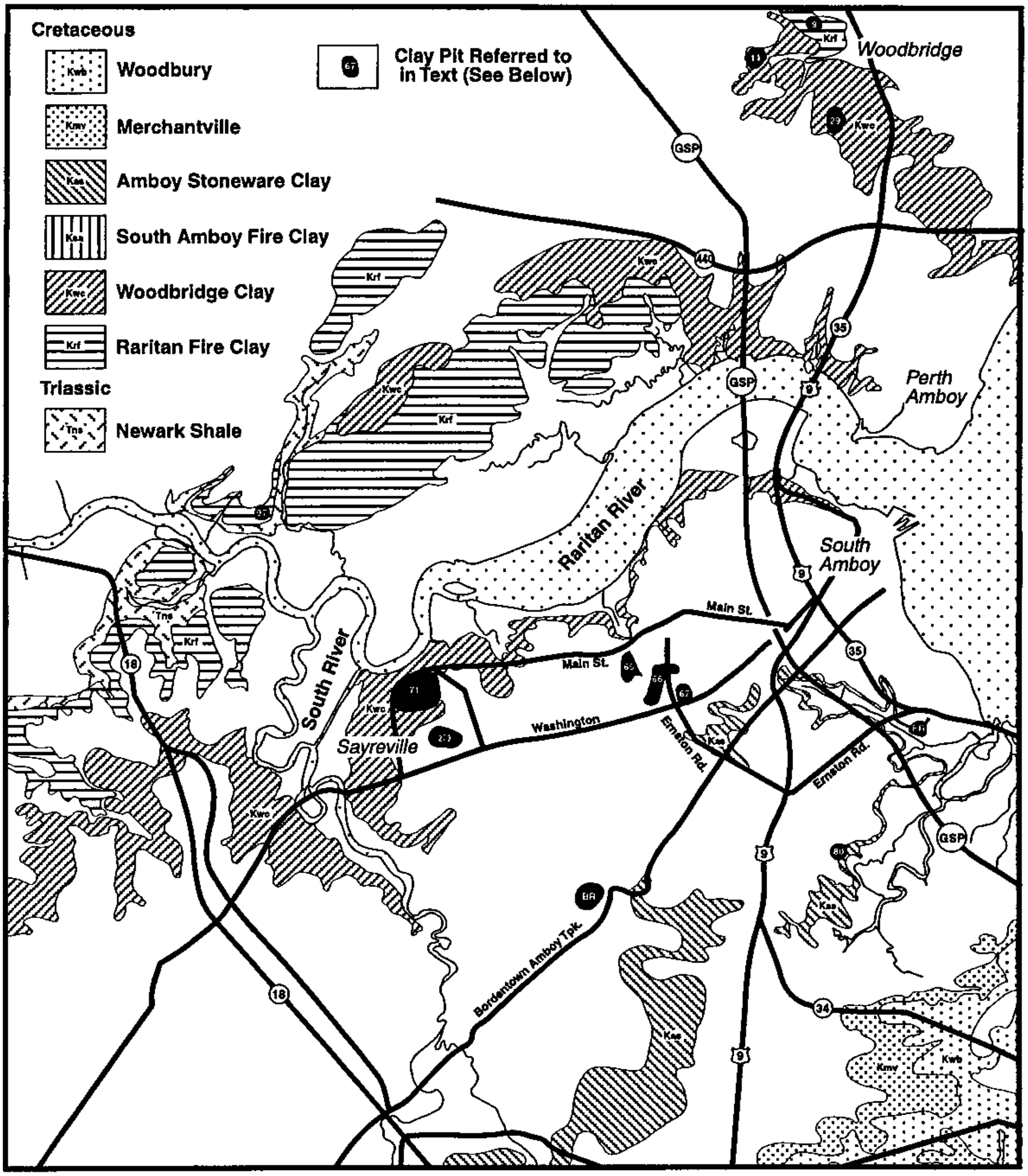

Figure 3. Geologic map of clay units within the Matawan Group, Magothy Formation, and Rartitan Formation (Modified after Ries et al., 1904). Mapped units are outcrop or covered by a thin layer of alluvium. The clay pits discussed in this paper are deignated with the numbers of Ries et al., (1904) where numbered; BR = Bordentown Road, ER = Ernston Road.

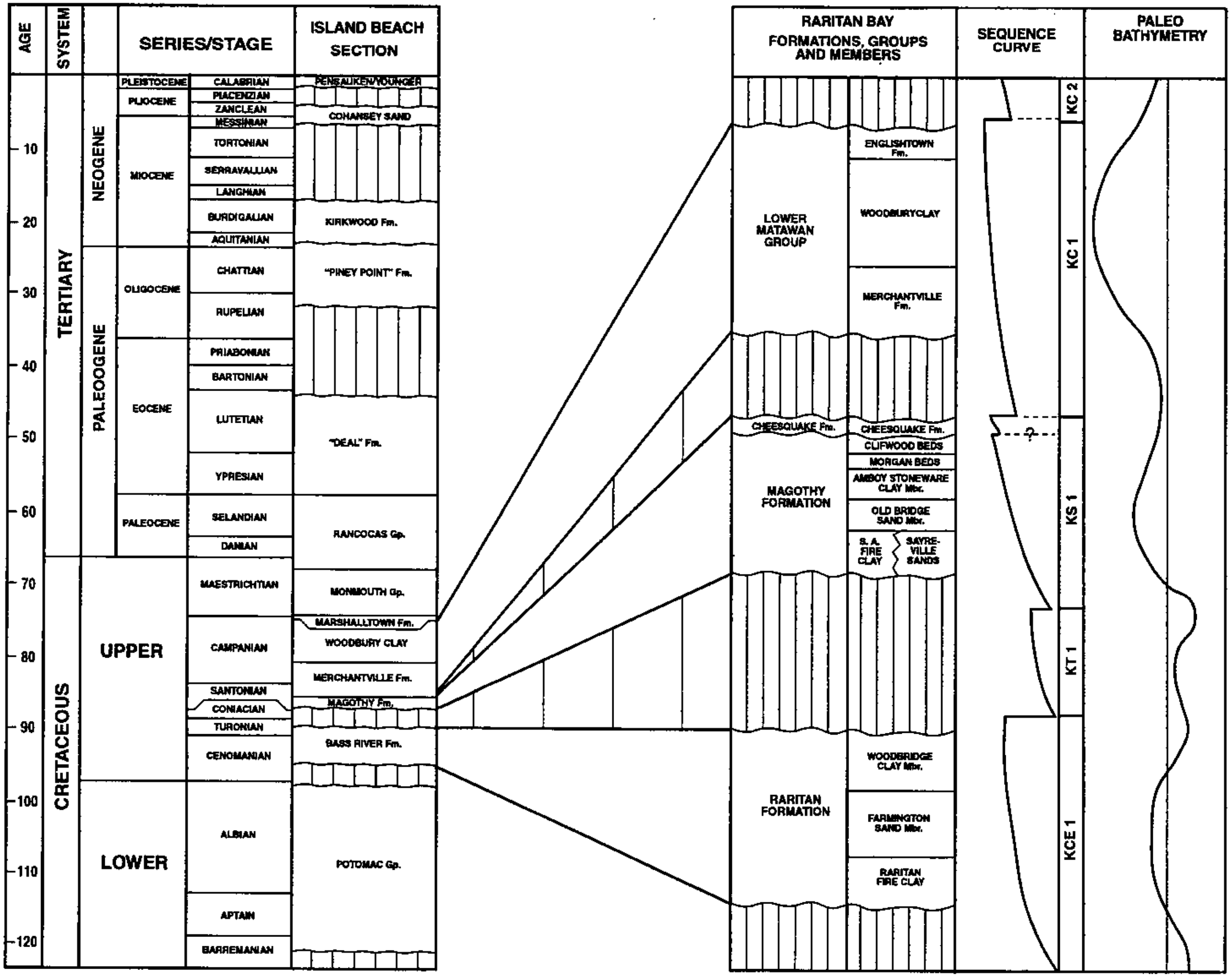

Figure 4. Generalized chronostratigraphy of the Cretaceous/Tertiary sedimentary units at Island Beach (Left) after Olsson et al., (1988) and of the Late Cretaceous units near raritan Bay (Right) modified after Olsson et al., (1987), COSUNA (Jordan and Smith, 1983). Placement of Cheesquake Fm. inferred from Sugarman (1996), and Miller et al. (1998).

Smock 1878; Ries et al., 1904; Dorf and Fox, 1957; Owens and Sohl, 1969; Owens et al., 1977, Olsson, 1980; Olsson, 1987; Sugarman, 1996; Miller, 1998, pers. commun.)

Potomac Group

Age: pre Cenomanian to early Cenomanian
Sequence: KAL1 (Cretaceous Albion 1: Olsson, 1987).

Sedimentation on the New Jersey coastal plain began during the Early Cretaceous (pre Cenomanian) with deposition of the Potomac Group (Olsson et al., 1987). In the central New Jersey "Clay District", the Potomac Group is does not crop out (e.g., Pucci et al., 1994), but in the subsurface at the Island Beach well site, it thickens to over 460 m (e.g., Olsson, et al., 1988). The Potomac Group sediments consists of interbedded quartzose sands, and variegated gray, red and white silts and clays of continental origin. The Potomac Group is interpreted as a complex of fluvial deltaic lithologies deposited by a major river centered in Maryland, including braided and meandering stream sands and gravel deposits, upper and lower flood plain deposits, and fringing swamp deposits (Owens and Gohn, 1985; Olsson et al., 1988 and references therein). Down-dip units of the Potomac Group contain marine fossils and are interpreted to represent a series of shoreface sands related to delta-front deposition (Olsson et al., 1988). The Potomac Group sediments fall within Palynozone I (Barremanian to Albian age), Palynozone II (Albian age), and Palynozone III (early Cenomanian age) (Olsson et al., 1988 and references therein).

Bass River Formation

Age: Cenomanian to early Turonian
Sequence: KCE 1 (Cretaceous Cenomanian 1; inferred form Olsson, 1987, Olsson et al., 1988)

Beginning in Albian time, a major cycle of sea level rise occurred in the Baltimore Canyon Trough area and marginal marine seas spread over the southern New Jersey coastal plain by the Cenomanian (Olsson et al., 1988). The Bass River Formation, first described by Petters (1976), occurs only in the subsurface in the southern portion of the New Jersey coastal plain. The Bass River marks the first major marine deposition on the coastal plain and is time transgressive representing early Cenomanian time in deep wells to early Turonian time in up-dip shallow wells (Petters, 1976; Olsson et al., 1988). The Bass River is the transgressive marine facies equivalent of the up-dip, coastal Raritan Formation described below (Petters, 1976; Olsson, 1980; Olsson, 1987; Olsson et al., 1988). The Bass River Formation is approximately 122 m thick at the Island Beach location and is composed of uniform lithology of olive-gray to olive-black chloritic and glauconitic clayey silt with shell fragments, which are occasionally cemented into massive limestones (Petters, 1976). The Bass River Formation was deposited in a shelf or sublittoral environment and rapidly thins to the northeast towards central New Jersey where it is replaced by the fluvial facies of the Raritan Formation (Petters, 1976).

Raritan Formation

Age: late Cenomanian to early Turonian
Sequence: KCE 1 (Cretaceous Cenomanian 1; Olsson, 1987).

The Raritan Formation, along with the Magothy Formation described below, contains some of the clay beds of economic importance to the Middlesex County Clay District. Lithostratigraphic units in the Raritan Formation consists of interstratified light colored sands and dark or variegated clayey silts or silty clays, which are laterally discontinuous and vary in thickness, texture and composition (Ries et al., 1904). The Raritan Formation represents the coastal fluvial to near-shore marine facies, which is time-equivalent to the marine Bass River Formation in the subsurface. The Formation is up to ~50 m thick in central New Jersey but thins southwestwardly along the outcrop belt (e. g., Olsson et al., 1988). Owens et al. (1977), using the nomenclature of Barksdale et al., (1943), included (from oldest to youngest) the Raritan Fire Clay, Farrington Sand, Woodbridge Clay, and Sayreville Sand as informal members of the Raritan Formation based on pollen correlations of Christopher (1977). However, the Sayreville Sand is now placed in the Magothy Group (e.g., Sugarman et al., 1993, Miller, 1988, pers. commun.) as described below. As presently described, the Raritan Formations consists of two informal units (from oldest to youngest) the Farrington Sand member (including the underlying beds previously attributed to the Raritan Fire Clay), and the Woodbridge Clay member (Owens et al., 1995, Sugarman, et al., 1995; Sugarman, 1996). For the purposes of this paper, the Raritan Fire Clay member, is described separately from the overlying units as it was an important clay producer in Middlesex County (Fig. 3).

Raritan Fire Clay or Terra-Cotta (Potter's) Clay is a massive, multicolored sandy clay that forms a gradational contact with saprolite overlying the silty to shaley bedrock of the underlying Triassic-age Newark Group (Cook and Smock, 1878; Ries et al., 1904). It may be a residuum formed from the decomposition of the shale, or reworked weathered material redeposited prior to deposition of the overlying Cretaceous units. The Raritan Fire Clay crops out in a thin discontinuous belt north and south of the Raritan River (Fig. 3). The Raritan Fire Clay has variable thickness ranging up to ~ 12 m (Cook and Smock, 1878; Ries et al., 1904).

Farrington Sand member: The Farrington Sand Member unconformably overlies either the Raritan Fire Clay in the northeastern portion of the Cretaceous outcrop belt towards New Brunswick, or Mesozoic age rocks towards the south (Ries et al, (1904). The Farrington Sand was referred to as the No. 1 Sand or Fire Sand by Ries et al. (1904). The Farrington Sand consists of light-colored, micaceous cross-stratified sands interbedded with lenses of clay and gravel. It varies in thickness from ~5-11 m (Ries et al., 1904; Owens et al. 1995). The Farrington Sand is interpreted to be a meandering stream deposit (e.g., Sugarman, 1996)

Woodbridge Clay member: The Woodbridge Clay member is a thin- to thick-bedded sequence of dark-gray micaceous silts and clays containing abundant lignite fragments (Ries et al. 1904; Owens and Sohl, 1969; Owens et al., 1977). Locally, laminated beds of light sand and dark silty clay are present (Owens et al., 1977). Numerous layers, typically at the contact between sandy and clayey layers, contain siderite concretions ranging in size from a few cm to slabs 0.3 m in diameter (Owens and Sohl, 1969; Owens et al., 1977). Owens and Sohl (1969) reported lignitized trees in growth position at the base of the Woodbridge in the Sayreville area. Pyrite nodules associated with lignite fragments are common. The Woodbridge Clay is relatively continuous in the outcrop belt and ranges in thickness from 15-25 m (Ries et al., 904;

Owens et al., 1977). Brackish water and marine fossils including bivalves and gastropods (Richards, 1943; Stephenson, 1954; Sohl, 1977) and ammonites (Cobban and Kennedy, 1990), and plants (Dorf and Fox, 1957) of upper Cenomanian age are also locally present in the Sayreville area. *Callianassa* burrows are present in some layers (Owens and Sohl, 1969) and a shark's tooth has been found within a siderite concretion (Case, 1989). Amber containing insects has also been found (Grogan and Szadziewski, 1988). The Woodbridge Clay is also the type section for the *Complexiopollis-Atlantolopollis* pollen zone (Christopher, 1977, 1979, 1982) of Cenomanian to early Turonian Palynozone IV (Sirkin, 1974, 1987; Perry et al., 1975).

Owens and Sohl (1969) suggest that the juxtaposition of carbonaceous rich layers with shallow marine layers is consistent with deposition in a marginal marine swampy (mangrove) environment such as a subaerial delta plain. Alternating beds of course sand and fine silt in the upper portion of the member may be overbank deposits associated with natural levees (Owens and Sohl, 1969). Sohl (in Owens et al., 1977) suggest the Woodbridge Clay is an inner neritic shelf deposit. Sugarman (1996) suggests it may represent a prodelta or inner neritic shelf deposit related to a delta system dominated by fine–grained sediment.

In the late Turonian, sea level fall resulted in a major regional unconformity and no Coniacian-age sediments were deposited in the New Jersey Coastal Plain (e.g., Petters, 1976; Olsson et al., 1988).

Magothy Formation

Age: Santonian to earliest Campanian
Sequence: KS 1 (Cretaceous Santonian 1; Olsson, 1987).

The Magothy Formation is the basal unit of the next cycle of sea level transgression and unconformably overlies the Raritan Formation in outcrop, and the Bass River Formation in the subsurface (e.g.; Petters, 1976; Olsson, 1980; Olsson et al., 1988; Miller et al., 1998). The Magothy Formation consists of light-colored cross-bedded sands interbedded with thin beds or lenses of light colored variegated or dark colored carbonaceous–rich clayey silts or silty clays containing abundant lignite. Upper units are more laterally continuous than lower units (Owens and Sohl, 1969). The Magothy Formation has been interpreted to represent a series of beach-zone deposits with related fluvial and estuarine facies including tidal delta sequences which formed the edge of the advancing Santonian sea (Lev, 1983; Olsson et al., 1988).

As in the Raritan Formation described above, the clay lithologies in the Magothy Formation were extensively utilized for brick and related applications. According to current usage of Owens et al. (1977, 1995) and Sugarman, et al. (1995) the Magothy is composed of the following informal members from oldest to youngest: the South Amboy Fire Clay member, the Old Bridge Sand member, the Amboy Stoneware Clay member, the Morgan beds, and the Cliffwood beds (Fig. 3). The Sayreville Sand member (of Barksdale et al., 1943), previously placed in the Raritan Formation, is now considered a facies equivalent to the South Amboy Fire Clay because it occurs at the same stratigraphic position (as in the former Sayre and Fisher clay pit, Saryreville) and is discontinuous over a large areas of the out crop belt (e.g., Peters, 1976; Sugarman, 1996; Miller, 1998, pers., commun.).

The Sayreville Sand member: The Sayreville Sand member (No. 2 Sand, "Feldspar"-"Kaolin" sand of Ries (1904)), where present, unconformably overlies the Woodbridge Clay Member and consists of light buff-colored, cross-stratified, fine to medium-grained sand layers interbedded with light-to dark-colored clayey silt layers (Owens et al., 1977) (the South Amboy

Clay member). The sand locally contains reworked strata producing clay "breccia" beds within the sand (e.g., former Sayre and Fisher clay pit) (Owens and Sohl, 1969; Owens et al., 1977). The Sayreville sand is irregular in thickness ranging from 0-12 m. Owens and Sohl (1969) suggested that the Sayreville Sand was deposited in high energy river channels.

The South Amboy Fire Clay member: The South Amboy Fire Clay member is similar to the Woodbridge Clay Member except that is lacks siderite concretions and marine fossils (Owens and Sohl, 1969). The Clay is massive to finely laminated, dark-gray locally, commonly oxidized to white or red (Sugarman, 1996). Pyritized lignite fragments and logs are common in the dark-gray layers. The clay beds are less continuous than the Woodbridge Clay (Owens and Sohl, 1969; Owens et al., 1977) and commonly occur in channels adjacent to the cross-stratified quartz sands (the Sayreville Sand member). The sands commonly contain lignite fragments up to log size. Small pieces of amber are also present in the South Amboy Fire Clay (Owens et al., 1977). The South Amboy Fire Clay has a maximum thickness of ~10-12 m (Owens and Sohl, 1969; Owens et al., 1977). Owens and Sohl (1969) suggest that the South Amboy Fire Clay may be deposited in abandoned meander channels (oxbow lakes) in a subaerial delta plain (Miller, 1998, pers. commum.). Sugarman (1996) suggests the pollen assemblage indicates deposition in a coastal lowland swamp environment. The South Amboy Fire Clay contains pollen species form the *Complexiopollis exigua-Santalacites minor* Zone and represent a sharp break from underlying Woodbridge Strata (Christopher, 1979). The pollen assemblage is assigned to Palynozone V (Sarkin, 1974, 1987); considered to be post Coniacian in age (Christopher, 1982).

Old Bridge Sand member: The Old Bridge Sand member (No. 3 Sand of Ries et al., 1904) consists of extensively cross-stratified light gray sand beds, weathered to pink and orange, containing medium to course grained quartz, mica and lignite fragments. Stratification includes trough and planar-tabular cross-beds of variable size interbedded with thin-to thick bedded dark discontinuous carbonaceous clay beds up to 1 m thick (Sugarman, 1996). The Old Bridge Sand is approximately 12 m thick in outcrop (Owens et al., 1995). Barksdale et al., (1943) observed that the contact of the Old Bridge Sand with the underlying South Amboy Fire Clay was sharp and undulatory and suggested a brief period of erosion followed the deposition of the South Amboy Fire Clay (e.g., Petters et al., 1976). Owens and Gohn (1985) interpreted the Old Bridge Sand member to be a lower delta-plain deposit; the cross bedded sands representing distributary channel deposits and the lignitic fine-grained deposits representing marsh, and flood-basin deposits.

Amboy Stoneware Clay member: The Amboy Stoneware Clay member is dark and micaceous laminated clayey-silt containing abundant fine-grained carbonaceous matter with associated pyrite, and carbonized wood (logs up to one meter), and small cylindrical burrows filled with light sand (Owen and Sohl, 1969; Owens et al., 1977). The laminated clay overlies massive white to pale-blue clay layers referred to as the Stoneware Clay proper (e.g., Ries et al., 1904). The Amboy Stoneware Clay is less continuous than the South Amboy Fire Clay and the unit ranges in thickness from 0-11 m (Owens and Sohl, 1969; Owens et al., 1977). It is interpreted to have been deposited in lensoid channels and may be a marginal marine deposit (Sugarman, 1996). The Amboy Stoneware Clay contains pollen assemblages belonging to the *Psuedoplicapollis longiannulata-Plicapollis incisa* zone (Christopher, 1979), corresponding to the lower part of Palynozone VII (Sirkin, 1974) interpreted to be Coniacian(?) to early Santonian in age. Sugarman et al., (1995) informally assigned the *Psuedoplicapollis longiannulata-Plicapollis incisa* zone to Palynozone VI, and suggested that the South Amboy Stoneware Clay disconformably overlies the Old Bridge Sand Member (e.g., Sugarman, 1996).

Morgan beds: The Morgan beds conformably overly the Amboy Stoneware Clay in the eastern portion of Middlesex and northwestern portion of Monmouth counties(Owens et al., 1977). They consist of finely interstratified light to medium gray clays and silts containing carbonaceous material interbedded with light colored sands which grade laterally into light colored cross-stratified lignite-bearing sand (Owens and Sohl, 1969; Owens et al., 1977). The Morgan beds are ~12 m thick and grade into the underlying South Amboy Stoneware Clay. The Morgan beds are interpreted to be tidal delta deposits (Olsson, 1987).

Cliffwood beds: The Cliffwood beds are composed of fine to medium grained, light colored, quartz sand with some clear and green mica, commonly cross-bedded, interbedded with thin dark micaceous and carbonaceous silt containing pyrite (Ries et al., 1904; Owen and Sohl, 1969; Owens et al., 1977). The base of the Cliffwood beds contains small siderite concretions containing marine fossils (Weller, 1907; Stephenson, 1954; Owens and Sohl, 1969; Owens et al., 1977). The maximum thickness of the Cliffwood beds is ~ 12 m. The presence of rare *Ophiomorpha* trace fossils indicate the Cliffwood beds were probably deposited in a shoreface environment (Olsson, 1980, 1987). The Morgan and Cliffwood beds have been assigned to the *?Pseudoplicapollis cuneata-Semioculopollis verrucosa* Zone (Christopher, 1979), which is equivalent to the upper part of Palynozone VII of Sirkin (1974). This zone is considered Santonian to earliest Campanian (e.g., Sugarman, 1996) .

Klewsaat and Gates (1994) suggest that deposition of the Raritan and Magothy Formations in central New Jersey was controlled, in part, by the presence of faulted blocks of diabase sill, which were part of the Rocky Hill-Palisades diabase intrusion (Fig. 5). The faulted and fragmented blocks acted as a barrier to marine transgressions, but were periodically breached. According to their model, the Rocky Hill-Palisades sill was faulted and fragmented prior to the Late Cretaceous sedimentation (Stage 1, Fig. 5a). Deposition of the Raritan Fire Clay provides the first record of breaching of the Sill. The Farmington Sand Member was deposited around diabase islands during Stage 2 (Fig. 5b). Deposition of the Woodbridge Clay occurred over the top of the diabase islands consistent with a relative rise in sea level. Deposition of the South Amboy Fire Clay and Sayreville Sand occurred during a regressive phase, which partially breached the Sill. The Old Bridge Sand Member was deposited only to the South of the Sill during the next phase of marine transgression (Stage 4; Klewsaat and Gates, 1994).

Cheesequake Formation

Age: Santonian to ?earliest Campanian
Sequence: ?? Between KS 1 and KC 1 (Cretaceous Santonian 1 and Cretaceous Campanian 1 of Olsson, 1987)

The Cheesequake Formation is a newly recognized formation (Litwin et al, 1993) which unconformably overlies the Magothy Formation (Sugarman, 1996). Sugarman (1966) describes the Cheesequake formation as an olive to dark-greenish-gray clay-silt, weathering to moderate brown. It is massive to burrowed with lighter colored very fine to fine sand burrow fillings. It contains mica (clear, some green and brown) and lignite. It grades upwards to olive-gray and dark yellowish-brown silty, very fine to fine quartz sand at the top. It is generally laminated where not extensively burrowed. The unit is very carbonaceous and micaceous , with up to 20% glauconite at the base. Gastropod molds and layers of large (10-30 cm) concretions occur in the base of the formation (Sugarman et al., 1996). Maximum thickness is about, 12-13 m in outcrop. The Cheesequake formation is interpreted to be an inner shelf or possibly, a tidal flat marine

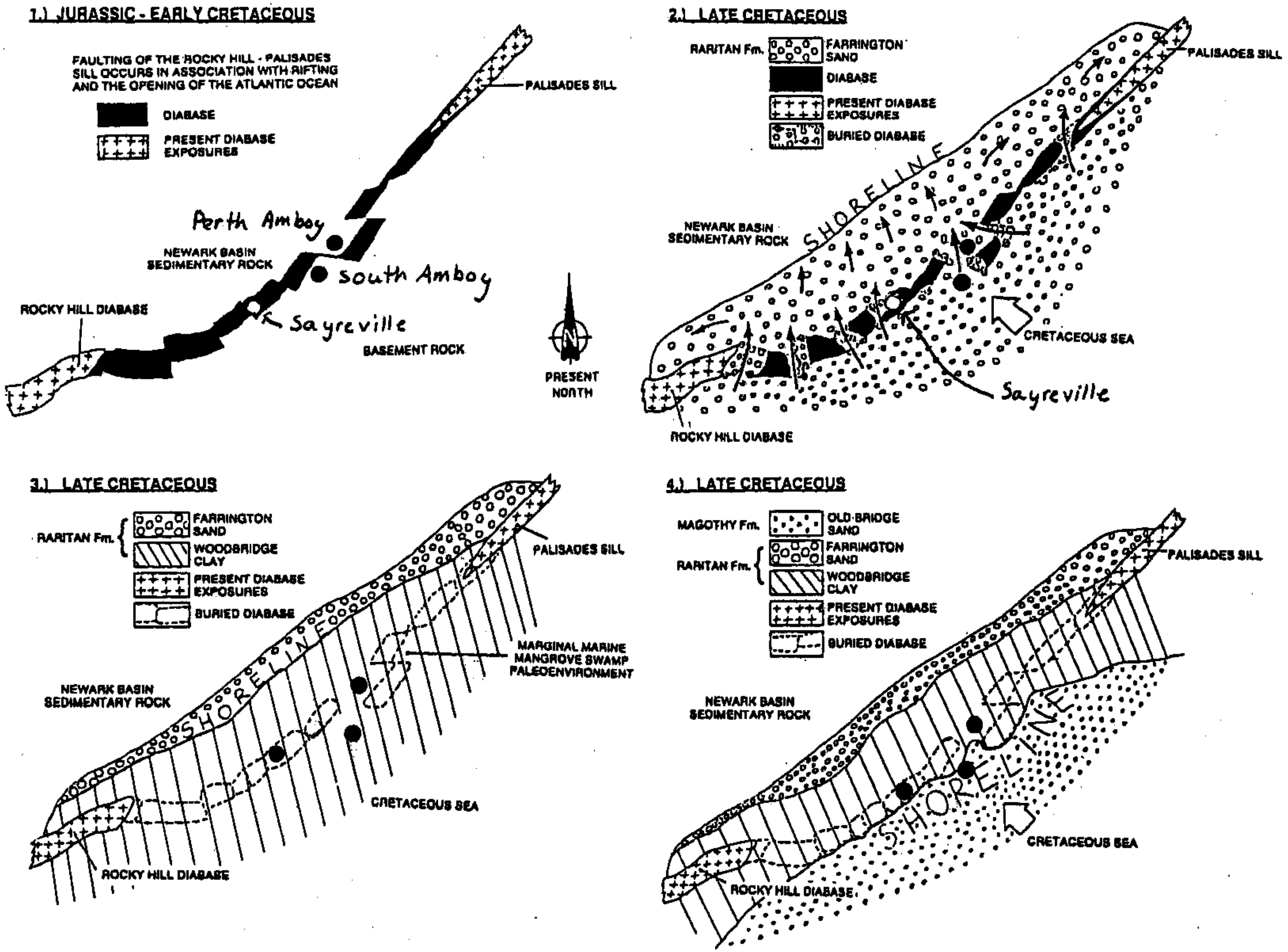

Figure 5. Four stage Palisades sill breaching model. Stage 1.) faulting and fragmenting of the sill prior to the Late Cretaceous; Stage 2.) breaching of the sill by the advancing Cretaceous Atlantic Ocean during deposition of the lower Raritan Formation; Stage 3.) the sill is later buried by the Woodbridge Clay; Stage 4.) with high relict topography, the sill became a barrier to the next transgression and deposition of the Magothy Formation. (from Klewsaat and Gates, 1994)

deposit. The Cheesequake Formation contains uppermost Santonian to lowermost Campanian pollen assemblage (Litwan et al., 1993). It has been previously placed in the upper Magothy (e.g., Owens et al., 1977) and the lower Merchantville (e.g., Weller, 1907). Peters (1976) did not recognize this unit in the subsurface and the Santonian to early Campanian foraminiferal assemblages he ascribed to the Merchantville Formation were probably in the Cheesequake Formation.

Merchantville Formation

Age: early Campanian
Sequence: KC 1 (Cretaceous Campanian 1; Olsson, 1987)

The Merchantville Formation is the oldest of the coastal plain sediments to contain glauconite (Owens and Sohl, 1969; Owens et al, 1970; Owens et al., 1977) and represents the basal transgressive unit of the next major stratigraphic sequence, which includes the Woodbury Clay and the Englishtown Formation (Fig. 3; Olsson, 1987; Olsson et al., 1988). In the outcrop area in central New Jersey, the Merchantville is about 15 m thick. It is mainly a sequence of thin (< 15 cm) very fine to fine-grained micaceous and carbonaceous sandy and silty beds containing discontinuous layers of siderite concretions, interstratified with less common, massive to heavily burrowed (1-2 m) beds of glauconite sand (Owens and Sohl, 1969; Owens et al., 1970; Owens et al., 1977). The basal 1-foot bed of the Merchantville Formation contains reworked gravel and rounded woody fragments (Owens et al., 1970), suggesting an unconformable contact with the underlying Cheesequake Formation (Sugarman et al., 1996). The presence of the ammonite *Scaphites hippocrepus* and a diverse marine mollusk assemblage (Owens et al., 1970) and marine foraminifera assemblage found in outcrop imply deposition of the Merchantville Formation during early Campanian time (Peters, 1976). The Merchantville was deposited in a middle to outer shelf environment (Olsson, 1987).

Woodbury Clay

Age: early Campanian
Sequence: KC 1 (Cretaceous Campanian 1; Olsson, 1987)

The Woodbury Formation was deposited during the regressive phase of the KC 1 stratigraphic sequence (Olsson, 1987; Olsson et al., 1988). It is a dark-gray to olive black clayey silt containing micaceous and chloritic silty clay, with very fine quartz sand, and occasional, carbonaceous material (lignite), finely disseminated pyrite, and fossiliferous siderite concretions (Owens and Sohl, 1969; Owens et al., 1970; Sugarman, 1996). The bedding is massive to finely laminated with interbedded layers of fine sand and clayey silt and commonly burrowed. Glauconite makes up from 5-10% of the lower part of the formation (Sugarman, 1996). The Formation averages ~ 15 m thick in outcrop (Owens and Sohl, 1969, Owens et al., 1970) but thins to < 6 m in the vicinity of Sayreville. The Woodbury Formation grades into and is replaced by the deeper shelf sediments of the Merchantville Formation in the subsurface (Petters, 1976, Olsson et al., 1988). It also grades into the overlying quartz sand-rich Englishtown Formation, which represents the last stage of the regressive pulse (Olsson et al., 1988). The Woodbury Formation is early Campanian in age based on presence of a diverse marine molluscan fauna assemblage (Stephenson et al., 1942; Owens and Sohl, 1969; Owens et al., 1970), and ostracode (Gohn, 1992) and foraminifera assemblages (Peters, 1976). Wolfe (1976) assigned the

Woodbury formation to Palynozone CA-1 (early Campanian). The Woodbury Formation is interpreted to be a prodelta and inner shelf-deposit (Sugarman, 1996) representing shoaling conditions (Olsson et al., 1988).

Relationship of Raritan and Magothy Members to Aquifer Terminology

The sediments of the Potomac Group and the Raritan and Magothy Formations comprise the Potomac-Raritan-Magothy aquifer system (Pucci et al., 1994). This aquifer system is generally divided into the lower, middle and upper aquifers, which are separated from each other by confining units (e.g. Zapecza, 1989). In the Middlesex County area, the middle aquifer is equivalent to the Farrington aquifer and the upper aquifer is equivalent to the Old Bridge aquifer of Farlekas (1979, cited in Pucci et al., 1994). Insofar as stratigraphic units correspond to aquifer units, the middle aquifer corresponds primarily of the Farrington Sand member of the Raritan Formation, and the upper aquifer corresponds to the Old Bridge Sand member of the Magothy Formation, respectively. The lower aquifer is not present in the central New Jersey area.

The middle aquifer (Farrington Sand member) is confined by the Raritan fire clay or bedrock units from below and the combined Woodbridge Clay, Sayreville Sand and South Amboy Fire Clay members units from above. The upper aquifer (Old Bridge Sand) is confined from above by the Amboy Stoneware Clay member of the Magothy Formation and the Merchantville-Woodbury Formations (Pucci et al., 1994 and references therein). Locally, the Sayreville Sand member is included in the upper aquifer where the South Amboy Fire Clay member is thin or absent.

THE CLAY INDUSTRY IN THE RARITAN RIVER VALLEY, MIDDLESEX COUNTY

The clay deposits in the Raritan River valley have been utilized for a variety of purposes since before the revolution. Remains of an old kiln fire hole were found south of South Amboy, which probably dates to Dutch settlement in the late 1600's.

White Woodbridge Clay called fuller's earth was used for cleaning buckskin breeches by soldiers quartered at Perth Amboy before and during the revolutionary war (Cook and Smock, 1878). Clay from the South Amboy area was used in making stoneware as early as 1800. Export of clay and clay products to other cities along the eastern seaboard from the Raritan Valley began in the early 1800s. Unprocessed clay was used in a variety of products including satinizing wall paper and paper coatings. New Jersey clay for fire brick and other refractory materials was exported to Boston in 1816 (Cook and Smock, 1878).

Common brick was first made in Middlesex county in 1851, at Roundabout, now Sayreville, by Mr. James Wood (Ries et al., 1904). In the fall of that year, Peter Fisher (a sailing ship owner) and James Sayre (a lime, cement, and building supplier) (e.g. Musser, 1988) purchased a small property of 23 acres and began the manufacture of common bricks and branched out to other grades of clay (Ries et al., 1904). The Sayre and Fisher Co. became the largest brick-making firm in New Jersey (Ries et al., 1904). The first fire-brick factory in the Raritan Valley was built in 1856 by Henry Mauer and Son. Other factories were built by M. D. Valentine & Bro. in 1865. Sayre and Fisher first manufactured fire brick in 1868.

The annual geological report of 1874 estimated that 265,000 tons of fire clay were dug annually in Woodbridge, Perth Amboy and South Amboy areas. It was marketed for making fire bricks, fine pottery, sewer pipe, terra cotta ware, retorts and crucibles, facing for wall paper, alum etc. Prices ranged from \$1.50 to \$13.00 (average \$3.50) per ton (Cook and Smock, 1979)

By 1912, Sayre and Fisher Co. owned over 2000 acres of clay producing land in the Sayreville area, had 15 brickyards and their brickworks in Sayreville extended for nearly two miles along the Raritan River (Musser, 1988). In 1917, many small firebrick companies in the mid-Atlantic States merged into the Harbison-Walker Refractories Company. Most of the Raritan Valley clay producers did not merge with this company and were unable to compete. The Sayre and Fisher Co. was able to survive to the mid 1950's, but eventually, also failed.

Clay Properties

The suitability of mined clay for various industrial applications depends on a number of physical properties of the clay. The firing of clay is a complex processes, of which any potter or ceramist is well aware, and brick-making in the early 20th century was often more "art" than science. A detailed discussion of clay properties and firing processes is beyond the scope of this paper. The following is a brief summary of major physical properties important to the finished clay products (Ries et al., 1904).

Color: Unfired clay colors are dependent on the amount of organic matter and Fe-oxides or hydroxides. Organic-rich clays are dark gray or black, only 3 % organic matter will make a black clay. Fe oxides will color the clay red (hematite), yellow (limonite) or brown (both) depending on the oxide present. The color of raw clay is not always an indicator of the color after firing. Because most clays were fired in oxidizing environments, any reduced iron typically oxidized to hematite or limonite phases, as dark organic matter was burned away. A raw red clay generally fires red, a deeply yellow raw clay fire buff, chocolate brown clays commonly burn red to reddish brown, white clays burn white or yellowish white, and gray or black ones may burn red, buff or white depending on the content of iron (Ries et al., 1904).

Plasticity: Plasticity is the ability of a clay to be molded into a desired shape when wet, and to remain in that shape when dry. Highly plastic clays, are "fat" clays; "lean" clays have low plasticity. Generally, very sandy clays have low plasticity, however, clays with high concentrations of kaolinite can also have low plasticity, so the property is not directly a function of clay concentration (e.g., Ries et al., 1904). Plasticity increases if clay grains are oriented so that parallel plates slide past each other. Plasticity also apparently increases with presence of colloidal size material.

Tensile Strength: The tensile strength of clay is the resistance to breakage when air dried. High tensile strength in unburned clay products is necessary to minimize breakage during the shrinkage which occurs during drying and the handling of materials before firing. Clays with low tensile strength have either a high proportion of clay (kaolinite) or sand. Clays with the highest tensile strength have more equal proportions of fine, medium, and course grains, which increases the ability of grains to form a dense, interlocking network (Ries et al., 1904). Tensile strength is measured by pulling the ends of a small briquette until it fractures and is expressed in pounds per in^{-2}.

Shrinkage: Shrinkage of clay occurs during both air-drying and firing. Air shrinkage occurs when moisture surrounding individual particles evaporates and the particles move closer to each other. Naturally, material with a high proportion of fine-grained particles has a higher surface area and thus, can absorb more water. Shrinkage is highest in clay-rich, very plastic, fat clays and lowest in lean clays. Sand is commonly added to clay-rich mixtures to reduce shrinkage. Most clays manufactured in New Jersey shrink approximately 5-6% (measured as reduction in length relative to freshly molded brick) during air drying (Ries et al., 1904).

Clays also shrink during the burning or firing operations. The amount of shrinkage depends on the amount of combined water (in clay minerals), organic matter and carbon dioxide (in calcium carbonate) present in the clay.

Fusibility: Fusibility of clay is the point at which fusion takes place and the brick become "steel hard" (Ries et al., 1904). In more modern terms, it is the point at which partial melting begins and the complex series of reactions including melting, recrystallization and reactions takes place. There are three burning stages of clays (Ries et al., 1904): incipient fusion, (initial partial melting), vitrification (matrix is partially melted, more refractory grains still visible and settled together) and viscosity (clay mass begins to flow). The temperature at which fusion, vitrification ,and viscosity takes place depends on the composition and proportions of constituent materials. The amount of temperature difference between incipient fusion and viscosity varies with composition, in carbonate-rich clays it may be, 30 °C apart, but in highly refractory clays, it may be over 400 °C apart. It is of considerable practical importance to have the fusion temperature and viscosity temperature widely separated so that irregularities in kiln temperature will not adversely affect certain portions of the bricks or other products being fired.

In the brick-making industry, the fusion and viscosity points are measured against a series of calibrated materials called Seger cones. (Similar cones are used today by ceramic artists when firing pottery.) The cones contain various proportions of Al_2O_3, SiO_2, Fe_2O_3 Na_2O, K_2O and CaO. A complete table of Seger cone compositions and fusion temperatures is given in Ries et al. (1904). The higher the proportion of Al_2O_3 and SiO_2, the higher the fusion temperature and the more refractory is the clay. Thus, pure kaolinite ($Al_2Si_2O_5(OH)_4$) is a highly refractory clay. The presence of alkaline oxides (as feldspars), Fe-oxides, and carbonates, reduces the fusion temperature by acting as a flux. For a given Seger cone mixture, the point at which fusion takes place is marked by the bending of the Seger Cone and is a function of the temperature and other pyrochemical effects such as kiln atmosphere. A series of Seger cones are placed in the kiln along with the clay products being fired as indicators of temperature and physical conditions in the kiln. Table 1 lists the range in Seger cones used to bracket the fusion temperature for the various brick products manufactured in New Jersey. Ries (1904) classified clays according to their fusion point:

1. Highly refractory clays: fusion point above cone 33 (1,790 °C).
2. Refractory clays: fusion point ranges from cone 31-33(1,750-1,790 °C). Some of the New Jersey clays fall within this category.
3. Semi-refractory clays: fusion point ranges from cone 27-30 (1,670-1,750 °C).
4. Low refractory clays: fusion point ranges from cone 20-26 (1,530 –1,650 °C).
5. Non refractory clays: fusion point less than cone 20 (< 1,530 °C). Most clays mined in New Jersey.

Clay Mining Terms and Manufactured Products

Clays beds were commonly classified on the basis of they uses. The following terms were used commonly in the clay-working industry of New Jersey (Ries et al., 1904):

Kaolins: White burning clay used in the manufacture of white earthenware, porcelain, white wall tile and paper coatings.

Table 1. Seger Cone Range and Fusion Temperature for New Jersey Clay Products (Ries et al., 1904).

Product	Seger Cone Range	Fusion Temperature (°F)	Fusion Temperature (°C)
Common (Building) Brick	08-01	1,814-2,066	990-1,130
Red Earthenware	08-05	1,814-1,922	990-1,050
Hollow Blocks and Fire Proofing	03-1	1,994-2,102	1,090-1,150
Hard-burned Common Brick	1-2	2,102-2,138	1,150-1,170
Terra Cotta	5-7	2,246-2,318	1,230-1,270
Buff Front Brick	6-8	2,282-2,354	1,250-1,290
Stoneware	6-8	2,282-2,354	1,250-1,290
White Earthenware	8-9	2,354-2,390	1,290-1,310
Fire Brick	9-12	2,390-2,498	1,310-1,370
Porcelain	11-13	2,462-2,534,	1,350-1,390

Ball clays: White-burning plastic sedimentary clays used chiefly in the manufacture of fine grades of pottery.

Fire Clay: A term loosely applied to clays considered suitable for making fire bricks, generally buff burning. No standard for degree of refractoriness was used in this country. Clays fusing above cone 27 (1,670 °C) are considered fire clays by Ries et al. (1904).

Stoneware Clay: Semirefractory clays which burn to a dense body and possess good plasticity and tensile strength.

Pipe Clay: Nonrefractory plastic clays which are vitrifiable. Used for the manufacture of sewer pipe.

Terra-Cotta Clay: Not a very useful term, applied indiscriminately to different beds of clays used for the manufacture of terra cotta. Most terra-cotta clays are semirefractory, and buff burning.

Brick Clay: Includes all impure nonrefractory clays suitable for the manufacture of common brick, usually red burning.

Table 2 lists some of the common (some arcane) uses and manufactured items made from clays deposits mined in New Jersey.

Important Clay Lithologies Mined in Middlesex County.

The major clay banks operating in Middlesex county as of 1904, are listed in Table 3. The location of the individual pits are given in Ries et al. (1904). In 1904, over 100 clay pits ranging in size from just a few acres to several hundred acres were in operation in the area. The important clay beds mined are described below and representative analyses are given in Table 4.

Raritan Formation:

Raritan Fire Clay: The lower portion of the Raritan Fire Clay consists of a white or white-blue clay up to 6 m thick referred to as the Terra-Cotta or Potter's Clay (Cook and Smock, 1878, Ries et al., 1904). It was mined primarily just north of the Raritan River (e.g., W. N. Weidner # 97, Fig. 3). (The pit location numbers used are those of Ries et al., 1904). This unit had relatively low plasticity compared to other clays mined in the district (Cook and Smock; 1878). The composition of the Terra-Cotta Clay is relatively Al_2O_3-rich similar to other fire clays mined in the area, but the relatively high K_2O-content (Table 4) causes fusion at lower temperatures than other fire clays mined in the area (e.g., Ries et al., 1904).

The upper portion of the Raritan Fire Clay is a drab or light blue, red mottled, sometimes black fire clay up to 5 m thick. It was mined primarily in the Woodbridge area (e.g., M. D. Valentine & Bros., formally Dickson's bank #9, Fig. 3). The composition of this so-called fire clay is relatively quartz-sand rich relative to other better grades of fire clay described below (Table 4).

Woodbridge Clay: The Woodbridge Clay member of the Raritan Formation was the most extensively mined clay deposits in the Middlesex County area (Table 3). It was the thickest unit of all clay members mined. Four districts were opened, a) south and east of Woodbridge, b) north of the Raritan River (Sand Hills), c) south of the Raritan River from South Amboy to Sayreville, and d) adjacent to the South River (Fig. 3).

Two of the large producers in the Woodbridge area were M. D. Valentine & Bros. (# 14) and W. H. Cutter (#29). Two horizons were actually mined in the member. The dark–gray

Table 2. Common Uses of Clay and Manufactured Items Made From Clay. (Ries et al., 1904)

Domestic.—Porcelain, white earthenware, stoneware, yellow ware and Rockingham ware for table service and for cooking; majolica stoves; polishing brick, bath brick, fire kindlers.

Structural.—Brick: common, front, pressed, ornamental, hollow, glazed, adobe; terra cotta; roofing tile; glazed and encaustic tile; draintile; paving brick; chimney flues; chimney pots; doorknobs; fireproofing; terra-cotta lumber; copings; fence posts.

Hygenic.—Urinals, closet bowls, sinks, washtubs, bathtubs, pitchers, sewer pipe, ventilating flues, foundation blocks, vitrified bricks.

Decorative.—Ornamental pottery, terra cotta, majolica, garden furniture, tombstones.

Minor uses.—Food adulterant; paint fillers; paper filling; electric insulators; pumps; fulling cloth; scouring soap; packing for horses' feet; chemical apparatus; condensing worms; ink bottles; ultramarine manufacture; emery wheels; playing marbles; battery cups; pins, stilts and spurs for potters' use; shuttle eyes and thread guides; smoking pipes; umbrella stands; pedestals; filter tubes; caster wheels; pump wheels; electrical porcelain; foot rules; plaster; alum.

Refractory wares.—Crucibles and other assaying apparatus; gas retorts; fire bricks; glass pots; blocks for tank furnaces; saggers; stove and furnace bricks; blocks for fire boxes; tuyeres; cupola bricks; mold linings for steel castings.

Table 3. Clay Producers Middlesex County in 1904 (Ries et al., 1904)

Formation/Member and Owner	**Pit No. (Ries et al., 1904**
Raritan/Raritan Terra-Cotta (Potter's) Clay	
Brinkman Terra Cotta Company	96
C. Pardee	237
J. Conger farm (formerly W. N. Weidner)	97
N. Lorensen	238
Raritan/Raritan Fire Clay	
C.A. Bloomfield	92
J. Pfeiffer	90
C. A. Edgar	89
M. D. Valentine and Bros. Co.	9
Raritan/Woodbridge Clay member, Fire Clay or "Best Clay"	
Woodbridge Area	
P. J. Ryan	1, 2, 8, 21
W. Berry	11, 13
M. D. Valentine & Bros. Co.	14, 15, 23
J. H. Leisen	16
Staten Island Clay Co.	17, 18, 19
A. Martin	20
Anness & Potter	6
H. Mauer & Son	24
W. H. Cutter	29, 30
J. P. Prall	31
Sand Hill Area	
International Clay Co.	48, 49
Goodrich's Bank	51
Ostrander's bank	53, 54
R. N. & H Valentine	55, 86
D. A. Brown	87
J. Pfeiffer	90
C. Edger	94, 98
Raritan Ridge Clay Co. (formerly A. Campbell)	99
South River Area	
N. A. Pyrogranite Co.	245
National Clay Manufacturing Co.	244
M. A. Edgar	232, 252
Sayre & Fisher Co.	233, 237, 259
American Enamel Brick and Tile Co.	256
Raritan/Woodbridge Clay member, Black Laminated Clay	
Woodbridge Area	
M. D. Valentine & Bros.	14
J. H. Leisen	16
Annes & Potter	6
Perth Amboy Terra Cotta Co.	7
P. J. Ryan	8
W. H. Cutter	29, 30
J. P. Prall	28, 31
Staten Island Clay Co.	33, 43
H. Maurer & Son.	36, 34

Table 3 Continued

Formation/Member and Owner	**Pit No. (Ries et al., 1904**
Raritan/Woodbridge Clay member, Black Laminated Clay (cont.)	
Sand Hills Area	
Perth Amboy Terra Cotta Co.	241
Standard Fireproofing Co.	46, 47
International Clay Co.	48, 49
H. Weber	52
Mrs. J. Goodrich	51
Ostrander Fire Brick Co.	53
R. N. & H. Valentine	55, 86
D. A. Brown	87
C. Edger	94
Sayreville Area	
Sayre & Fisher Co.	71
W. F. Fisher	74
D. Furman	72
Boehm & Kohlhepps	73
South River Area	
J. Bissett	85
Yates Bros.	82
T. Willets	83
J. Whitehead	84
Pettit & Co.	247, 249
National Clay Manufacturing Co.	244
N. A. Pyrogranite Co.	246
M. A. Edgar	252
Sayre & Fisher Co.	253, 254
Magothy Formation/South Amboy Fire Clay member	
North of Raritan River	
McHose Bros.	45
H. Maurer & Son	42
Sayreville Area	
J. R. Crossman	63, 65, 66
J. R. Such	67
Sayre & Fisher	71/273, 274, 267
C. Edgar	268
Old Kearny Tract	60, 61, 62
Magothy Formation/Amboy Stoneware Clay member	
H. C. Perrine & Son	77, 78, 81
Ernst Bank	80
Whitehead	76
Magothy Formation/Cliffwood beds	
Geldhaus's bank	223
Cliffwood Brick Co.	220
Gaston's pit	221
Furman's Bank	222

Table 4. Composition of Various Clays Mined in Middlesex County (Ries et al., 1904).

Formation/Member	Clay Type	Sand[1]	SiO_2,	Al_2O_3	Fe_2O_3	TiO_2	MgO	CaO	K_2O	Na_2O	Loss on Ignition
Raritan/Potter's Clay[2]	Potter's or Terra Cotta	0.71	45.61	39.04	1.13	--	--	--	2.26	0.25	10.90
Raritan/ Raritan Fire Clay[3]	Fire Clay	28.81	31.12	26.99	1.24	1.90	0.07	--	tr.	tr.	9.63
Raritan/ Woodbridge Clay[4]	Common Brick		60.18	23.32	3.27	--	0.67	1.00	2.58	0.80	8.54
Raritan/ Woodbridge Clay[5]	Fire Clay	1.10	44.26	37.94	0.96	1.30	0.11	tr	0.15	0.00	14.10
Magothy/South Amboy Fire Clay[6]	Fire Clay	3.10	41.10	38.66	0.74	1.20	--	--	0.28	0.18	13.55
Magothy/South Amboy Fire Clay[7]	Fire Clay		40.64	41.19	3.27	--	tr.	0.65	tr.	tr.	14.74
Magothy/Amboy Stoneware Clay[8]	Stoneware Clay	39.95	28.80	20.20	1.45	0.90	0.50	tr.	1.58	--	5.80

[1] The sand content is listed separately for clay mixtures where quartz sand is present. The total silica is the sum of the sand and SiO_2. Otherwise, the total silica is listed under SiO_2.

[2] Weidner # 97

[3] Dickson Bed in M. D. Valentine & Bros. # 9

[4] Sayre & Fisher #71

[5] H. Cutter & Sons #29

[6] Sayre & Fisher #273

[7] J. R. Crossman #66

[8] Ernst's Pit #80

laminated pyritic clay comprising most of the member was utilized primarily for common brick, fire-proofing brick, and terra cotta lumber (Ries et al., 1904). The composition of the black laminated and pyritic clay used for common-brick is relatively non-refractory and is SiO_2-, Fe_2O_3- and K_2O-rich (Table 4). Near the base of the Woodbridge Clay member, however, a persistent fire clay of light blue to gray with red mottling was also mined in many of the pits in the Woodbridge area. The thickness of this bed varied from 2-12 m as did the quality of the clay (Ries et al., 1904). The composition of the fire clay beds of the Woodbridge Clay member are more refractory than the material mined for common brick and contain more Al_2O_3 and less SiO_2 (Table 4). Most of the pits in the Woodbridge area, unfortunately, underlie the Woodbridge Mall, Garden State Parkway and other developments.

To the south of the Raritan River, the fire clay horizon occurs below sea level and only the upper gray-black laminated horizons of the Woodbridge were mined for common brick (Ries et al., 1904). The largest pit was owned by the Sayre and Fisher Co. (#71) and the town of Sayreville owes its name to this clay industry and the large brick manufacturing facility along the Raritan River Bank. The Sayre and Fisher pit currently offers some of the best exposures of the Woodbridge Clay member and the overlying unconformable contact with the South Amboy Fire Clay/Sayreville Sand members. This unconformity marks the mid Turonian sea level fall (Haq et al., 1987). Over 5 m of relief can be observed along the contact between the Woodbridge Clay and overlying units. Although it is possible to go into the pit from Main street, the pit is privately owned by K-land Corporation #5. We could not obtain permission for GANJ to enter.

Magothy Formation:

South Amboy Fire Clay: The South Amboy Fire Clay was mined extensively along the southern bank of the Raritan River between Sayreville and South Amboy (Fig. 3). The best clay material sought consisted of sandy buff colored clays, blue fire clay, and a sandy red mottled clay (from top to bottom) (Ries et al., 1904). Vertical and lateral variation in the extent of these clay beds was common ranging from 0-8 m (e.g., Ries et al., 1904). Some of these clay beds were mined at Sayre and Fisher pit (#273) and J. R. Crossman (#65 and 66) in Sayreville. The composition of the fire clay are relatively Al_2O_3-rich (Table 4).

A black lignitic clay containing numerous pyrite clasts overlies the fire clay proper in the banks of J. R. Crossman (#65 and 66) and J. R. Such (#67) in Sayreville. These are the beds that now yield amber. They were mined primarily for common brick similar to the Woodbridge Clay described above. White to light gray ball clay, used for pottery, was also mined at Such's pit.

J. R. Such's pits are now transformed to the supermarket shopping center at the corner of Ernston and Washington Road in Sayreville. Part of Crossman's Pit abuts Kennedy Park along the southern boundary and Main street along the northern boundary (Fig. 3). Although accessible from the Park, these pits are privately owned. Some of the red mottled clay is visible on the Kennedy Park side, and black lignitic clay is exposed near the present floor on the Main street side of the pit.

Amboy Stoneware clay. The semi-refractory white to blue-gray clay layers, below the gray laminated clay were sought for use in the manufacture of stoneware and other higher grades of material along the extent of outcrop to the south and west of South Amboy. The major clay pits were located along Raritan Bay and Cheesequake Creek (e.g., Perrine's Bank, formally Ernst's bank #80). The composition of the Stoneware Clay is relatively SiO2-rich and Al_2O_3-poor relative to the fire clays mined in the district.

The Amboy Stoneware Clay is no longer exposed in the Ernst's Bank location or along Raritan Bay. However, possible clay clasts of this member occur within sandy layers at the base of the Morgan Beds exposed in a gullies near intersection of Ernston Road and the Garden State Parkway (ER) (Gondek Dr.) near Cheesequake Creek (Olsson, 1987; Sugarman, 1996). These clay clasts may be rip up clasts of the underlying Stoneware Clay.

CLAY MINERALOGY OF THE RARITAN AND MAGOTHY FORMATION CLAYS

X-ray diffraction patterns of the clay separate fraction of several samples from the Raritan Formation Woodbridge Clay member and the Magothy Formation South Amboy Fire Clay member, Stoneware Clay? member, and Morgan Beds are shown in Figure 6. Sample locations are given in Figure 3. The <2-µm clay fraction was obtained by centrifugation and filtration and transferred to glass slides using the filter paper transfer method. X-ray diffraction patterns were obtained on air-dried, and ethylene glycol solvated (not shown) samples. The XRD analyses were carried out using a GE model XRD-5 diffractometer operated at 40 kV and 20 mA, using Ni-filtered Cu$K\alpha$ radiation, a scintillation detector 1° entrance slit and 0.2° receiving slit. Digitally recorded patterns (step size of 0.01 °2θ and count rate of 1 s/step) were obtained and peak positions determined manually.

Interestingly, the clay fractions in the laminated gray pyritic lithologies of the Woodbridge Clay (Sayre and Fisher pit #71) and the South Amboy Fire Clay (Crossman's pit, #66) used for common bricks, contain a similar assemblage, kaolinite, illite and/or mica, and chlorite and/or possible vermiculite and a possible trace of swelling smectite or mixed-layer illite/smectite. Illite cannot be distinguished from mica (muscovite) on the basis of X-ray diffraction methods alone as their 10-Å (~8.65° 2θ) diffraction peaks overlap. Likewise, the 14-Å (~6.1° 2θ) chlorite cannot be distinguished from vermiculite in air-dried patterns. More detailed work is underway to characterize the 14-Å and swelling material. The Woodbridge Clay member contains a higher proportion of kaolinite than the South Amboy Fire Clay (Fig. 6).

Several almost pure kaolinite beds were sampled in the South Amboy Fire Clay at Crossman's pit (#66) and the Sayre and Fisher pit (#273). The kaolinitic clay pattern shown in Figure 6 is from a light gray and red mottled clay in the Sayre and Fisher pit above the major unconformity with the underlying Woodbridge Clay. Similar, "pure" kaolinite diffraction patterns were obtained from cream-colored clay beds in the same pit and from red clay beds sampled in Crossman's pit. These dominantly kaolinite clays are probably representative of the fire clays originally mined from these pits.

A light-gray to cream colored clay layer at the base of the Old Bridge Sand member of the Magothy Formation collected at the pit located on the Bordontown-Amboy Turnpike (BR) contains kaolinite, illite/mica, chlorite/vermiculite and also a relatively high proportion of mixed-layer swelling clay (Fig. 6).

A light tan to cream colored, red-mottled clay clast, which may be a rip-up clast of the underlying Amboy Stoneware included within sandy layers of the Morgan Beds (ER), contains kaolinite, illite/mica and swelling smectite (Fig. 6). The dark-gray pyritic clay layers of the Morgan Beds at the same location contain a kaolinite, illite/mica and chlorite/vermiculite and swelling smectite

The proportions of clay minerals in the clay beds of the Raritan and Magothy Formations reflect provenance of the source area, weathering regimes, transport mechanisms and depositional environments. Kaolinite is generally formed in deeply weathered environments

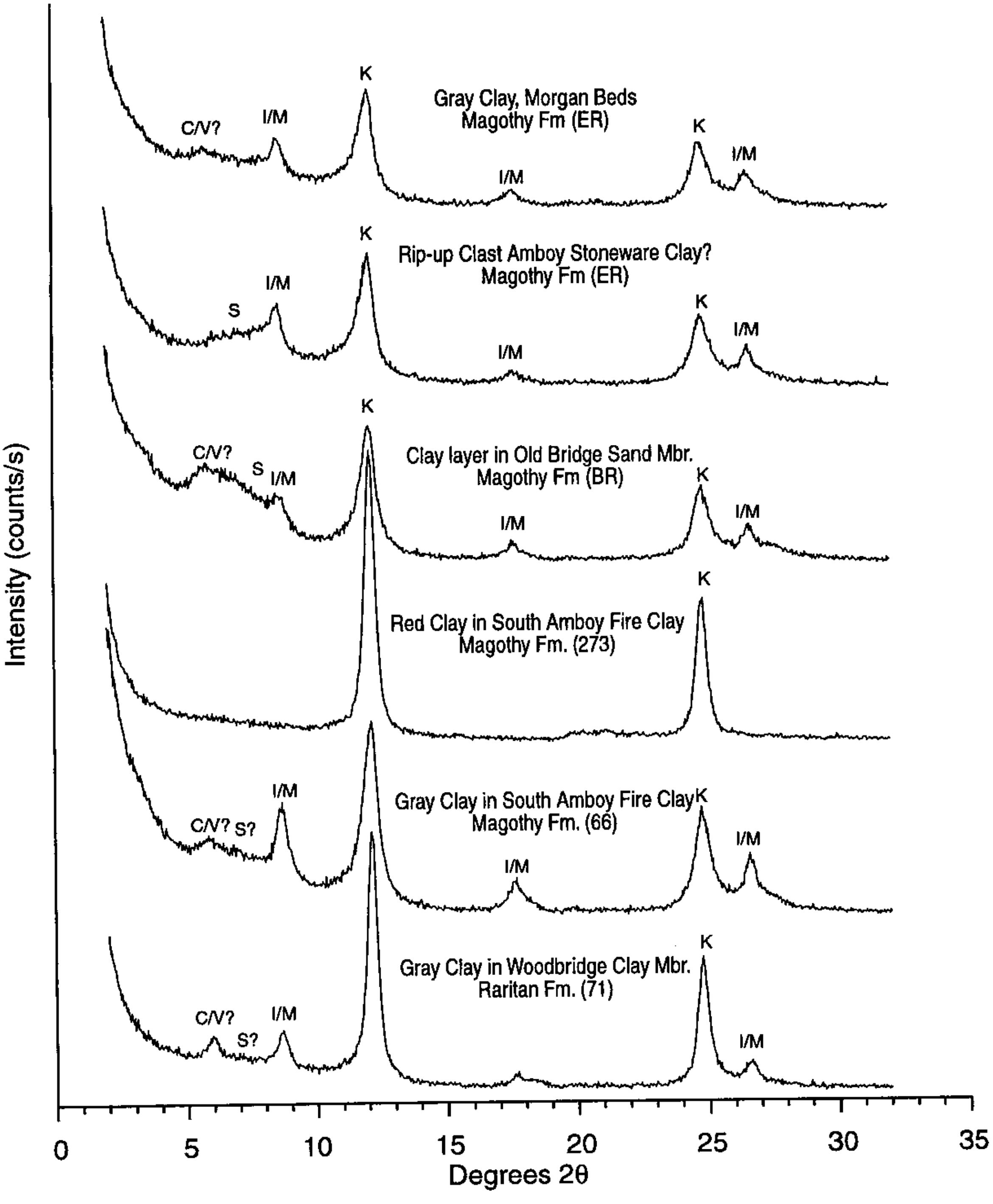

Figure 6. X-ray diffraction patterns of air dried, clay size (<2 μm) separates. Samples are from various clay-bearing units from both the Magothy and the Raritan Formations. Identified peaks are as follows: C/V?-chlorite/possible vermiculite, S-smectite, S?-possible smectite, I/M-illite/mica, K-kaolinite. Sample localities in parentheses are located in Figure 3.

where significant rainfall and generally acidic water conditions have altered granitic rocks containing feldspar and muscovite (e.g., Force and Moncure, 1978; Murry, 1988). The kaolinite-rich clays found in the Upper Cretaceous of New Jersey were likely redeposited kaolinite whose origin was in soils of the deeply weathered crystalline highlands to the north and west (e.g., Force and Moncure, 1978).

Groot and Glass (1959) noted that kaolinite and illite were the primary clay minerals present in non-marine dominated deposits of the Cretaceous coastal plain. They noted that the four clay minerals, illite, kaolinite, chlorite and smectite were present in marine facies. The X-ray diffraction patterns obtained in the present study are consistent with these previous observations. The gray-pyritic laminated beds in the Woodbridge Clay member, in the South Amboy Fire Clay, and the Morgan beds, which were deposited under near-shore marine or estuarine conditions, all contain the four clay minerals kaolinite, illite, chlorite, and smectite (Fig. 6). The fire clay beds in the South Amboy Fire Clay and the Amboy Stoneware Clay, interpreted to be non-marine and fluvial in origin are dominated by kaolinite and illite.

More work is needed to better understand how the relative proportion of clay minerals can be used to constrain paleo-weathering regimes, provenance and depositional environments.

ACKNOWLEDGEMENTS

Use of the X-ray diffraction instrument, under the direction of Dr. Andreas H. Vassiliou, was kindly provided by the Department of Geological Sciences/Rutgers Newark. We thank Pat Larkin and Johanna MacTaggart for preparation of clay separates for X-ray diffraction analyses.

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TITANIUM RICH SANDS OF THE LAKEHURST AREA, NEW JERSEY

John H. Puffer
Department of Geological Sciences
Rutgers University
Newark, NJ 07102

Lloyd Mullikin
N.J. Dept. of Environmental Protection
Geological Survey
29 Arctic Parkway
Trenton, NJ 08625

ABSTRACT

Sands enriched with titanium oxides (largely pseudorutile, rutile, and ilmenite) were mined at two sites in the vicinity of Lakehurst, New Jersey from 1962 to 1982. Mining activity at the Glidden Pigment Group of SCM Corp., Jackson Township site extracted ore averaging 6 to 7-percent titanium oxide from the Cohansey Sand. At the ASARCO, Inc. mine in Manchester Township, the ore averaged 1.5 to 4-percent titanium oxide, from the Cohansey Sand and the underlying Kirkwood Formation.

The titanium oxide enriched Cohansey Sand, particularly near the base of the formation is a well sorted, positively to slightly negatively skewed, laminated, and burrowed sand facies. Peat interbedded with the titanium-rich sand is typically less than a foot thick but can be upwards of 15-feet in total thickness. The peat contains a subtropical palynomorph suite and dinoflagellates interpreted by Puffer and Cousminer (1982) as evidence of lagoonal deposition that was flooded with marine water. The titanium rich sand was interpreted as a backshore beach and dune facies.

The Kirkwood Formation, mined at the ASARCO site, is gray, well sorted, uniform, fine to medium grained, and micaceous. It is predominantly a shallow-marine unit containing shelf and deltaic facies (Owens and others, 1988). Titanium rich sand found in the upper part of this formation, is concentrated primarily in east-west trending heavy mineral rich intervals, up to 30-feet thick, 200 to 600-feet across, up to several miles long, that can average 5 to 20-percent titanium oxide. This is interpreted as an east-west trending barrier beach type facies.

The subtropical climate during deposition of these Miocene formations favored deep saprolitic weathering of ilmenite bearing granitic source rock. The resulting

Figure 1. Geologic Map of the Lakehurst Area with sample locations and figure caption of Puffer and Cousminer (1982).

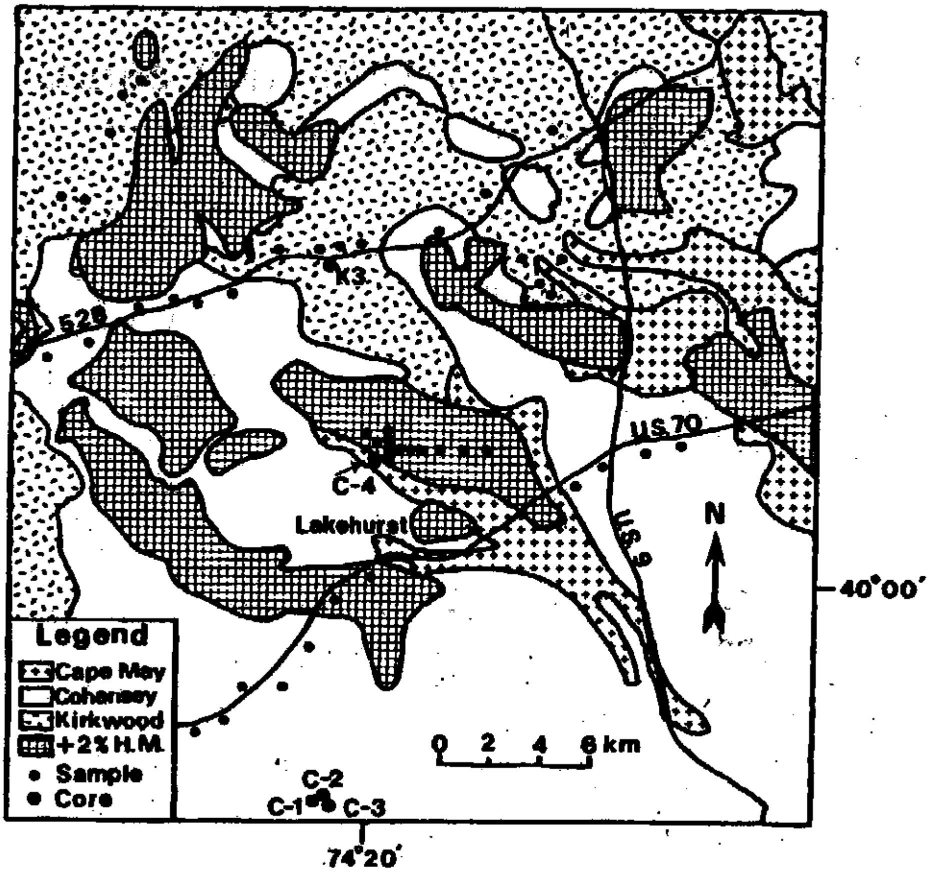


FIG. 1. Geologic map of the Lakehurst area, New Jersey, indicating exposures of sand containing heavy mineral concentrations greater than 2 weight percent (modified after Markewicz, 1969). Samples from sites C-1, C-2, and C-3 were collected as channel samples at 5-ft (1.52 m) intervals from drill cores. Samples collected at site C-4 are channel samples collected by hand along quarry walls through high-grade ore to a depth of 13.7 m. Samples at site C-4 from 13.7 to 16.8 m below the original surface were collected with a hand-driven piston sampler. Samples at site K-3 were collected with a hand-driven piston sampler at 1.5-m intervals to a depth of 6 m. All other samples were collected below any evidence of recent vegetation at a depth of ~1 m along road cuts, at the bottom of clean holes dug with a shovel in loose sand or with a posthole auger in coherent sand.

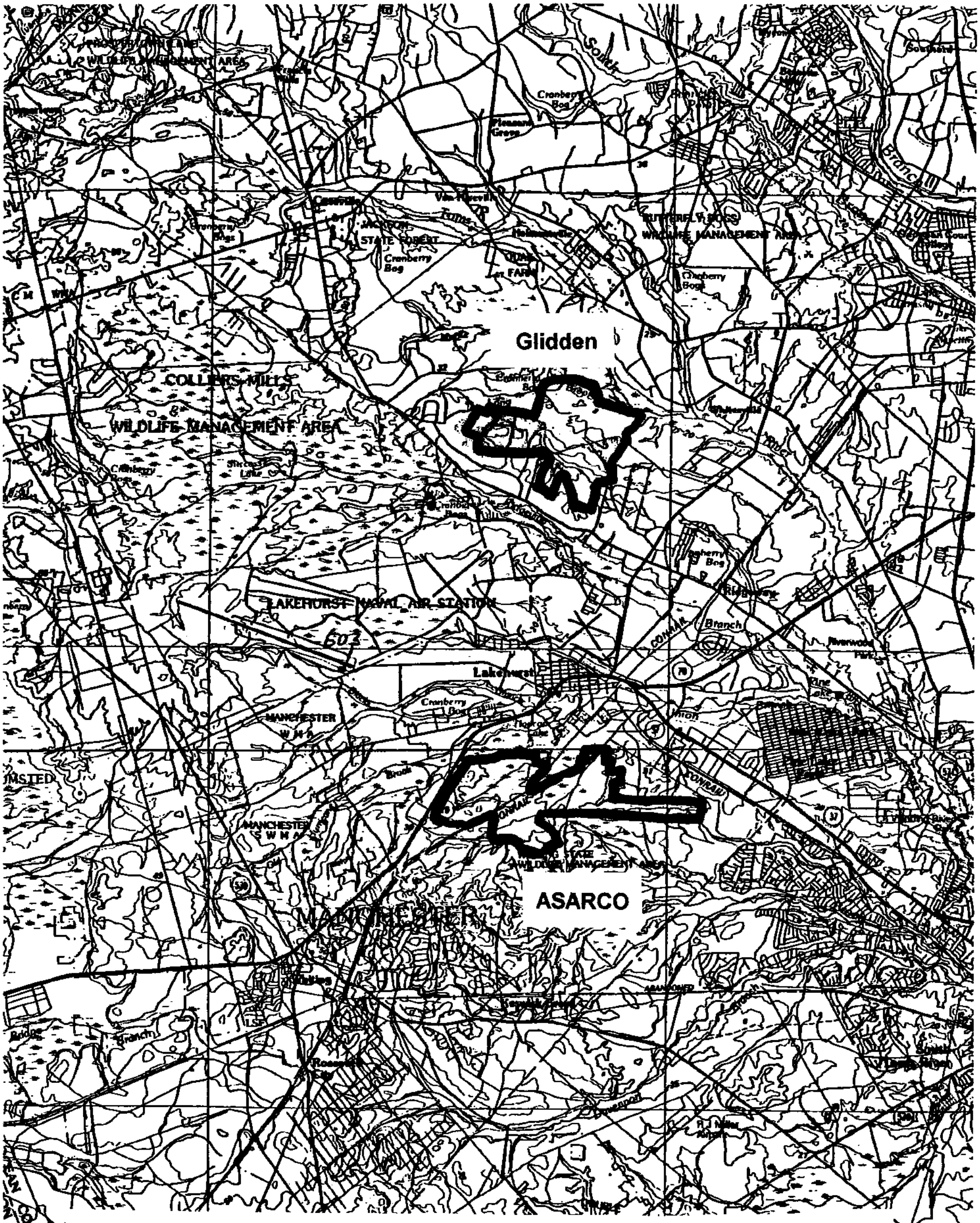


Figure 2. Topographic Map of the Lakehurst, New Jersey area with the location of the Glidden Pigment and ASARCO titanium oxide mines (use section lines for scale).

saprolites were titanium enriched and silica depleted. These climatic conditions are similar to those found at most of the earth's largest titanium mining districts including the Quaternary shoreline deposits of Stradbroke Island, Australia; Richards Bay, South Africa; and Trail Ridge, Florida.

MINE HISTORY

Deposits of unconsolidated Miocene sand, containing heavy minerals enriched in Ti-Fe oxides are found throughout the Lakehurst, Ocean County, New Jersey area, (Figure 1). Following their discovery by Markewicz and Parrillo (1957) two of these deposits were developed and later mined for their titanium content. This mining activity took place at the Glidden Pigment, Jackson Township site from 1962 until 1978, and at the ASARCO, Inc., Manchester Township site from 1973 until 1982 (Figure 2). Mining at both sites involved the use of cutterhead suction type dredges, capable of mining to a depth of 65-feet below the water table.

Later mining activities at these sites included the reprocessing of the heavy mineral tailings for zircon and monazite in addition to titanium oxides. This took place at Glidden Pigment from 1991 until 1994 through a lease agreement between Nord Ilmenite Corporation and the properties current owner Ralph Clayton and Sons, Inc. At ASARCO reprocessing took place from 1986 until 1987 after the property was sold to Heritage Minerals, Inc. Sand mining is currently taking place at the Glidden site, and the ASARCO site is in a standby mode with all necessary mining permits still active.

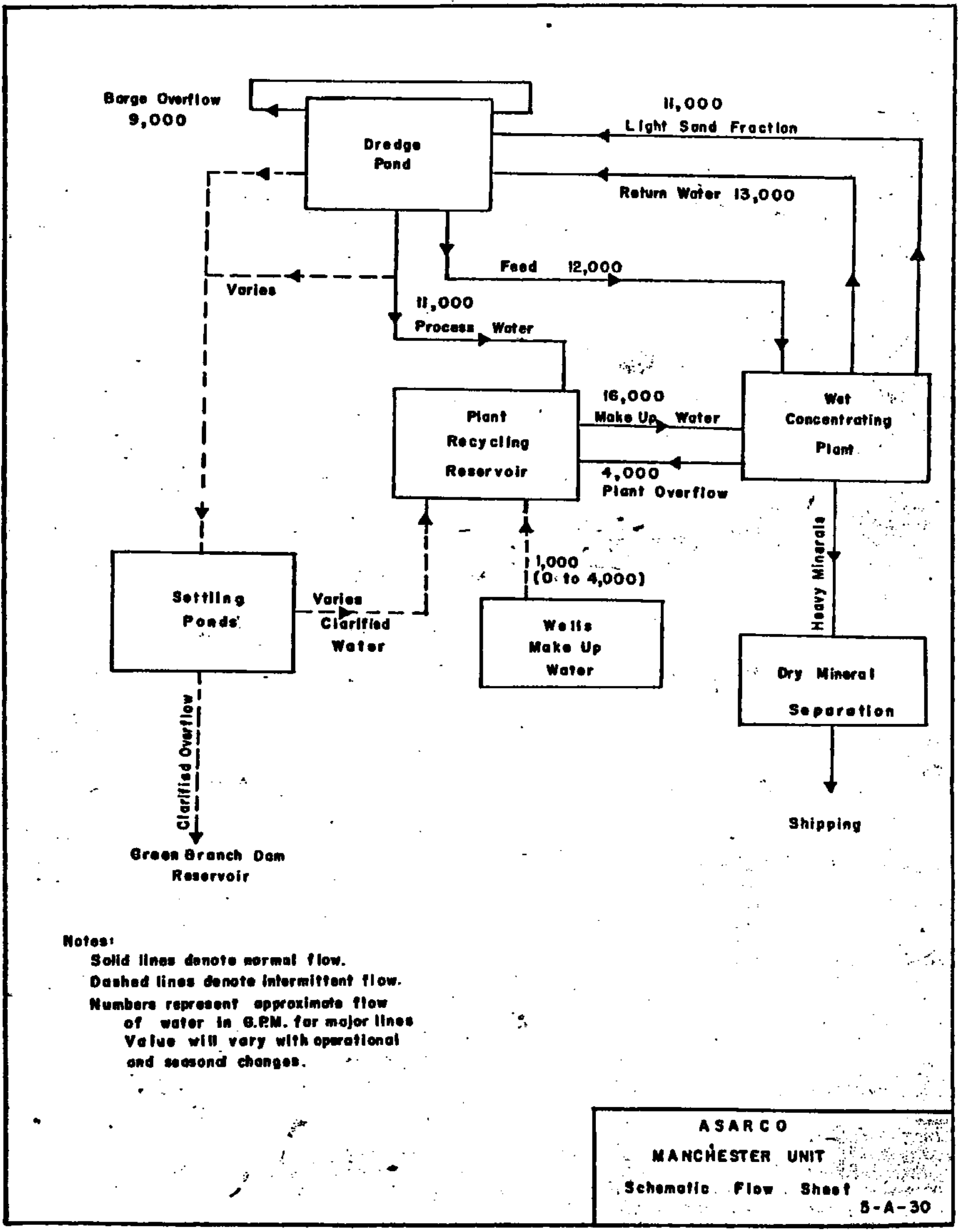
Both mines were major producers of titanium ore. Glidden produced about 90,000 short tons per year of Ti-Fe oxide concentrate averaging 61.5 percent TiO_2 while the ASARCO operation produced 185,000 short tons of concentrate per year averaging 63 percent TiO_2. During the productive years of the ASARCO mine it was the largest single producer of Ti-Fe oxide in the United States. At its largest, the ASARCO property was over 9,000 acres in area (Figure 2). ASARCO and Glidden's heavy mineral tailings piles, which are still intact, hold the largest stockpile of zircon in the United States.

MINING AND MILLING METHOD

Placer mining methods of similar design were utilized at both the Glidden and ASARCO mines. Dredges would float on small lakes that would continuously move forward. As the dredges would advance, the lakes would close in behind as processed sand was returned. A generalized flow sheet describing the entire mining and milling process at the ASARCO mine with rate of production data is presented as figure 3. A more detailed description of the mining and milling process at ASARCO as of 1980 is presented as figure 4. An air photograph of the ASARCO mine is presented as figure 5.

The ASARCO dredge was a 20 inch (discharge) cutterhead suction type dredge. It was built by the Dixie Dredge Corporation of St. Louis, Mo. The Hull was 120 feet long, 32 feet wide and 7 feet deep. The dredge was capable of digging 65 feet across the

Figure 3. Generalized Flow Sheet with Production Rates of ASARCO Titanium Oxide Mining and Milling at Manchester, New Jersey.



Notes:
Solid lines denote normal flow.
Dashed lines denote intermittent flow.
Numbers represent approximate flow of water in G.P.M. for major lines
Value will vary with operational and seasonal changes.

Figure 4. Detailed Schematic Flow Sheet of ASARCO Titanium Oxide Mining and Milling at Manchester, New Jersey.

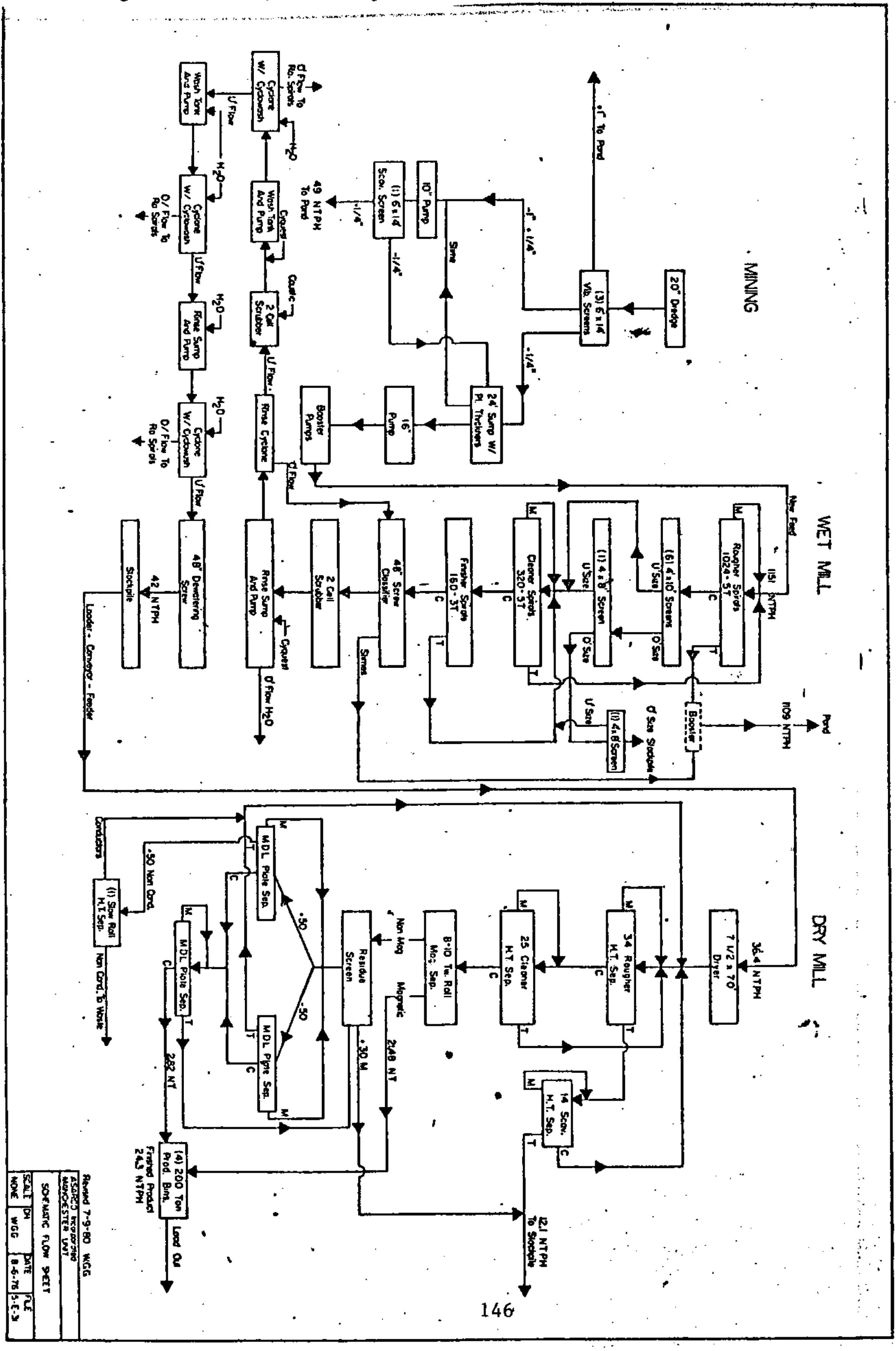
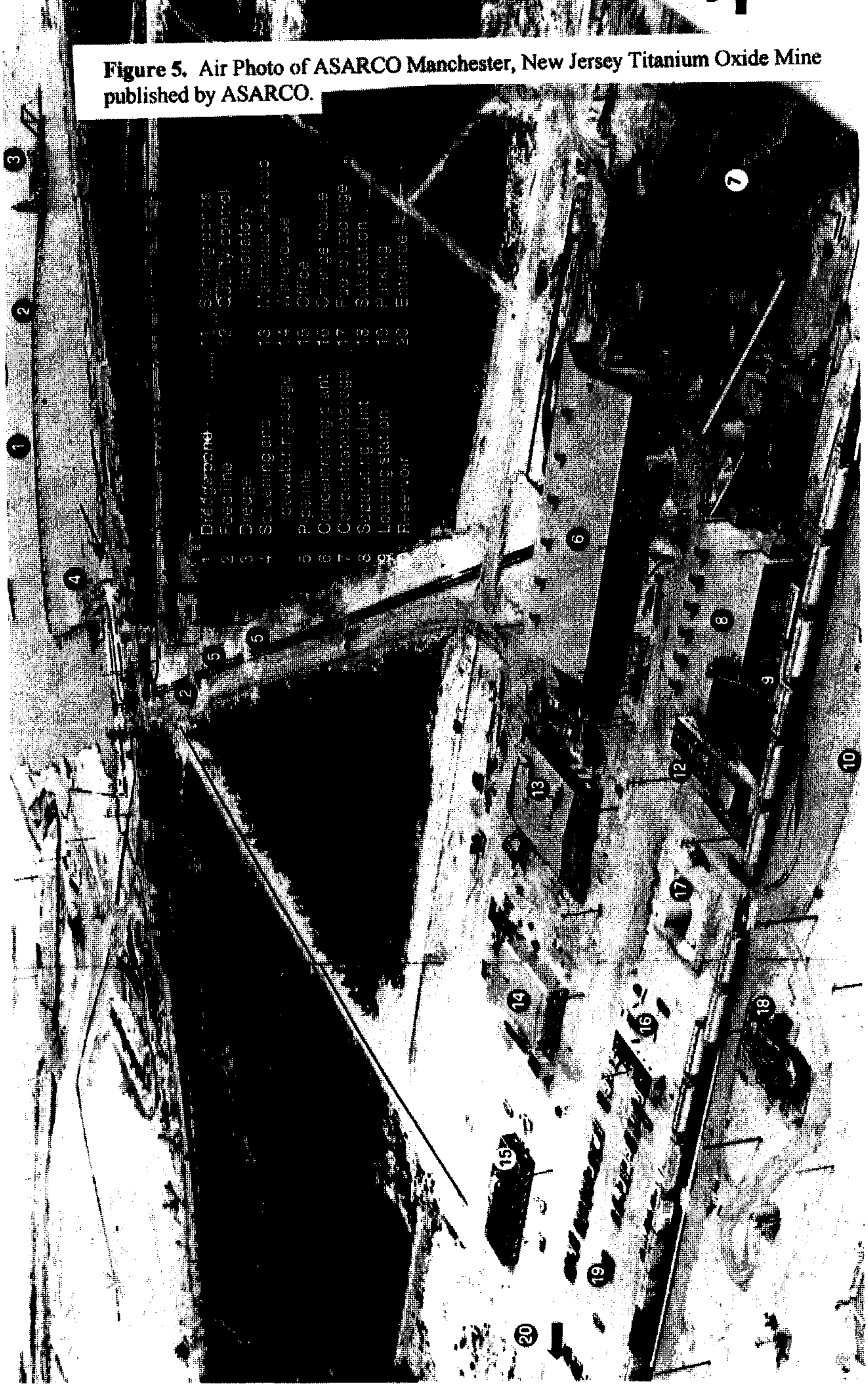


Figure 5. Air Photo of ASARCO Manchester, New Jersey Titanium Oxide Mine published by ASARCO.



Mineral-bearing feed is pumped from dredge ③ through floating pipeline to dewatering barge ④ to wet mill ⑥ where mineral fraction is concentrated, sand returned to dredge pond ①. Concentrate, partially dried in storage ⑦, is moved to dry mill ⑧ where TiO_2 mineral is separated.

surface of the water to a depth of 20 to 65 feet. The dredge worked 7 days per week, 24 hours per day and extracted as much as 1,250 tons of sand per hour for an anual production of about 8 million tons. The dredge was connected by pipes to a screening and dewatering barge. The dredge dug forward cutting a face made up of several cuts approximately 150 feet wide. The ore bearing sand was pumped to the screening and dewatering unit through a 24" pipeline mounted on floats. The pipeline varied in length from 600 to 1,000 feet. The feed from the dredge was distributed onto three vibrating screens. The top deck had 1.25 inch openings to remove large roots, rocks and aggregated clay. The lower decks wad 0.25 inch openings which removed small gravel. The minus 0.25 inch material dropped into a sump and was dewatered then pumped to the wet mill (Figures 3, 4 and 5).

The wet mill consisted of three stages of Humphries spiral concentrators which concentrated the heavier oxide grains from the quartz sand. Each spiral resembled a shallow trough shaped in the configuration of a spiral staircase. Concentrate containing about 40 percent TiO_2 was produced by the spiral concentrators and then pumped to a dewatering and conditioning unit. The concentrate was thin scrubbed in a mild caustic solution to remove and organic or clay coatings. After scrubbing, the concentrate was poured onto a high speed conveyor belt called a slinger which would "sling" the concentrate onto a stockpile. Front-end loaders would then move the concentrate from the stockpile to the dry mill through an oil fired rotary dryer.

The dry mill utilized two methods of concentration (Figure 4). The first was called high tension separation where titanium oxides were separated from remaining sand on the basis of differences in their response to high voltage electrical charge. The concentrate was fed over a high speed roll and a highly charged electrical field was aimed at the point where the concentrate would normally roll off. The silicates, having relatively poor conductivity, would be pinned to the roll and removed by a brush while the oxides that do not hold the surface charge would would fall off the role onto a collector.

The second method was a magnetic separator where the concentrate was fed over another series of spinning rolls. The rolls were magnetized so that the relatively magnetic Ti-Fe oxides would cling to the rolls then removed by a brush while the nonmagnetic silicates would fall off the rolls. The resulting finished concentrate contained 63 percent TiO_2 and was then shipped to the Du Pont paint pigment plant in Wilmington, Delaware in 100 ton railroad cars and 25 ton trucks.

Since the recovered heavy mineral content of the mined sand was only about 4 percent, the remaining 96 percent of the sand (the tailings) were pumped back into the dredge pit. Topsoil that was removed and stockpiled prior to mining was than placed back over the tailings. Approximately 500 pounds of fertilizer and 1,000 pounds of lime per acre was applied to the topsoil and planted with grass and trees.

STRATIGRAPHIC POSITION OF TITANIUM DEPOSITS

The titanium deposits of the Lakehurst area are in the Cohansey Sand and the Kirkwood Formation. The boundary between these formations is an erosional truncation

Table 1. Mineralogy of Heavy Mineral Fraction (SG>2.85) in weight percent after Puffer and Cousminer (1982).

	Cohansey Formation			Kirkwood Formation		
	Isphording[1] (1966)	Markewicz (1969)	This study	Isphording (1966)	Markewicz (1969)	This study
Number of samples	22		31	39		16
Andalusite	tr.		tr.	tr.		tr.
Anatase	tr.					
Chloritoid	tr.		tr.	2		1 (tr.–4)
Corundum	tr.			tr.		
Epidote	tr.		tr.	tr.		tr.
Garnet	tr.		tr. (tr.–3)	tr.		tr. (tr.–2)
Kyanite	1		tr.	tr.		tr.
Monazite	tr.			tr.		
Rutile	1	2		2	3	
Sillimanite	2	2[*]	3 (tr.–4)	3	4[*]	6 (tr.–8)
Sphene			tr.			tr.
Staurolite	2	1	1 (tr.–4)	3	4	3 (tr.–4)
Tourmaline	2		1 (tr.–2)	4		1 (tr.–2)
Zircon	6	5	7 (4–10)	6	10	9 (tr.–15)
Opaques	86	85	87 (79–93)	81	76	80 (70–88)
Ilmenite-pseudorutile intergrowths			2 (tr.–3)			6 (2–8)
Pseudorutile			60 (45–69)			59 (53–65)
Rutile-pseudorutile intergrowths			25 (20–28)			15 (11–19)

tr. = trace

[1] Lower Cohansey Formation

[*] Including undetermined amount of kyanite

Heavy mineral fractions were separated from sand samples collected from widely spaced locations (Fig. 1) at a depth of approximately 1 m

Table 2. Sieve Size Distribution of Cohansey and Kirkwood sand after Puffer and Cousminer (1982).

Sample	Number of samples	First moment (mean)	Second moment (sorting)	Third moment (skewness)	Fourth moment (kirtosis)
Cohansey sand > 5% heavy minerals	8	2.15 (1.8–2.5)	0.68 (0.5–0.9)	+0.10 (−0.4–+0.8)	5.25 (2.4–6.5)
Cohansey sand < 5% heavy minerals	23	1.95 (0.8–3.7)	0.95 (0.6–1.6)	−0.05 (−1.4–+0.9)	4.15 (2.2–8.2)
Cohansey heavy minerals	19	2.93 (2.7–3.1)	0.63 (0.6–0.8)	−0.05 (−0.6–+0.6)	4.05 (3.7–5.4)
Kirkwood sand	16	2.60 (2.2–3.7)	1.20 (0.7–2.0)	−0.41 (−1.8–+0.2)	6.20 (2.0–11.6)
Kirkwood heavy minerals	8	3.63 (3.5–3.8)	0.58 (0.5–0.6)	−0.75 (−0.2–−1.7)	5.10 (2.9–6.40)

Sand samples weighing approximately 1 kg were collected from widely spaced locations (Fig. 1) at a depth of ~ 1 m

Data presented in $\phi = -\log_2$ diameter (mm)

(Mullikin and others, 1989). At the Glidden Pigment mine site the Cohansey Sand is enriched in titanium oxides, averaging 6 to 7 percent, near its base. At ASARCO the ore averaged 1.5 to 4-percent titanium oxide and was derived from the Cohansey Sand and the upper 20 to 30-feet of the underlying Kirkwood Formation. The sand of the upper Kirkwood Formation at the ASARCO site is of the lower of three Kirkwood sequence, as described by Sugarman and others (1993). An approximately middle Miocene age has been assigned to the lower Cohansey although the age of the Kirkwood is more accurately constrained as lower to middle Miocene (Sugarman and others (1993). Their strontium-isotopic age estimates indicate that the three Kirkwood sequences were deposited 19.2 to 22.6 Ma, 15.5 to 17.4 Ma, and 11.5 to 13.6 Ma with sedimentation rates as high as 40 m per million years.

DESCRIPTION OF LAKEHURST AREA TITANIUM DEPOSITS

The heavy mineral content (SG > 2.8) of 31 samples of Cohansey sand from the Lakehurst area averages 2.3 weight percent, ranging from 0.4 to 12 percent (Puffer and Cousminer, 1982). The heavy mineral fraction consists of an average of 87 % opaque Ti-Fe oxides, 7 % zircon, 3 % sillimanite, 1 % staurolite, 1 % tourmaline, and traces of andalusite, garnet, chloritoid, epidote, kayanite, and sphene (Table 1). The heavy mineral content of 16 samples of Kirkwood sand from the Lakehurst area (Figure 1) averages 1.65 weight percent, ranging from 0.4 to 5.3 weight percent and consists of 80 % opaque Ti-Fe oxides, 9 % zircon. 3 % staurolite, 6 % sillimanite, 1 % tourmaline, 1% chloritoid, and trace amounts of andalusite, epidote, garnet, kyanite, and sphene (Table 1).

The lower Cohansey sand of the Lakehurst area is typically a pale buff colored, medium to coarse grained sand that is laminated and burrowed and is sparsely interbedded with lignite, or laminated clay, or limonite cemented (bog iron). Sieve-size analyses of 31 samples of Cohansey sand from the Lakehurst area (Figure 1) including titanium enriched sand have been reported by Puffer and Cousminer (1982), Table 2. Their data indicate that Cohansey sand containing > 5 % heavy minerals is better sorted (standard deviation ave. 0.65) than Cohansey sand containing < 5 & heavies (standard deviation ave. 0.95). Their data also indicate a strong positive correlation of skewness with heavy mineral content. Positive skewness and high degrees of sorting are characteristics of wind-blown sand (Friedman, 1961). The base of the Cohansey is marked by a thin gravel layer that unconformably overlies the Kirkwood.

The Kirkwood sand of the Lakehurst area is a yellow to brown, fine to medium grained sand interbedded with silt. Sieve-size analyses of 16 samples of Kirkwood sand indicate an average first, second, third, and fourth moment of 2.6, 1.2, -0.4 and 6.2 respectively (Puffer and Cousminer, 1982), Table 2. It is, therefore, much finer, more highly sorted, and less positively skewed than Cohansey sand, particularly titanium enriched titanium sand. Sugarman and others (1993) conclude that the Kirkwood Formation can be divided into three sequences characterized by both marine shelf and delta deposition. Each cycle represents a transgressive-regressive event in which deltaic deposits have prograded over marine shelf deposits (Sugarman and others, 1993). The lower Kirkwood sequence is exposed at the ASARCO mine and is the most completely developed of the three. It contains basal glauconite sand, a middle silt, and an upper quartz sand.

At the Glidden mine (Figure 2 and location C-4, Figure 1) the ore grade sand averaged 5 percent Ti-Fe oxides throughout an average thickness of 8 m but ranging from less than 5 m to more than 13 m. The ore grade sand rests on a relatively barren, reddish brown ferruginous, medium grained to gravely sand that marks the base of the Cohansey Formation.

At ASARCO (Figure 2) the orebody had an average grade of 1.5 to 4-percent Ti-Fe oxide mineral content. Both the Cohansey Sand and the upper part of the Kirkwood Formation were mined. Heavy mineral values occurred throughout the Cohansey, and ore grade lenses were found randomly around the property. The ore zones within the Kirkwood primarily occur as east-west trending heavy mineral rich intervals, up to 30-feet thick, 200 to 600-feet across, up to several miles long, spaced 800 to 1,600-feet apart, and averaged 5 to 20-percent Ti-Fe oxide. This is interpreted as an east-west trending Barrier Beach facies.

The boundary between the Kirkwood Formation and the Cohansey Sand is an erosional truncation. Nearer the Atlantic coast, to the southeast, this same Kirkwood sand would be part of the hydrogeologic unit referred to as the Atlantic City 800-foot sand. The Diatomaceous clay unit, which overlies the Atlantic City 800-foot sand is absent this far inland (Millikin and others, 1989).

THE LAKEHURST DEPOSITS COMPARED TO OTHER TITANIUM DEPOSITS

Most world-wide titanium production is derived from shoreline placer deposits including very large deposits at Stradbroke Island, Australia; Richards Bay, South Africa; and Trail Ridge, Florida. Large igneous deposits of titanium include the ilmenite deposit of Alard Lake, Canada and the rutile deposit of Kragerd, Norway. In the USA virtually all production is out of shoreline placer deposits although huge reserves are found in some igneous rocks that may go into future production. However, the Lakehurst deposit is rare and perhaps unique among shoreline placer deposits because it is found in Miocene sand unlike others that are typically found in Quaternary sand. According to Force and Lynd (1984) 10.1 million metric tons of TiO_2 are contained in the reserves of the Lakehurst district ranking it just behind the 11.4 million tons at Trail Ridge (although there may be about 20 million tons of Perovskite reserves at Powderhorn Colorado).

In general, the Lakehurst district shares several of the characteristics of Quaternary placer deposits including 1.) their occurrence on the coastal trailing margins of continents, 2.) a provenance derived from high-grade metamorphic terrain, sand that is well sorted, medium to fine grained, well rounded, and mature, and 3.) typical confinement to beds less than 10 m thick, and about 1 km wide and 5 km long (Force, 1991). However, Quaternary deposits are also confined to latitudes lower than 35 degrees unlike the Lakehurst deposit located at about 40 degrees north. Warm climates, therefore, also seem to be a factor in the generation of titanium enriched sand. But since the Lakehurst district was deposited during the Miocene, it too was deposited in a warm climate roughly equal to the current climate of Trail Ridge, Florida (Puffer and Cousminer, 1982).

DESCRIPTION OF TITANIUM OXIDES

Most of the titanium in the Lakehurst area sands occurs as grains of pseudorutile together with grains of intergrown rutile and pseudorutile and minor ilmenite-pseudorutile. The heavy mineral content of both Cohansey and Kirkwood sand consists of about 60 % pseudorutile on the basis of X-ray and optical determinations (Puffer and Cousminer, 1982). The Kirkwood heavy fraction is richer in grains of intergrown ilmenite-pseudorutile (6 %) than the Cohansey heavy fraction (2 %) with correspondingly less intergrown rutile-pseudorutile (15 %) than the Cohansey (25 %).

Pseudorutile was recognized as a new mineral by Teufer and Temple (1966) who describe it as an alteration product of ilmenite that is chemically intermediate between ilmenite and rutile. Pseudorutile was, and still is, commonly referred to as "leucoxene". The "altered ilmenite" content of the Lakehurst Ti deposits described by Meglio (1979) and Mathis and Sclar (1980) also is largely pseudorutile although it is accurate to say that very little of the ilmenite content of the sand has completely escaped alteration. Alteration begins with hydration of any exsolved hematite exsolution lamellae which softens the hematite and increases its corrodability. Corrosion is accompanied by some leaching of iron from the hemo-ilmenite intergrowths producing pitted, almost sponge-like, grains of ilmenite partially altered to pseudorutile. The distribution of the largely empty to "limonite" lined pits or cavities is approximately the same as the distribution of hematite exsolution lamellae typically found in hemo-ilmenite intergrowths. Hemo-ilmenite is the dominate titanium-iron oxide in each of the Precambrian granitic rocks of the New Jersey Highlands which is the presumed provenance of the Lakehurst area sands (Puffer and Cousminer, 1982).

As alteration proceeds, ilmenite becomes completely altered to pseudorutile. Then, at advanced stages of alteration, iron continues to become leached out of pseudorutile as it becomes progressively altered to rutile. The rutile content of the Lakehurst area sand, however, is typically confined to grain margins and veins within grains of pseudorutile.

ENVIRONMENT OF TITANIUM SAND DEPOSITION

There is general agreement among geologists that have worked on titanium enriched sand deposition that the principal enrichment process involves beach processes. The general mechanism as summarized by Force (1991) begins with detritus sorted in the upper part of the beach face (the swash zone) according to particle settling velocity. This results in coarse light minerals (principally quartz) deposited with fine heavier minerals (including Ti-Fe oxides). The backwash then plucks the larger grains from the bed while smaller heavy grains are left behind in the upper part of the swash zone. Repeated recycling of beach sand in the swash zone further concentrates heavy minerals. Some redistribution of heavies can occur in dunes, but the role of eolean processes is not as generally understood and remains controversial.

The specific depositional environmental factors responsible for the concentration of Ti-Fe oxides in the Lakehurst Ti sands was studied by Puffer and Cousminer (1982) who based their conclusions on mineralaogical, textural, structural, and paleobotanical evidence.

Mineralogical evidence

The absence of Quaternary Ti-Fe placer sand deposits north of 35 degrees latitude is interpreted by Puffer and Cousminer (1982) as evidence that warm climates are an important factor controlling the enrichment of Ti-Fe oxides in beach sand. Warm subtropical climates also correlate with the development of thick saprolites. Minerals such as garnet and magnetite that are common in the sands of temperate beaches are destroyed during saprolite development and are sparse to absent in the Lakehurst sand. Saprolite development concentrates the relatively insoluble Ti-Fe oxides in an easily eroded silica depleted residue. The solubility of silica is greatly increased by increased temperatures and is approximately doubled by an increase from 10 degrees to 30 degrees C (Siever, 1962). Relatively easily weathered minerals such as garnet are weathered during saprolite development and prevented from entering the erosional cycle. The heavy fraction of modern beach sand between South Carolina and south Florida typically contains only 1 percent garnet compared to 26 percent garnet in the heavies of sand along the south shore of Long Island (Martens, 1935).

Textural and structural evidence

The highest concentrations of Ti-Fe oxides are found near the base of the Cohansey Formation. The base of the Cohansey under the ore zone was recognized by miners as a barren reddish brown ferruginous sand that is coarse grained and poorly sorted. Carter (1972) interpreted this "interbedded sand and grit facies" as a beach foreshore and surf zone. Most of the ore zone just above the base is finer grained and relatively well sorted and is equal to Carter's burrowed, laminated sand facies that he interpreted as a beach backshore to dune facies. The highest Ti-Fe oxide content is found in well-sorted positively-skewed sand suggesting a dune environment of deposition although considerable Ti-Fe ore is burrowed and negatively skewed, suggesting a beach environment.

Sand deposited above the ore zone is typically not as well sorted, is positively skewed, and is crossbeded and channeled; all characteristics of fluvial deposition (Friedman, 1961). However, these textures and structures are also consistent with a tidal channel to tidal flat environment as proposed by Carter (1972).

Paleobotanical evidence

At the Glidden Pigment mine a lignite facies (The Legler Lignite, Rachele, 1976) is found within the 8 m thick ore grade zone. The lignite is about 1.3 m thick throughout 270 m of exposure across the mine and is as much as 5 m thick. The lignite to peat layer was deposited in a protected lagoon environment, but, as indicated by the presence of dinoflagellates, with some connection to the ocean. The lignite provides abundant palynological evidence of a subtropical climate (Puffer and Cousminer, 1982). The subtropical pollen identified by Puffer and Cousminer (1982) is evidence of a continuation of the warming trend indicated by Goldstein's (1974) paleobotaical analysis of the underlying Kirkwood Formation. Mottled clay found overlying the ore zone is, however, rich in pollen typical of temperate climates and includes spruce pollen. The Ti-Fe ore zone was, therefore, followed by an improvement in drainage or a lowering of the water table and a distinct decrease in temperatures.

ACKNOWLEDGMENTS

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ROAD LOG
OF
THE ECONOMIC GEOLOGY OF CENTRAL NEW JERESEY
FIELD-TRIP

Victoria C. Hover
and
John H. Puffer
Department of Geological Sciences
Rutgers/Newark
195 University Ave.
Newark, NJ 07102

MILEAGE		REMARKS
INCR.	CUM.	
0.0	0.0	From Somerset Quality Inn, proceed out of parking lot past building 2, and turn left into Worlds Fair Dr.; proceed to light at intersection with CR 527
0.1	0.1	Turn right (SE) at intersection with CR 527 (Easton Ave.); proceed to light
0.2	0.3	Turn right (SW) at intersection with CR 619 (Cedar Grove Lane)
3.2	3.5	Turn right (E) at intersection with CR 514 (Amwell Rd.)
2.7	6.2	Turn left (S) at intersection with CR 533 (Millstone River Rd.)
0.3	6.5	Turn right (E) at intersection with CR 514 (Amwell Rd.)
3.3	9.8	Turn left (S) at intersection with US 206 to Belle Meade
2.6	12.4	Turn right (E) at intersection with CR 601 (Belle Meade-Blawenburg Rd)
2.2	14.6	Turn right (E) at unmarked road into 3M Quarry; proceed to Quarry
1	15.6	**STOP 1: 3M TRAP ROCK QUARRY, BELLE MEADE, NJ**

The tour through the 3M Quarry will be conducted by the quarry operators and Steven Laney. The crushed black medium grained diabase is a trap-rock product or gravel that has several important uses. Diabase is a relatively inert rock type which makes the gravel product useful as road aggregate, as a component of asphalt and concrete, as construction fill where good drainage is required and for several other purposes. The mineralogy of the rock is very simple consisting of roughly equal portions of plagioclase feldspar (labradorite) and pyroxene (augite) with minor ilmeno-magnetite.

The 3M Quarry is cut into the northern end of the Lambertville/Sourland Mt. Sill (typically referred to as the Lambertville Sill) that has intruded into the Lockatong Formation. The Lambertville Sill and adjacent Lockatong sedimentary rocks, including lacustrine argellites, are terminated on the east by the Hopewell fault. Steve Laney will describe other structural aspects of the sill.

The Lambertville together with all analyzed early Jurassic diabase intrusions in the Newark Basin are classified as HTQ-type or high-titanium-quartz tholeiites on the basis of the close correspondence of the chemical composition of their fine grained chilled margins to the HTQ-type as defined by Weigand and Ragland (1970). However, four course grained samples

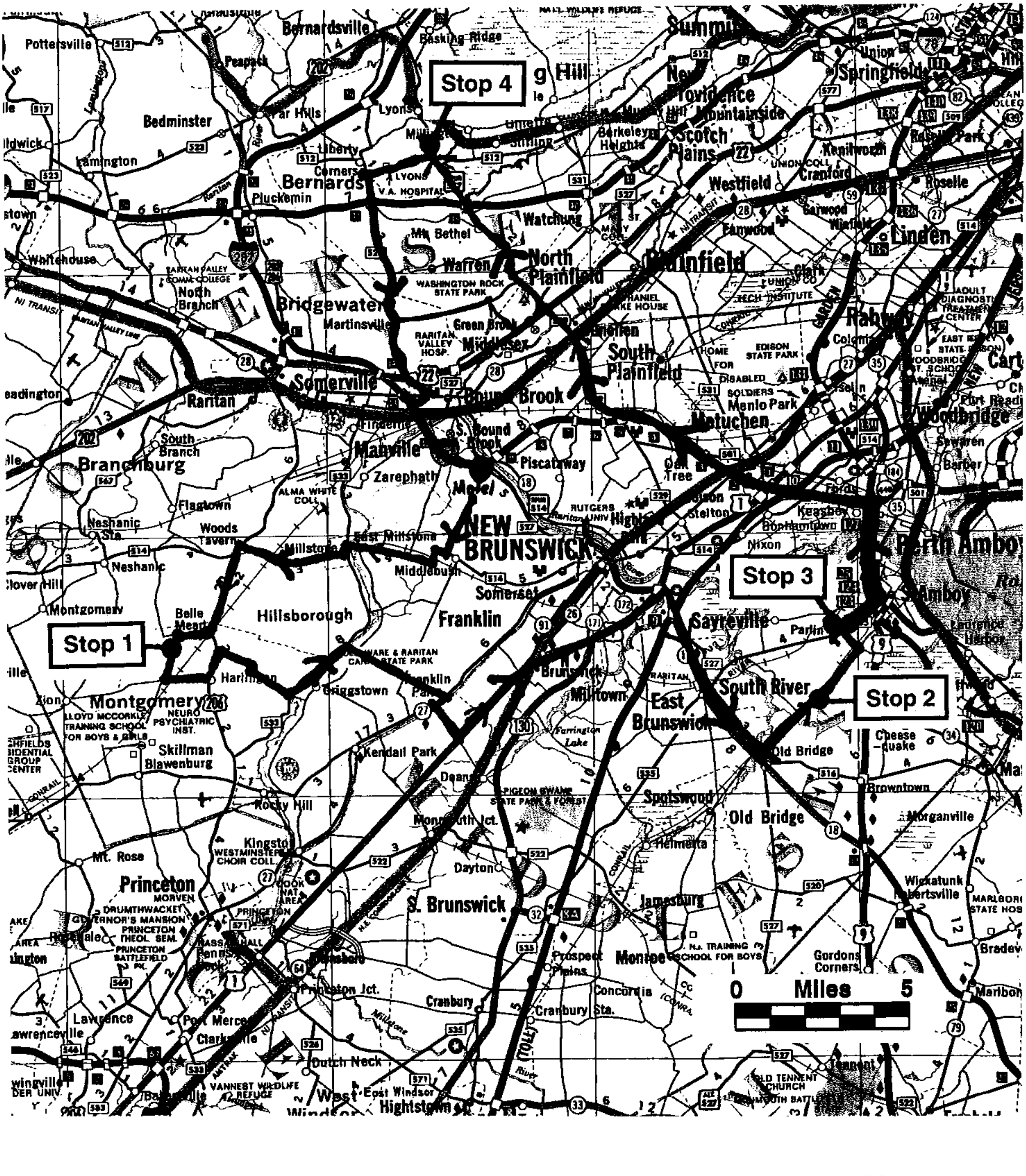


Figure 1. Field trip route with location of stops plotted on New Jersey State Highway Map.

from the northeast end of the sill, presumably from the 3M Quarry, chemically resemble the LTQ-type or low-titanium-quartz tholeiite (Husch, 1992). The Orange Mountain (or First Watchung) basalt is also a HTQ-type tholeiite but the Preakness (or Second Watchung) basalt is an LTQ type. The HTQ-type Palisades Sill is an obvious feeder source of the Orange Mountain flood basalt but no clear Palisades source has been determined. The LTQ chemistry of 3M diabase, however, is very similar to Preakness Basalt. The chemistry of the four 3M diabase samples analyzed by Husch (1992) average 0.79 % TiO_2 and 15.11 % Al_2O_3 which closely compare to the 0.77 % TiO_2 and 15.09 % Al_2O_3 of the type LTQ basalt of Weigand and Ragland (1970). Titanium and aluminum content are two of the more diagnostic characteristics of LTQ basalt. For a detailed discussion of the petrogenesis of the Lambertville sill and other Mesozoic intrusions in the area see Puffer and Husch (1996).

Several very coarse grained bodies of diabase that have recently been described in the literature as "pegmatites" have been found in the 3M quarry. Similar pegmatites found near the north end of the Palisades Sill have been described by Steiner and others (1992). Some large mafic pegmatites or "pegmatoids" also occur in the Preakness Basalt and are the chief topic of a manuscript currently under preparation by Volkert and Puffer.

1	16.6	Leave 3M Quarry and return to CR 601 Turn right (S) at intersection with CR 601 (Belle Mead-Blawenburg Rd).
0.3	16.9	Turn left (E) at intersection with CR 604 (Dutchtown Harlingen Rd.)
1.5	18.4	Turn left (N) at intersection with US 206
0.9	19.3	Turn right (E) at intersection with CR 630 (Belle Meade-Griggstown Rd.)
2.8	22.1	Turn left (N) at intersection with CR 533 at Griggstown (Millstone River Rd.)
3.7	25.8	Turn right at Blackwells Mills Rd.
2.1	27.9	Turn right (S) at intersection with CR 615 (South Middlebush Rd.)
0.1	28	Turn left (E) into Skillsman Lane
2.4	30.4	Turn right (S) at intersection with Route 27 (Lincoln Hwy)
0.2	30.6	Turn left (E) into Cozzens St.; follow signs to US 1 N at jug handle
1.1	31.7	Enter US Route 1 N
4.8	36.5	Exit at Route 18 S, (towards Old Bridge)
6	42.5	Turn left (NE) at intersection with CR 615 towards the Amboys (Bordentown Ave.) Pass Fort Grumpy
2.8	45.3	Turn left into dirt road leading NE into pit (before rail road underpass).

0.5 45.8 STOP 2: TOWN OF SAYREVILLE CLAY/GRAVEL PIT AND FORMER IRON MINE

Follow dirt road to right, go through gate and park in large open area adjacent to first sandy exposure.

Units:

Pensauken (?Pliocene):

Unconformity
Magothy Formation (Upper Cretaceous): Old Bridge Sand (Upper Cretaceous)
Unconformity
Magothy Formation: South Amboy Fire Clay

The Old Bridge Sand, along with the overlying Pensauken sands and gravels were extensively mined from this pit. Removal ceased when the underlying clay horizon was encountered. Although, the South Amboy Fire Clay was not commercially mined from this pit, the pit provides reasonable exposures of this member and its contact with the overlying Old Bridge Sand.

Iron ore was commercially mined from this pit during the late 1800's.

0.5 45.8 STOP 2A: PENSAUKEN GRAVELS (Vicky Hover)

In the Sayreville area, the ?Pliocene-age Pensauken Formation unconformably overlies the Upper Cretaceous Raritan and Magothy Formations. At this stop, approximately 25-30 ft. of Pensauken sands and gravels overlies the Old Bridge Sand Member of the Magothy Formation. The Pensauken Formation is a fluvial deposit resulting from deposition from a major river system, which drained southwestward from the Long Island Sound area to the Delmarva Peninsula, along the contact between the Newark Basin and Coastal Plain onlap zone (Stanford, 1997). The Pensauken is a yellow-tan, arkosic sand and pebbly sand dominated by tabular, and planar cross beds suggesting shallow, braided stream deposition. The gravel composition is dominantly quartz, quartzite and chert; with some mudstone, sandstone, gneiss, diabase, and basalt in basal gravels. The gravel clasts are commonly iron stained. Feldspar containing clasts and sand grains are commonly decomposed (Stanford, 1977).

Heavily iron stained horizons approximately 3-6 inches thick, are exposed in the outcrop in the pit. These probably represent paleo water-table horizons.

Walk or board bus to travel further into Pit parking in compost area. Proceed to low Grey outcrops of clay towards the south

0.4 46.2 STOP 2B: IRON DEPOSITS (Bruce Archer)

The occurrence and economic history of the iron deposits in the quarry will be described by Bruce Archer. For a clear understanding of role that this and other bog iron deposits played in the history of New Jersey read the chapter in this guide book "The Bog Iron Industry in the New Jersey Coastal Plain" written by Bruce Archer.

Walk towards northeast and follow creek bed to view more exposures of Cretaceous Clays.

STOP 2C: CRETACEOUS MAGOTHY FORMATION; SOUTH AMBOY FIRE CLAY AND OLD BRIDGE SAND MEMBERS. (Vicky Hover).

The South Amboy Fire Clay member of the Magothy Formation forms the base of the pit, with exposures visible in gullies and along the creek bed. Here, the member is a light olive-gray finely laminated to burrowed silty, micaceous clay containing pyrite (or marcasite?) encrusted lignite fragments. The pyrite is commonly altered to rusty-red to brown iron oxides. X-ray diffraction analyses of the clay member indicates kaolinite, illite, and swelling smectite are present in the gray clay units. The South Amboy Fire Clay was deposited in relatively large oxbow lakes in a subaerial delta plain setting (e.g., Owens and Sohl, 1969, Sugarman, 1996, Miller 1998, pers. commun.)

The Old Bridge Sand member of the Magothy Formation unconformably overlies the Clay member. It consists of light gray to white, course- to medium- grained crossbedded micaceous sand containing abundant comminuted lignite fragments. Some layers are Fe-stained light tan to yellowish orange. Fe-reduction spots occur around lignite fragments. Owens and Gohn (1985) interpreted the Old Bridge Sand member to be a lower delta plain deposit. The contact between the Old Bridge Sand and underlying South Amboy Fire Clay is irregular with about 5 meters of relief. In the creek-bed gully a channel over 1 meter deep, filled with crossbedded sand, incises the clay horizon. Rip-up clasts of predominantly kaolinitic clay are common at the contact. Owens and Gohn (1985) interpreted the Old Bridge Sand member to be a lower delta plain deposit.

Secondary alteration of the sandstone horizons include occurrence of limonitic concretions at the contact between the less permeable clay and overlying sand layers. These limonite concretions probably resulted from the oxidation of pyrite or marcasite in underlying clay layers by as percolating ground waters became ‘impounded” against less permeable clay horizons.

		Leave Stop 2
0.9	47.1	Turn left (NE) on CR 614 (Bordentown Ave.)
1.4	48.5	Turn left (E) at Cheesequake Rd.
1.3	49.8	Bear right (N) at S. Minisink Ave.
0.2	50	Turn right (NE) CR 535 (Washington Rd.)
1.3	51.3	Enter John F Kennedy Park

OPTIONAL STOP 3

The exposures behind J. F. Kennedy Park were part of Crossman’s Clay Pits (# 65 and #69 of Ries et al., (1904)). Several horizons of the Upper Cretaceous South Amboy Fire Clay member of the Magothy Formation were mined at this site and the adjacent pit to the north and east. The base of the pit contains a gray to black lignitic and pyritic laminated clay. Some patches of red mottled clay are also visible. Much of the surface of the pit has been disturbed by dumping of dredge spoils taken from the pond in Kennedy park, however, approximately 5 ft of “in-place” exposures are visible.

		Leave John F. Kennedy Park.
1.1	52.4	Turn left (NE) into CR 535 (Washington Rd.); Follow Signs to US Route 9 and 35
2.1	54.5	Enter Routes 9 and 35 N under the overpass; stay on route 9 at split with 35; cross Raritan River
2.1	56.6	Follow signs to Interstate 287 and Route 440
0.8	57.4	Enter Routes 287/440; follow signs to 287 N
7.9	65.3	Take exit 5, CR 529 N (Stelton Ave./Washington Ave.) towards Dunellen
4.3	69.6	Turn left (W) on US Route 22
0.9	70.5	Turn right on CR 651 (Warrenville Rd.)
5.7	76.2	Turn left at intersection with CR 512 (Valley Rd.)
0.4	76.6	Turn right at intersection with CR 613 (Stonehouse Rd.)
1.3	77.9	Enter Millington Quarry

STOP 4: THE MILLINGTON TRAP ROCK QUARRY (John Puffer)

The trap-rock gravel product mined at Millington is approximately the same as the product mined at the 3M Quarry. However the Millington rock is extrusive volcanic flood basalt, whereas the 3M product is shallow intrusive diabase. The Millington trap rock is, therefore, finer grained and a bit more friable but the mineralogy of both rocks consists of plagioclase and pyroxene with minor ilmeno-magnetite and co-existing ilmenite.

The basalt mined at Millington is the Hook Mountain Formation also known as the Third Watchung Basalt. The Millington quarry is the only large trap-rock quarry cut into Hook Mountain basalt. However, there are several large quarries cut into Orange Mountain Basalt and a few more in the Preakness.

The Hook Mountain basalt represents the last volcanic activity in New Jersey. It was extruded as a flood basalt onto the red-bed sediments of the Towaco Formation about 197 million years ago during the early stages of the break-up of the Pangean supercontinent. The chemical composition of the Hook Mountain basalt does not fit into the HTQ or LTQ classification scheme of Weigand and Ragland (1970) but may fit into a basalt type they describe as HFQ or high iron quartz tholeiite. One of the chief characteristics of the HFQ type is the elevated iron content (16 % Fe_2O_3) and a chemistry that is more highly evolved or fractionated than the underlying flows (Puffer 1992).

There are at least two subaerial flow units exposed in the mine. The contact is recognized by the red scoriaceous flow top of the lower unit and some discontinuous red siltstone deposited between the two flows. The rocks dip to the north at about 10 degrees although the structural picture, particularly to the west, has been complicated by some complex faulting including vertical "strike-slip" faults. The lower flow is about 30 m thick and the upper flow is about 45 m thick.

Considerable secondary mineralization is found along fault and joint plains, in half-moon shaped vesicles, and along flow contacts. Most of the secondary mineralization was developed during zeolite facies burial of the flows and includes collectable prehnite, amethyst, and several zeolites. The secondary mineralization has been described in detail by Cummings (1985). Fortunately, Warren Cummings will be on site to help identify mineral specimens.

		Leave Stop 4.
	77.9	Turn right (S) into CR 613 (Stonehouse Rd.)
1.3	79.2	Turn right (W) at intersection with CR 512 (Valley Rd.)
1.6	80.8	Turn left (S) at intersection with CR 525 (Martinsville Rd.)
4.3	85.1	Bear left and continue on CR 525 S at intersection with SR 620
0.3	85.4	Bear right and continue on CR 525 S (Chimney Rock Rd.)
1.7	87.1	Pass Chimney Rock Quarry. Sheets of Native Copper were found at lower contact of First Watchung Basalt with underlying Newark Group Sediment.
0.3	87.4	Turn right at CR 623 (Chimney Rock Rd.)
0.2	87.6	Cross US Route 22
0.6	88.2	Enter Route 28 E (W. Union Ave.)
0.3	88.5	Enter 287 S
3.2	91.7	Take Exit 10; 527 S (Easton Ave.)
0.4	92.1	Arrive Quality Inn, Somerset

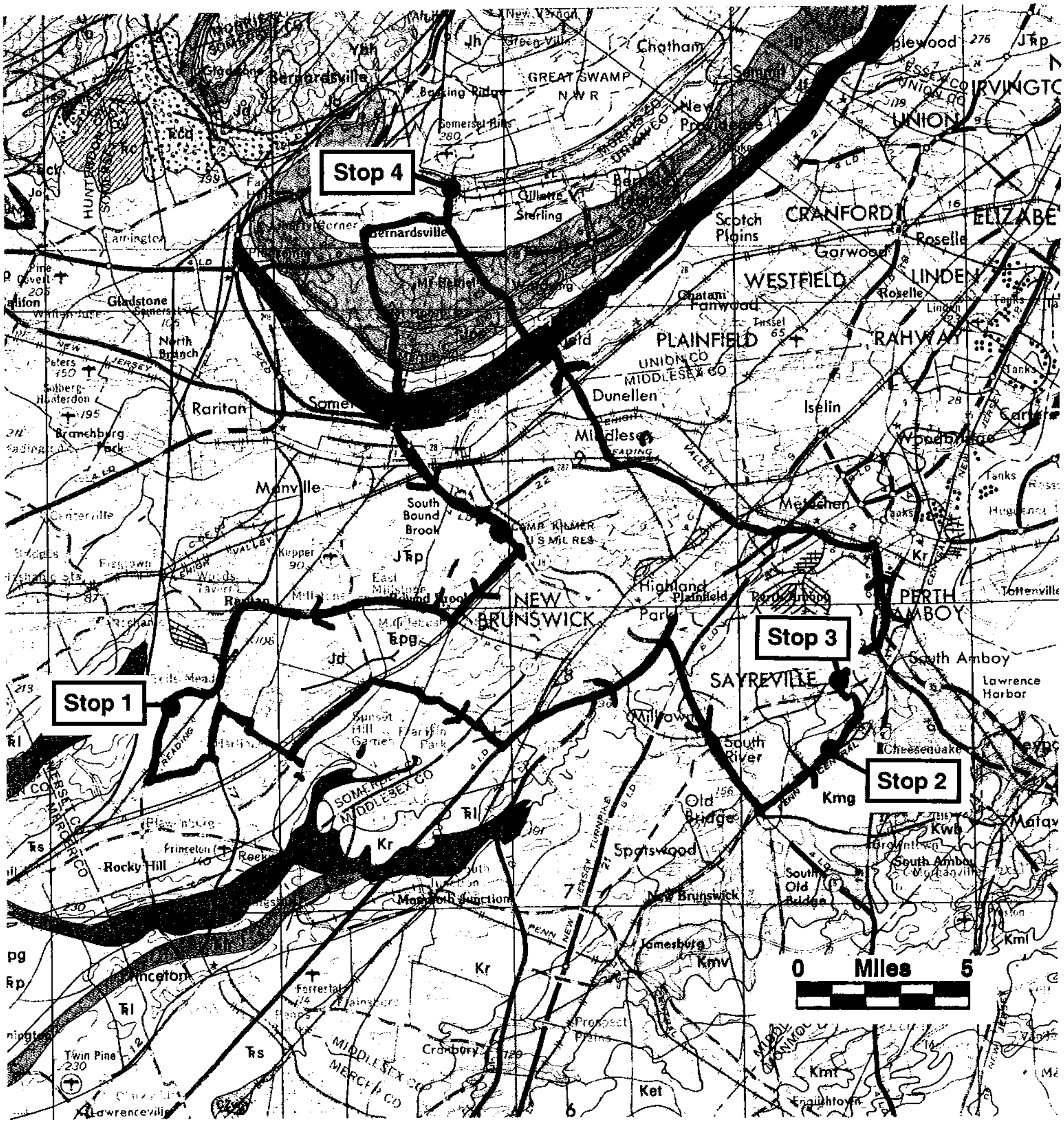


Figure 2. Field trip route with stop locations plotted into a portion of the Bedrock Geology Map.

DESCRIPTION OF MAP UNITS

Note: A variety of Holocene deposits and Pleistocene glacial sediments are present throughout the quadrangle, and Pleistocene and Tertiary terrace deposits of gravel, sand, and clay are common along the area of the Fall Line. None of these units are shown on the map.

COASTAL PLAIN

Kw	**Wenonah Formation (Upper Cretaceous)**—Generally dark, thick-bedded, fine- to medium-grained, poorly to moderately sorted, carbonaceous, pyritic, very silty and clayey, quartzose glauconite sand. 21–30 m (70–100 ft) thick
Kmt	**Marshalltown Formation (Upper Cretaceous)**—Dark, fine-grained, massive, fossiliferous, very silty and clayey, quartzose glauconite sand with common mica, feldspar, pyrite, and carbonaceous matter. 5–6 m (15–20 ft) thick
Ket	**Englishtown Formation (Upper Cretaceous)**—Light-colored, well-sorted, fine- to medium-grained, crossbedded, glauconitic, feldspathic, and micaceous quartz sand, and interbedded clayey silt and sand with numerous siderite concretions. 6–46 m (20–150 ft) thick
Kwb	**Woodbury Clay (Upper Cretaceous)**—Dark-gray, massive to crudely laminated, carbonaceous, pyritic, partly glauconitic, micaceous, very clayey (dominantly illitic) silt. As much as 30 m (100 ft) thick
Kmv	**Merchantville Formation (Upper Cretaceous)**—Dark, clayey, micaceous, quartzose, carbonaceous silt with interbedded gravel containing reworked siderite concretions; thick-bedded glauconite and quartz sand. 6–30 m (20–100 ft) thick
Kmg	**Magothy Formation (Upper Cretaceous)**—Dark, micaceous, pyritic, kaolinitic, clayey silt and light-colored quartz sand with large lignitized logs. Lower contact is unconformable, but is buried by surficial deposits and precise location is poorly known on Staten Island and in Brooklyn, N.Y. 3–61 m (10–200 ft) thick
Kr	**Raritan Formation (Upper Cretaceous)**—Massive, crossbedded quartz sand; thick-bedded clayey silt; laminated clay and silt; and minor gravel. About 61 m (200 ft) thick
Kp	**Potomac Formation (Upper and Lower Cretaceous)**—Moderately well sorted, crossbedded, quartzose sand; gravelly sand with quartz and quartzite pebbles as much as 13 cm (5 in) long; and black, red, white, and yellow, massive, kaolinitic and illitic, crudely stratified, lenticular clay. 76–244 m (250–800 ft) thick. Lower contact unconformable

NEWARK AND GETTYSBURG BASINS

The Newark basin, and west of the Schuylkill River, the Gettysburg basin, form a rolling lowland underlain by a thick succession of sedimentary rocks and basalt flows of Early Jurassic and Late Triassic age. Jurassic diabase dikes, sills, and stocks cut and metamorphose older rocks in the basin. The rocks generally dip gently to moderately to the north toward a large fault zone that forms the basin boundary, although many open folds with axes at high angles to the strike of the faults have been mapped. The rocks form a northward thickening wedge with a composite thickness that may exceed 10,000 m (33,000 ft); however, not all of the units are preserved in one area. Several generations of folds may affect the rocks of the basin, but do not appear to affect the older pre-Triassic rocks outside the basin. The basin may have formed as a pull-apart structure with significant strike-slip movement along the larger faults. This could account for local horsts and grabens within the basin, possible sequential development of different parts of the basin, the compressional regime that produced the folds and local thrust faults, as well as decoupling of the folds within the basin from structures outside the basin. Some of the gently dipping listric normal faults may represent reactivated segments of Paleozoic thrust faults, but with the opposite sense of movement. Limestone conglomerate (TRcl), quartzite conglomerate (TRcq), and unclassified conglomerate (TRc) may be partly Jurassic in age. Figure 1 shows stratigraphic and intrusive relationships.

Jd ■	**Diabase (Lower Jurassic)**—Dikes, sills, and sill-like intrusives. Dark-gray to black, fine- to coarse-grained (except very fine to fine-grained near chilled borders), diabase composed largely of calcic plagioclase and augite. Some of the dikes are several miles long and as much as 0.8 km (0.5 mi) wide; some may have been intruded along faults. Generally deeply weathered. Larger bodies, as much as 520 m (1,700 ft) thick, interpreted as sills or discordant sheets with oval or ringlike outcrop patterns. Shales and siltstones surrounding these bodies have been thermally metamorphosed to a purplish-red, light-gray, and dark-gray, indurated, brittle, and fine-grained homfels with quartz, plagioclase, sericite, biotite, cordierite, epidote, chlorite, magnetite, hornblende, pyroxene, tourmaline, nepheline, cancrinite, and zeolite in a zone averaging about 610 m (2,000 ft) wide. The width of this zone depends on the thickness of the intrusive, its topographic expression, and its inclination

NEWARK SUPERGROUP*

Jc	**Conglomerate (Lower Jurassic)**—Generally poorly exposed conglomerate and conglomeratic sandstone with clasts of quartz, sandstone, conglomerate, granite, metamorphic rocks, limestone, and basalt; clasts may be more than 15 cm (6 in) in diameter. Overlies Boonton Formation, Hook Mountain Basalt, and Towaco Formation. Thickness not known
Jb	**Boonton Formation of the Brunswick Group (Lower Jurassic)**—Lower part is red, gray, brown, and black, blocky, partly dolomitic siltstone; locally contains hopper (salt crystal) casts pseudomorphic after gypsum, glauberite, and halite. Overlain by red, well-bedded and thick-bedded siltstone and sandstone and thin beds of gray-green siltstone. Bed of microlaminated, gray, calcareous siltstone with fossil fish near the top, 1 m (3.3 ft) thick with thin, gray and brown pebble-conglomerate beds as much as 0.5 m (1.6 ft) thick. Reptile and arthropod fossils also present. Northeast of Morristown, N. J., includes thick sequences of red-, gray-, and brown-matrix conglomerate and breccia. More than 500 m (1,640 ft) thick
Jh	**Hook Mountain Basalt of the Brunswick Group (Lower Jurassic)**—Two tholeiitic basalt flows composed mainly of aphanitic to finely crystalline plagioclase and augite. In places, the flows contain vesicles near the top. As much as 110 m (361 ft) thick
Jt	**Towaco Formation of the Brunswick Group (Lower Jurassic)**—Red, gray, and black, fine- to coarse-grained sandstone, siltstone, and conglomerate in fining-upward cycles. Medial black and gray, microlaminated, calcareous siltstone containing diagnostic pollen, fish, and dinosaurs. Cycles average about 35 m (115 ft) in thickness with maximum thickness of unit 340 m (1,115 ft)
Jp Jps	**Preakness Basalt of the Brunswick Group (Lower Jurassic)**—At least three tholeiitic basalt flows, with some pillows and basaltic breccia resembling aa. Columnar with characteristic platy prismatic joint pattern. Locally, thin red siltstone (Jps) separates the flows. Thickness is 215–300 m (705–984 ft) or more
Jf Jbu	**Feltville Formation of the Brunswick Group in New Jersey and upper part of the Brunswick Group in Pennsylvania (Lower Jurassic)**—Red, buff, gray, black, and white, partly crossbedded, fine- to coarse-grained feldspathic sandstone; gray and black siltstone in fining-upward cycles; and a laterally continuous, gray, laminated limestone. Lower half contains a unit of black to white laminated limestone, calcarenite, graded siltstone, and crossbedded siltstone and sandstone about 1–10 m (3–39 ft) thick. Fossiliferous, with reptiles, arthropods, abundant fish, and diagnostic spores and pollen. About 170–600 m (558–1,969 ft) thick. Only lower 215 m (705 ft) preserved near Reading, Penn.
■	**Orange Mountain Basalt of the Brunswick Group in New Jersey and Jacksonwald Basalt of the Brunswick Group in Pennsylvania (Lower Jurassic)**—The Orange Mountain Basalt comprises at least two tholeiitic, pillowed pahoehoe, and columnar basalt flows, with thin interbedded volcaniclastic rocks that are about 1-4 m (3-13 ft) thick, in the First Watchung Mountain of New Jersey. The Jacksonwald Basalt (Wherry, 1910; also called the Jacksonwald Basalt Member of the Brunswick Formation by MacLachlan, 1983), 9 km (5.6 mi) east of Reading, Penn., and another flow 8 km (5 mi) south of Flemington, N. J., may be the same extrusive unit. Probably between 100 and 200 m (328 and 656 ft) thick
JTRp TRpg JTRbl TRblg	**Passaic Formation of Olsen (1980a) of the Brunswick Group in New Jersey and lower part of the Brunswick Group in Pennsylvania (Lower Jurassic and Upper Triassic)**—Predominantly grayish-red to reddish-brown, evenly to irregularly bedded, thin- to thick-bedded shale, siltstone, very fine to coarse-grained sandstone, and red-matrix conglomerate. Generally becomes coarser in the northeastern half of the basin in New Jersey. Mudcracks, ripple marks, crossbeds, and burrows are common. Contains detrital cycles of medium- to dark-gray and olive- to greenish-gray, thin-bedded and evenly bedded shale and siltstone (TRpg, TRblg), similar to the rocks in the underlying Lockatong Formation (TRl). Many cycles are known near New Brunswick and northeast of Lambertville, N. J., but are not shown on the map (Olsen, unpub. data, 1983). Greenish and brownish, fine- to coarse-grained, arkosic sandstone grades in places to quartzite fanglomerate (TRcq), and contains some interbedded red beds and impure limestone or calcareous shale. Locally contains dinosaur footprints. Individual cycles as much as 76 m (250 ft) thick; some cycles are too thin to show on this map. Lower contact with the Lockatong Formation (TRl) gradational through about 500 m (1,640 ft) and is mapped where thickness of red beds is dominant over thickness of gray and black beds. Interfingers laterally with the Lockatong (TRl) and Hammer Creek (TRh) Formations. Where the unit grades laterally into the Lockatong, lower contact is either conformable and gradational to older rocks of the Newark Supergroup, or is unconformable on basement rocks. Contains reptiles, arthropods, pelecypods, plant impressions, spores, and pollen. The Jurassic-Triassic boundary lies within the uppermost 100 m (328 ft). The maximum thickness may exceed 6,000 m (19,685 ft) in the western part of the basin and is about 2,670 m (8,760 ft) in the northeastern part

Ŧl Ŧlr

Lockatong Formation (Upper Triassic)—Predominantly laminated to thick-bedded, gray and black siltstone and shale; rich in fossils, including plants, reptiles, fish, and diagnostic spores and pollen. Unit composed of alternating detrital and chemical-lacustrine cycles. *Detrital cycles*: lower part laminated, medium-dark-gray to black, calcareous, pyritic siltstone and shale overlain by platy to massive, disrupted (mudcracked and burrowed), dark-gray, calcareous siltstone, ripple-bedded siltstone, and fine-grained sandstone; more common in the lower Lockatong. Averages about 5.2 m (17.1 ft) in thickness. *Chemical cycles*: Lower part platy, medium-dark-gray to black, dolomitic siltstone and marlstone with shrinkage cracks and lenses of pyritic limestone, overlain by massive, gray or red, analcime- and carbonate-rich, disrupted siltstone. Average thickness about 3.2 m (10.5 ft). Lower contact of Lockatong gradational, placed at base of lowest continuous black siltstone bed. Contains interbedded, reddish-brown, sandy siltstone in units from about 3 to 82 m (10 to 270 ft) thick (Ŧlr). Interfingers laterally with and gradationally into the underlying Stockton Formation (Ŧs) as well as up into the Passaic Formation (JŦp) and lower part of the Brunswick Group (JŦbl). Wedges out between the Stockton (Ŧs) and Hammer Creek (Ŧh) Formations west of the Schuylkill River. Maximum thickness about 1,180 m (3,871 ft)

Ŧsu Ŧsm Ŧsl Ŧs Ŧsc

Stockton Formation (Upper Triassic)—Light- to medium-gray and light-yellowish-gray to pale-reddish-brown, thin- to thick-bedded, fine- to coarse-grained sandstone, arkose and arkosic conglomerate with pebbles of quartz, quartzite, feldspar, shale, limestone, and metamorphic rocks locally more than 8 cm (3 in) long; grayish-red to moderate-reddish-brown, and light- to medium-gray siltstone and shale, bioturbated by roots and burrows; and grayish-red to reddish-brown, thin- to thick-bedded, very fine to medium-grained, arkosic sandstone, generally fining upward with abrupt lateral lithic changes. These rocks contain channels, ripple marks, mudcracks, crossbeds, pinch-and-swell structures, and minor burrows. Purplish siltstone near the middle and top. Well-bedded, gray and gray-green, fossiliferous siltstone present locally in upper Stockton. Locally contains red limestone breccia filling solution cavities in Ordovician-Cambrian limestones. Local gray and buff, thick-bedded to crudely bedded, arkosic conglomerate and arkose with subangular to rounded pebbles of quartz, quartzite, limestone, and underlying basement rocks as much as 8 cm (3 in) long in a red, arkosic sand to silty shale matrix (Ŧsc). Units containing conglomerate average about 100 m (320 ft) in thickness. Lower contact unconformable. The Hammer Creek (Ŧh) is a partial lateral correlative and unconformably overlies this unit. Maximum thickness is 1,830 m (6,000 ft) in the center of the basin, thinning in all directions to less than 250 m (820 ft) near Hoboken, N.J. In Montgomery County and eastern Chester County, Penn., the Stockton is divided into three members. Upper shale member (Ŧsu), red shale and siltstone with some fine-grained, arkosic sandstone. 18–305 m (60–1,000 ft) thick. Middle arkosic member (Ŧsm), fine- to medium-grained, arkosic sandstone with red shale and siltstone. 518–1,280 m (1,700–4,200 ft) thick. Lower arkosic member (Ŧsl), medium- to very coarse grained, arkosic sandstone and conglomerate, with fine-grained, arkosic sandstone and red shale and siltstone. 168–823 m (550–2,700 ft) thick

Ŧcl

Limestone conglomerate (Upper Triassic)—Subangular, medium- to dark-medium-gray limestone and dolomite clasts as much as 1 m (3.3 ft) in diameter (derived from Cambrian limestones in the immediate area) and rare gneiss pebbles and cobbles in a matrix of red, partly arkosic sandstone and siltstone. Generally becomes finer grained southward

Ŧcq

Quartzite conglomerate (Upper Triassic)—Rounded pebbles, cobbles, and boulders, as much as 30 cm (1 ft) long, of white, light-gray, and reddish quartzite, and lesser calcareous sandstone in a matrix of red, partly arkosic siltstone and sandstone. Source from Silurian rocks to north. Generally becomes finer grained southward. About 305 m (1,000 ft) thick

Ŧc

Unclassified conglomerate (Upper Triassic)—Conglomerate and conglomeratic sandstone with rounded to angular quartzite, limestone, gneiss, and basalt clasts as much as 1 m (3.3 ft) long. As much as 305 m (1,000 ft) thick in places

Paleozoic and Late Proterozoic Cover Rocks of the Southern Piedmont

€Zw

Wissahickon Formation* (Cambrian and Late Proterozoic)—Fine- to medium-grained, medium- to dark-gray to black, brownish-gray to slightly rusty weathering, aluminous, pelitic schist, feldspathic metagraywacke with thin interbedded amphibolites, and lenses and pods of altered ultramafic rocks. Rocks range in metamorphic grade from greenschist through upper amphibolite facies, including partial melting producing migmatites. Where the unit is exposed in thin fault slivers between the Cream Valley fault and the fault contact on the south side of the Octoraro Phyllite (€Zo), it is a highly crenulated, coarse-grained, garnet-mica schist. Southeast toward the type sections along Wissahickon Creek in Philadelphia the metamorphic grade increases and the percentage of feldspathic metagraywacke increases. In south part of map area the unit becomes gneissic. Contact with the Swarthmore Granodiorite (Osg) within the map area is a thrust fault (probably a back-thrust) bringing the Wissahickon south over the granodiorite

PROTEROZOIC ROCKS OF THE READING PRONG

Losee Metamorphic Suite

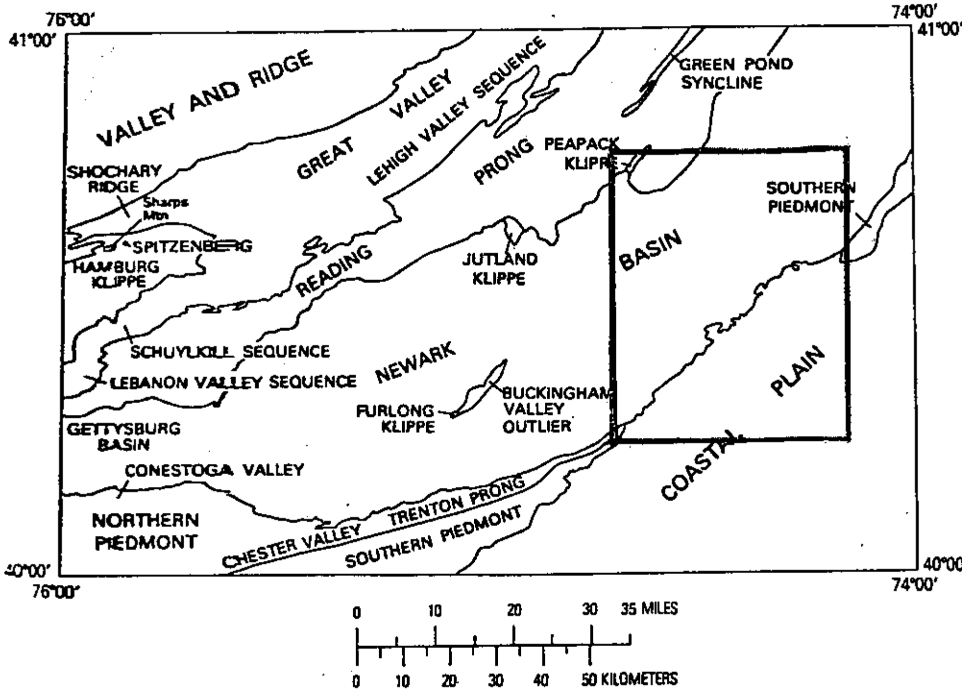
Ylo

Oligoclase-quartz gneiss (Middle Proterozoic)—Light-greenish-gray to grayish-green, medium-fine- to medium-coarse-grained, poorly foliated, granoblastic gneiss and minor granofels. Composed principally of oligoclase and quartz. Minor amounts of biotite, magnetite, and typically shredded and chloritized augite. Unit contains sparse to moderate amounts of interlayered amphibolite

Byram Intrusive Suite

Ybh

Hornblende granite and associated biotite granite (Middle Proterozoic)—Pink to light-gray, medium- to coarse-grained, gneissoid granite, foliated granite, and sparse granite gneiss composed principally of microperthite, quartz, oligoclase, hornblende and (or) biotite. In granite gneiss phases, microperthite has typically recrystallized. Rock contains free microcline and oligoclase. Includes bodies of alaskite, amphibolite, and potassic-feldspar gneiss that are too small to map



STRUCTURAL AND PHYSIOGRAPHIC REGIONS OF THE NEWARK 1° x 2° QUADRANGLE

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MINERALS, ROCKS AND SEDIMENTS OF NEW JERSEY

John Marchisin
Dept. of Geoscience/Geography
New Jersey City University
Jersey City, New Jersey 07305

Rocks and sediments exposed in New Jersey range in age from 1.3 billion year old Precambrian rocks to sediments deposited on the surface in the recent past. Many of these rocks and sediments have been and/or are still of economic value and are therefore of historical or current interest.

The New Jersey Department of Environmental Protection (DEP) recently produced a set of 17 New Jersey Rocks and Sediments accompanied by a twenty-page booklet which describes each mineral, rock or sediment and discusses their use and other pertinent information. The booklet contains a list of resources and organizations where additional information may be obtained , as well as maps showing where the specimens were obtained which makes it easy to determine the geologic province represented by each specimen.

Professor Marchisin, who has taught Geology of New Jersey at New Jersey City University (formerly Jersey City State College) for 30 years will discuss the DEP set and how it, and other relevant materials, can be used in the K-12 classroom. Emphasis will be placed on how the set can be used to enhance units on the geology and geological provinces of New Jersey. Information will also be provided on field localities for minerals, fossils, rocks and sediments where K-12 students can learn first hand about the geological history of the state of New Jersey.