IGNEOUS PROCESSES DURING THE ASSEMBLY AND BREAKUP OF PANGAEA: NORTHERN NEW JERSEY AND NEW YORK CITY

CONFERENCE PROCEEDINGS AND FIELD GUIDE

EDITED BY
Alan I. Benimoff

GEOLOGICAL ASSOCIATION OF NEW JERSEY

XXX ANNUAL CONFERENCE AND FIELDTRIP

OCTOBER 11 – 12, 2013

At the College of Staten Island, Staten Island, NY

IGNEOUS PROCESSES DURING THE ASSEMBLY AND BREAKUP OF PANGAEA: NORTHERN NEW JERSEY AND NEW YORK CITY

CONFERENCE PROCEEDINGS AND FIELD GUIDE

EDITED BY

Alan I. Benimoff

GEOLOGICAL ASSOCIATION OF NEW JERSEY

XXX ANNUAL CONFERENCE AND FIELDTRIP

OCTOBER 11 – 12, 2013

COLLEGE OF STATEN ISLAND, STATEN ISLAND, NY

GEOLOGICAL ASSOCIATION OF NEW JERSEY

2012/2013 EXECUTIVE BOARD

Front Cover: I-278 Road Cut, Staten Island, NY. Photograph: Jane Alexander

First Annual Meeting - 1984
Puffer, John H., ed., 1984, *Igneous Rocks of the Newark Basin: Petrology, Mineralogy, and Ore Deposits, and Guide to Field Trip.*
Second Annual Meeting - 1985*
Talkington, Raymond W., and Epstein, Claude M., eds., 1985, *Geological Investigations of the Coastal Plain of Southern New Jersey: Part 1 - Field Guide; Part 2A - Hydrology and Coastal Plain; Part 2B - Paleontologic Investigations (The set, Parts 1, 2A, 2B, priced as one volume).*
Third Annual Meeting - 1986
Husch, Jonathan, M., and Goldstein, Fredric R., eds., 1986, *Geology of the New Jersey Highlands and Radon in New Jersey.*
Fourth Annual Meeting - 1987*
Gallagher, William B., ed., 1987, *Paleontology and Stratigraphy of the Lower Paleozoic Deposits of the Delaware Water Gap Area.*
Fifth Annual Meeting - 1988
Husch, Jonathan, M., and Hozik, Michael J., eds., 1988, *Geology of the Central Newark Basin.*
Sixth Annual Meeting - 1989*
Grossman, I. G., ed., 1989, *Paleozoic Geology of the Kittatinny Valley and Southwest Highlands NJ*
Seventh Annual Meeting - 1990
Brown, James O., and Kroll, Richard L., eds., 1990, *Aspects of Groundwater in New Jersey.*
Eighth Annual Meeting - 1991
Crawford, Maria L., and Crawford, William A., eds., 1991, *Evolution and Assembly of the Pennsylvania - Delaware Piedmont.*
Ninth Annual Meeting - 1992
Ashley, Gail M., and Halsey, Susan D., eds., 1992, *Environmental Geology of the Raritan River Basin.*
Tenth Annual Meeting - 1993
Puffer, John H., ed., 1993, *Geologic Traverse Across the Precambrian Rocks of the New Jersey Highlands.*
Eleventh Annual Meeting – 1994
Benimoff, Alan I., ed., 1994, *Geology of Staten Island*, *New York*.
Twelfth Annual Meeting – 1995
Baker, John E. B., ed., 1995, *Contributions of the Paleontology of New Jersey.*
Thirteenth Annual Meeting - 1996
Dalton, Richard F., and Brown, James O., eds., 1996, *Karst Geology of New Jersey and Vicinity.*
Fourteenth Annual Meeting - 1997
Benimoff, Alan I., and Puffer, John H., 1997, *The Economic Geology of Northern New Jersey.*
Fifteenth Annual Meeting – 1998
Puffer, John H., ed., 1998, *The Economic Geology of Central New Jersey.*
Sixteenth Annual Meeting – 1999
Puffer, John H., ed., 1999, *New Jersey Beaches and Coastal Processes from a Geologic and Environmental Perspective.*
Seventeenth Annual Meeting – 2000
Harper, David P. and, Goldstein, Fredric L., eds., 2000, *Glacial Geology of New Jersey.*
Eighteenth Annual Meeting – 2001
Lacombe, Pierre, and Herman, Gregory, eds., 2001, *Geology in Service to Public Health.*
Nineteenth Annual Meeting – 2002
D'Amato, Dana, ed., 2002, *Geology of the Delaware Water Gap Area.*
Twentieth Annual Meeting – 2003
Hozik, Michael J., and Mihalasky, Mark J., eds., 2003, *Periglacial Features of Southern New Jersey.*
Twenty-first Annual Meeting – 2004
Puffer, John H., and Volkert, Richard A, eds., 2004, *Neoproterozoic, Paleozoic, and Mesozoic Intrusive Rocks of Northern New Jersey and Southeastern New York.*
Twenty-second Annual Meeting - 2005
Gates, Alexander E., ed., 2005, *Geology of the Central Newark Basin - The View From the 21st Century.*
Twenty-third Annual Meeting - 2006
Macaoay, Suzanne, and Montgomery, William, eds., 2006, *Environmental Geology of the Highlands.*
Twenty-fourth Annual Meeting - 2007
Rainforth, Emma C., ed., 2007, *Contributions to the Paleontology of New Jersey (II).*
Twenty-fifth Annual Meeting - 2008
Gorring, Matthew L., ed., 2008, *Environmental and Engineering Geology of Northeastern New Jersey.*
Twenty-sixth Annual Meeting – 2009
Freile, Deborah, ed., 2009, *New Jersey Coastal Plain Stratigraphy and Coastal Processes*.
Twenty-seventh Annual Meeting – 2010**
Lacombe, Pierre, ed., 2010, *Geology of the Greater Trenton Area and Its Impact on the Capitol City*
Twenty-eighth Annual Meeting – 2011
Rainforth, Emma C., and Uminski, Alan, eds., 2011, *Environmental Geology of Central New Jersey*
Twenty-ninth Annual Meeting – 2012 J
Alexander, Jane, ed. *Geology and Public lands*

Field Guides & Proceedings of Prior Annual Meetings

Price: $20.00** (includes shipping and handling for hard copies)

Order online from http://shop.ganj.org

or by mail Geological Association of New Jersey

P.O. Box 5145; Trenton, NJ 08638-0145

ATTN: Publications Order

*out of print-available for download only

**out of print-available by print-on-demand for $40.00

IGNEOUS PROCESSES DURING THE ASSEMBLY AND BREAKUP OF PANGAEA: NORTHERN NEW JERSEY AND NEW YORK CITY
GANJ XXX Conference and Field Trip

SCHEDULE

Friday, October 11th – Green Dolphin Lounge – Campus Center College of Staten Island, Staten Island, NY 10314

12:00-4:30	Registration
1:15-1:30	Welcoming Remarks Alan Benimoff, College of Staten Island/CUNY, and GANJ President
1:30-2:00	Igneous processes During the Assembly and Breakup of Pangaea: Northern New Jersey and New York City John H. Puffer, Ph.D., Rutgers University-Newark
2:00-2:20	The Manhattan Serpentinite Suite: Mineralogy, Geochemistry, and Petrogenesis Mark Germine, M.D., Ph.D.
2:20-2:40	The Staten Island Serpentinite Alan I. Benimoff, Ph.D., College of Staten Island/CUNY
2:40-3:00	The Lower New Street Quarry Christopher Laskowich
3:00-3:20	Break
3:20-3:40	The Structure of CAMP Intrusions and Bouger Gravity Anomalies of the New York Recess Gregory Herman, Ph.D. New Jersey Geological Survey
3:40-4:00	Generation and Evolution of Granophyre in the Palisades Sill Karin Block, Ph.D. CCNY/CUNY
4:00-4:20	New York City Geology and its Influence on Geothermal Heat Pump Systems: With a case Study at Snug Harbor, Staten Island, NY Dennis Askins, Alex Posner, and Brett Miller, New York City Department of Design and Construction
4:45-5:45	<u>Keynote Speaker</u> Jeffrey Steiner, Ph.D CCNY/CUNY Unraveling Pangea Flood Basalts From The Bottom Up: The Orange Mountain Basalt Mixed Lava
6:00	Dinner and Business Meeting – Campus Center, Park Café, College of Staten Island

Saturday, October 12th - Field Trip

8:00 am - 5:00 pm. Meet at Lot 6 CSI campus.

IGNEOUS PROCESSES DURING THE ASSEMBLY AND BREAKUP OF PANGAEA: NORTHERN NEW JERSEY AND NEW YORK CITY
GANJ XXX Conference and Field Trip

TABLE OF CONTENTS

IGNEOUS PROCESSES DURING THE ASSEMBLY AND BREAKUP OF PANGAEA: NORTHERN NEW JERSEY AND NEW YORK CITY
GANJ XXX Conference and Field Trip

INTRODUCTION

John McPhee (1993) wrote: "Southeastern Staten Island is a piece of Europe glued to an ophiolite from the northwest Iapetus floor"

It has been 30 years since the first GANJ meeting was held. The meeting was held at Kean University on October 19, 1984 and the field trip was on October 20, 1984. We used vans to transport the participants. The field trip leader and author of the field trip guide, *Igneous Rocks of the Newark Basin: Petrology, Mineralogy, and Ore Deposits,* was Dr. John Puffer.

We have come a long way since then. Thirty years later and we are at the 30th annual meeting of the Geological Association of New Jersey (GANJ). We now benefit from 30 years of further research on these rocks by Dr. John Puffer, Dr. Karin Block, Dr. Jeffrey Steiner, Dr. Gregory Herman, Dr. Mark Germine and Mr. Christopher Laskowich. Scanning the titles of the guidebooks on page iii shows you the extent of 29 years of field trips. We even had field trips into Pennsylvania and Staten Island, NY.

This year's meeting focuses on *IGNEOUS PROCESSES DURING THE ASSEMBLY AND BREAK-UP OF PANGAEA: NORTHERN NEW JERSEY AND NEW YORK CITY.* Within a short distance we have an ancient convergent plate boundary and an ancient divergent plate boundary. We will see evidence of this on this year's field trip. I thank all the speakers and authors for their important contributions to this meeting. We also thank our sponsors for their contributions.

IGNEOUS PROCESSES DURING THE ASSEMBLY AND BREAKUP OF PANGAEA: NORTHERN NEW JERSEY AND NEW YORK CITY

John H. Puffer

Dept. of Earth & Environmental Sciences, Rutgers Univ. Newark NJ 07102
jpuffer@andromeda.rutgers.edu

Abstract

Geochemical, stratigraphic, and structural evidence leave little doubt that the emplacement of an island arc during the Taconic Orogeny (the Hartland Formation) obducted onto the Laurentian continental shelf onto Kittatinny and Martinsburg sediments thus beginning their metamorphism into Inwood marble and Manhattan schist. The ocean crust under Hartland arc volcanoclastics was obducted as a Tethyan ophiolite along Cameron's line consistent with each of the criteria described by Wakabayashi and Dilek (2003). Acadian deformation accompanying the accretion of Avalonia onto Laurentia involved further regional metamorphism and emplaced a subduction zone under eastern Laurentia. The Avalonian subduction zone enriched the sub-continental-lithosphere (SCLM) in incompatiable element content and hydration. Incubation of this enriched SCLM under central Pangaea during the upper Paleozoic and Triassic allowed for temperature increases permitting fusion triggered by decompression accompanying the initial break-up of Pangaea. Evidence for a non-plume, SCLM source for the Central Atlantic Magmaic Province (CAMP) includes: a. lack of a clear hot-spot track; b. upper Paleozoic accumulation of heat beneath a thickened insulating sub-CAMP lithosphere; c. lack of a radiating dyke pattern; d. absence of a diverse plume-type or OIB chemical signature among CAMP basalts; e. presence of a homogeneous Arc-like geochemical signature among CAMP basalts; f. evidence of an increase in depth of melting among CAMP magmas in contrast to the decrease predicted by plume models; g. evidence of mantle potential melting temperatures for CAMP that are less than predicted by plume models; and h. new Sr, Nd, Pb, and Os isotopic data consistent with an enriched SCLM but inconsistent with plume models.

The Assembly of Pangaea

When John Rogers described "A history the Continents in the past 3 billion years" the assembly of Pangaea was relatively straightforward. Rogers (1996) described the collision of the continents Nena, Ur, and Atlantica to form the supercontinent Rodina at ~1 Ga. Then rifting of Rodinia until 0.5 Ga formed three continents: East Gondwana, Atlantica and Laurasia (which contained North America, Greenland, Baltica, and Siberia). Then finally during the Paleozoic various plates accreted to Laurasia and collision of Gondwana with Laurasia created Pangaea at ~0.3 Ga. However, since 1996 things have gotten complicated**.** There are currently as many theories and models as there are authors and there is very little general consensus as to the timing and sequence of events. There are at least 7 competing models for the configuration of Rodinia, for example SWEAT (Southwest United States-East Antarctica where Antarctica is on the Southwest of Laurentia and Australia is at the North of Antarctica), AUSWUS (Australia-southwest United States) where Australia is at the West of Laurentia, AUSMEX (Australia-Mexico), where Australia is at the location of Mexico relative to Laurentia, The "Missing-link" model by Li et al. (2008) which has South China between Australia and the east coast of Laurentia, the model of Searse and Price (2000) which has Siberia attached to the western US (via the Belt Supergroup), and the evolving models of Scotese (Scotese.com) and Blakey (cpgeosystems.com). Several of these models call for a second supercontinent (Pannotia).

There is a general consensus that all Rodinian rifting did not start simultaneously. The best evidence for rifting is the distribution of plume-type volcanism and A-type granites. About 800 million years ago rifts developed between Australia, eastern Antarctica, India and the East African portion of Rodinia and the Laurentia, Baltica, Amazonia, West African and Rio de la Plata portions. This rift developed into the Adamastor Ocean during the Ediacaran. The Adamastor Ocean lasted until about 550 million years ago when the Pan-African orogeny formed the continent Gondwana.

During a later Rodinian rifting event about 610 million years ago the Iapetus Ocean formed between Amazonia and Laurentia. However some evidence suggests that all continental masses joined into another supercontinent (Pannotia, Fig. 1) between 600 and 550 million years ago in which case the Iapetus did not open until 550 million years ago. In either case, (latest Rodinian or Pannotian) the Iapetus rifting event was described in some detail by Puffer (2002) and was probably driven by a superplume located near Quebec, Canada. Radiometric data pertaining to the volcanic activity emanating from the superplume is ambiguous and ranges from 610 to 550 Ma, therefore either scenario may be consistent with the superplume event.

Fig. 1 After Blakely (cpgeosystems.com). If Laurentia was in contact with South America about 540 million years ago the super-continent is called Pannotia. Then Laurentia (proto North America), and Baltica (proto Western Europe) and the Avalonian volcanic arc drifted away from Gondwana.

The Taconic Orogeny

The timing of the closure of the Iapetus is also controversial but a growing consensus would agree with the general model accepted by the USGS (Fig. 2) modified after Plank and Schenck (1998).

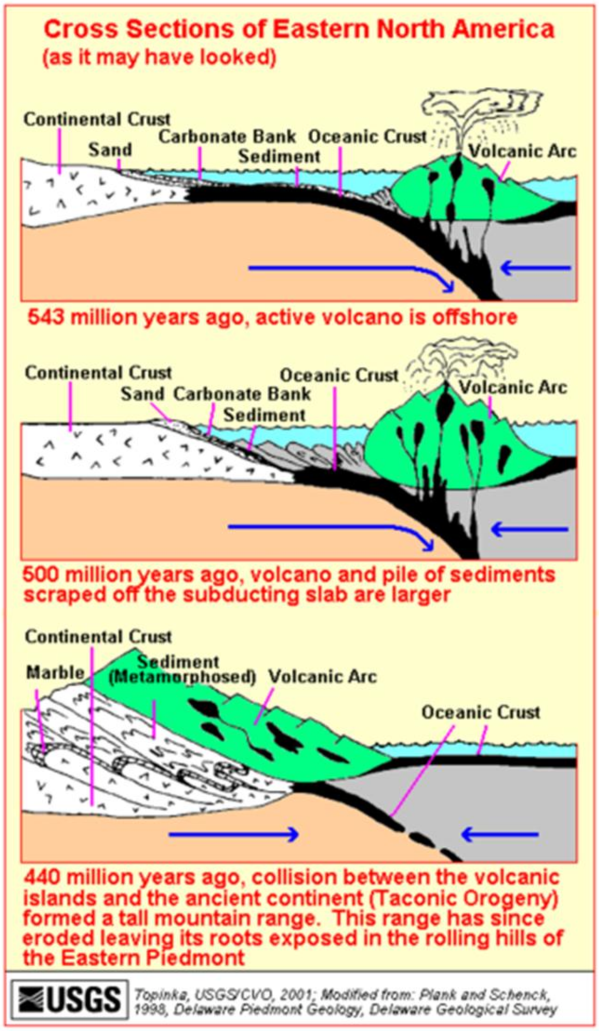


Fig. 2. The Taconic Orogeny as interpreted by the USGS.gov modified by Plank and Schenck (1998).

The scenario depicted in Fig. 2 nicely applies to what clearly occurred in the New York City area. The "Sand and Carbonate Bank sediments" depicted in Fig. 2 on the "Continental Crust" is consistent with Hardyston sand, Martinsburg shale, and Kittatinny limestone deposition in the waters of the Iapetus Ocean on the Laurentian shelf during the Cambrian and Ordovician 543 to 500 MA. Then as the Taconic volcanic arc obducted Laurentia during the 440 Ma Taconic Orogeny these sediments were metamorphosed into Lowerre Quartzite, Inwood Marble, and Manhattan Schist. The evidence for this obvious correlation includes geochemical evidence presented by Puffer et al., (1994 and 2010), (Fig. 3).

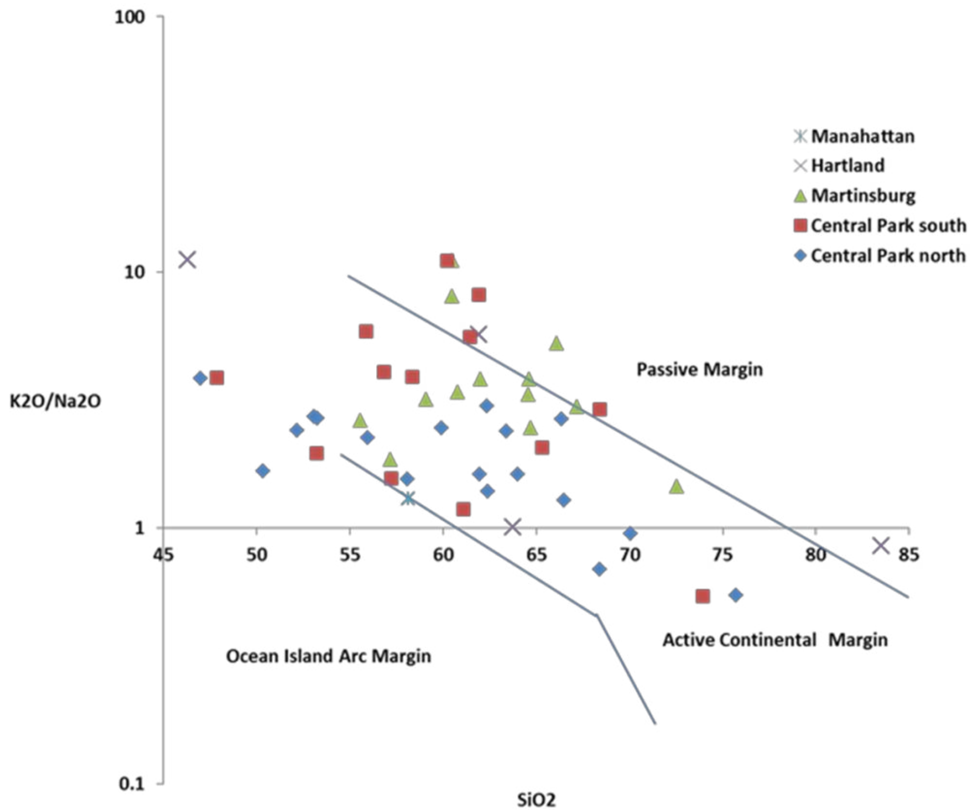


Figure 3 from Puffer et al., (2010). Roser and Korsch (1986) type plot of K2O/Na2O vs. SiO2 composition of schist and slate formations from Manhattan and northern New Jersey.

Figure 3 shows that the geochemical range of the Martinsburg Formation of Northern New Jersey completely overlaps the schists of northern and southern Central Park, Manhattan, and plot in the “Active Continental Margin” field of Roser and Korsch (1986) consistent with Figure 2. The Martinsburg Formation is therefore interpreted as the protolith of the Manhattan Schists.

The only important New York City lithology missing from Figure 2 is the Staten Island Serpentinite and other serpentinites exposed along Cameron’s Line such as the Castle Point Serpentinite of Hoboken and the Manhattan Serpentinite (Germine and Puffer, this volume). Figure 2 illustrated the obduction of an Iapetus “Ocean Crust” but is not specifically obducted as a serpentinite. Serpentinite very similar to the Staten Island serpentinite is an intergral part of ophiolite emplacement along the plate sutures of California. Wakabayashi and Dilek (2003) have described four types of ophiolites (1) 'Tethyan' ophiolites, obducted onto continental margins as a result of collisional events; (2)

'Cordilleran' ophiolites emplaced onto subduction complexes through accretionary processes; (3) 'ridge-trench intersections' ophiolites emplaced through the interaction between a spreading ridge and a subduction zone; and (4) the unique Macquarie Island ophiolite. Types 3 and 4 are uncommon while most ophiolites are either Tethyan or Coredilleran. The Franciscan Formation associated with one of the more extensive Californian Cordilleran-type ophiolites is an example of an accretionary wedge or mélange scraped off the ocean floor during accretion. Lithologies similar to the Franciscan Formation are absent from the New York City area. The Franciscan Formation is a mélange composed of glaucophane, jadite, lawsonite, blueschist facies schist, with pelagic cherts, black slates, and pelagic meta-limestone facies components in contrast to Hartland schists typically described as a meta-volcanic and meta-volcanoclastic assemblage.

However, all the tectonic characteristics of Tethyan emplacement as described in detail by Wakabayashi and Dilek (2003) occur in Figure 2 including emplacement up a seaward dipping ramp onto a continental margin. Another important characteristic of Tethyan ophiolites is the development of a “metamorphic sole” under the ophiolite. Figure 4, therefore, depicts the likely emplacement of a Tethyan ophiolite together with an island arc (the Hartland Formation) onto the Laurentian margin and the metamorphic sole interpreted as Manhattan Schist and related meta-sediments.

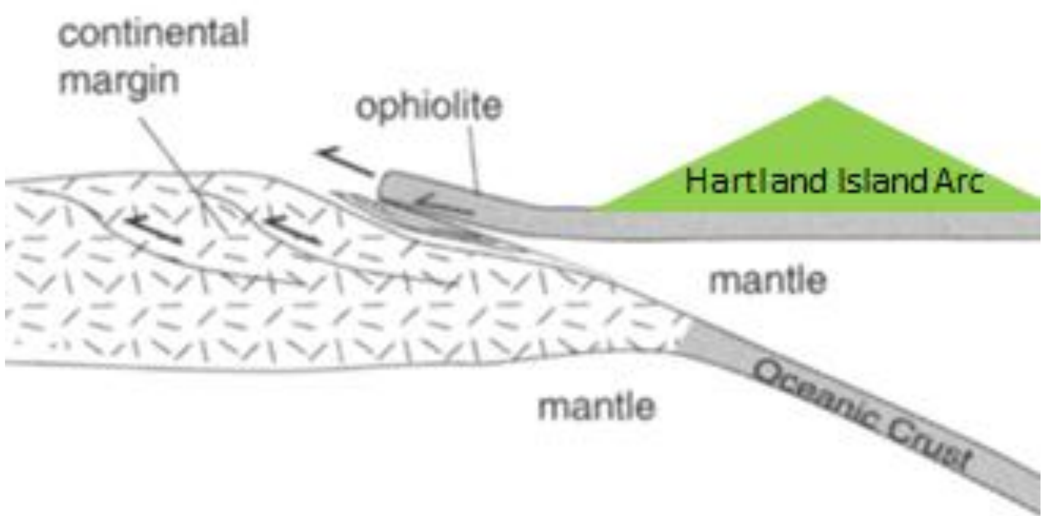


Figure 4. Emplacement of ophiolite, modified after Wakabayashi and Dilek (2003), during the Taconic Orogeny. Note the development of a metamorphic sole beneath the ophiolite interpreted as Manhattan Schist and the obduction of an Island Arc interpreted as Hartland Formation.

Although clear evidence of an accretionary wedge is absent from New York City, Taconic metamorphism of presumably Cordilleran-type accretionary wedge sediments, ophiolitic rocks, and related materials has been interpreted by Rowley and Kidd (1981) for western New England. In addition the Hartland is described by Merguerian (1983) in western Connecticut as "… a deep-seated, sheared accretionary complex". However, an important characteristic of Cordilleran-type ophiolites is the occurrence of an accretionary complex structurally <u>beneath</u> the ophiolite component. In contrast, the Hartland Island arc structurally <u>overlies</u> the Staten Island ophiolite as nicely depicted by the cross-section interpretation through eastern New Jersey and western New York made by Little and Epstein (1987), Figure 5.

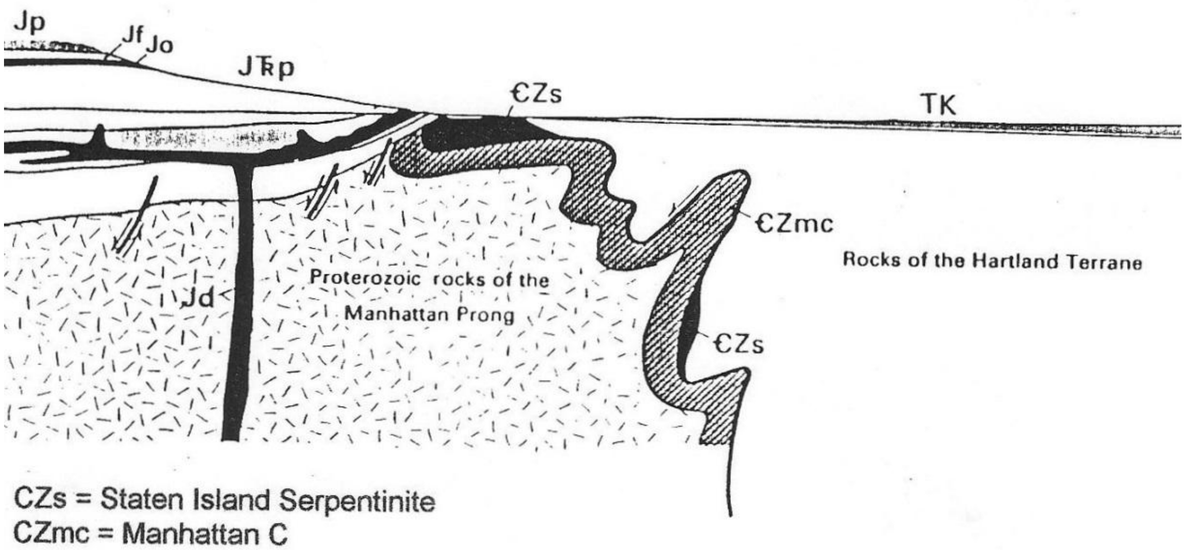


Figure 5. Cross section through the New York City area after Little and Epstein (1987).

The depiction of CZs serpentinite in Figure 5 as an irregular discontinuous body is consistent with the pinch and swell characteristic of serpentinite occurrences along most plate sutures including Californian sutures and the entire length of Cameron's Line. Serpentinite is relatively pliable compared to most rocks because it consists of soft hydrous minerals. It tends to respond to high pressure as if it was viscous grease acting as a lubricant along shear zones. In active shear zones it is squeezed into local relatively low pressure accumulations such as the Staten Island occurrence and is thinned along relatively active high pressure zones. It may also accumulate at fault intersections and other structural traps.

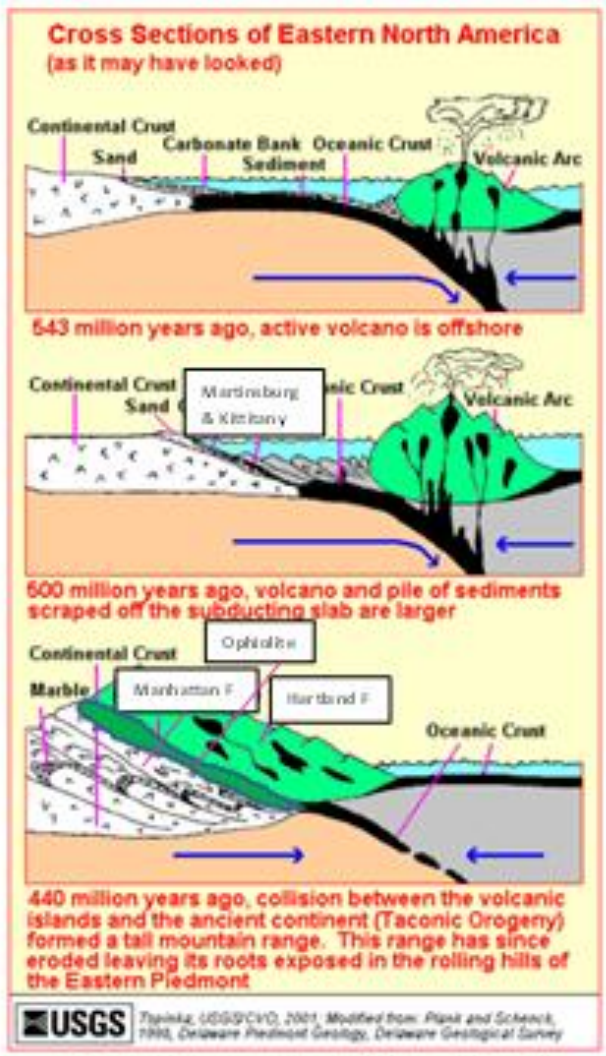


Figure 6. The USGS interpretation of the Taconic Orogeny modified to include a Tethyan ophiolite (Staten Island, Castle Point, and Manhattan Serpentinites), the meta-sediments of Manhattan, and the Hartland Formation.

The Tethyan ophiolite of Figure 4 is completely consistent with the Taconic structures illustrated in Figure 2 and is, therefore, added as a modification of Figure 2 to generate Figure 6. Each of the component parts of Figure 6 including the Hartland Formation have been metamorphosed to at least the almandine amphibolite facies of regional metamorphism and therefore must have been deeply buried under overturned lower Paleozoic rock formations, upper Paleozoic, and Mesozoic formations. Arching of the Hartland Formation and underlying ophiolite must have preceded erosion and exhumation of the current bedrock distribution as illustrated in Figure 7.

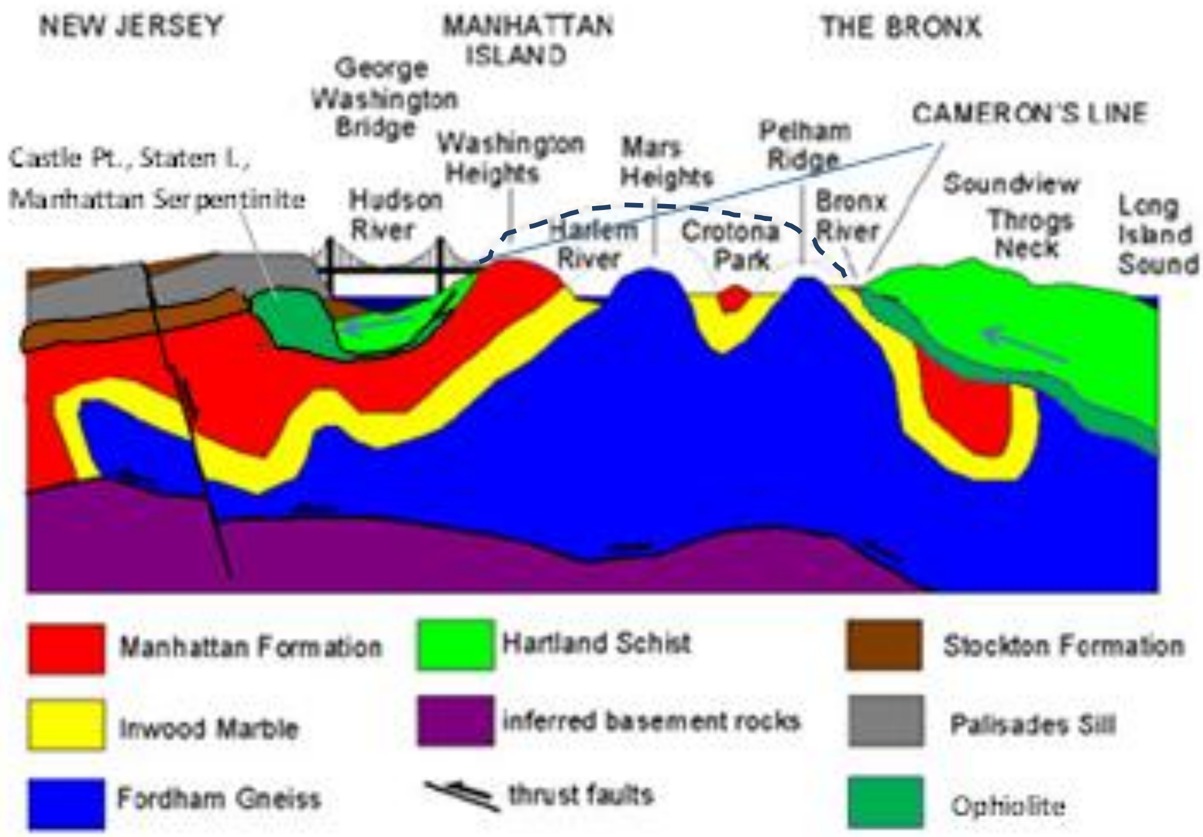


Figure 7. Cross Section through New York City modified from Schuberth (1968) with the addition of an ophiolite unit representing the Castle Point, Staten Island and Manhattan Serpentinites. Erosion of the anticlinal portion of the Hartland Schist and the Ophiolite located over Mars Heights has exposed the early Paleozoic schist and marble stratigraphically below.

An ophiolite unit consistent with Figure 6 has, therefore, been added to the Schuberth (1968) cross-section where it is represented by Castle Point, Staten Island, and Manhattan Serpentinites. Much more complicated Taconic interpretations of New York City geology have recently been proposed in the literature but are not tenable unless they are consistent with: 1. A direct correlation of Inwood, and Manhattan Formations with

Kittatinny and Martinsburg sediments based on complete overlap of chemical compositions and an obvious stratigraphic sequence (Puffer et al., 2010), and 2. Tethyan ophiolite emplacement along Camerons Line over a metamorphic sole during the Taconic Orogeny. Any alternative scenario may be possible but is much less probable.

Acadian Orogeny

The seaward dipping ramp depicted in Figures 2, 4, 5 and 6 is an essential prerequisite for Tethyan ophiolite emplacement but is only one of many possible subduction configurations. Wakabayashi and Dilek (2003) recognize both seaward and contra-seaward sloping configurations. However almost all of several depictions of Avalonian drift (Figure 8) are contra-seaward with ocean crust sloping away from the leading edge of the Avalonia, including the model proposed by Cook et al. (1979) as modified by Puffer (2003). The Acadian Orogeny, therefore, emplaced a subduction zone under what later became the thickened center of Pangaea, under New Jersey, and under most Eastern North American occurrences of Mesozoic flood basalt. Heat accumulation (incubation) of sub-continental lithospheric mantle (SCLM) over this entrapped subduction zone began during the Acadian Orogeny and is likely to have been a major factor in flood basalt magma development about 150 Ma later during the end of the Jurassic. This idea (Puffer, 2003) will be described later in this chapter in “the Break-up of Pangaea” section.

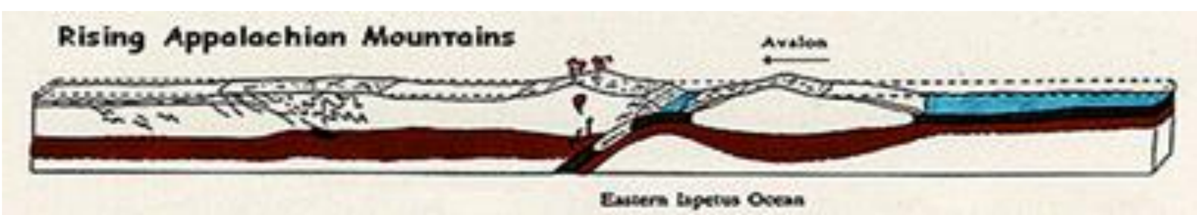


Figure 8. Generic model of the collision of Avalonia and Proto North America (see New York State Education Department, New York State Museum, and New York State Geology Survey web sites (www.nysm.nysed.gov/nysgs/nygeology/tectonic). Note the emplacement of a subduction zone under eastern Laurentia.

Figure 9. Paleographic view from "Earth history" by Blakey (cpgeosystems.com) depicting drift of Baltica and Avalonia toward Laurentia about 430 Ma.

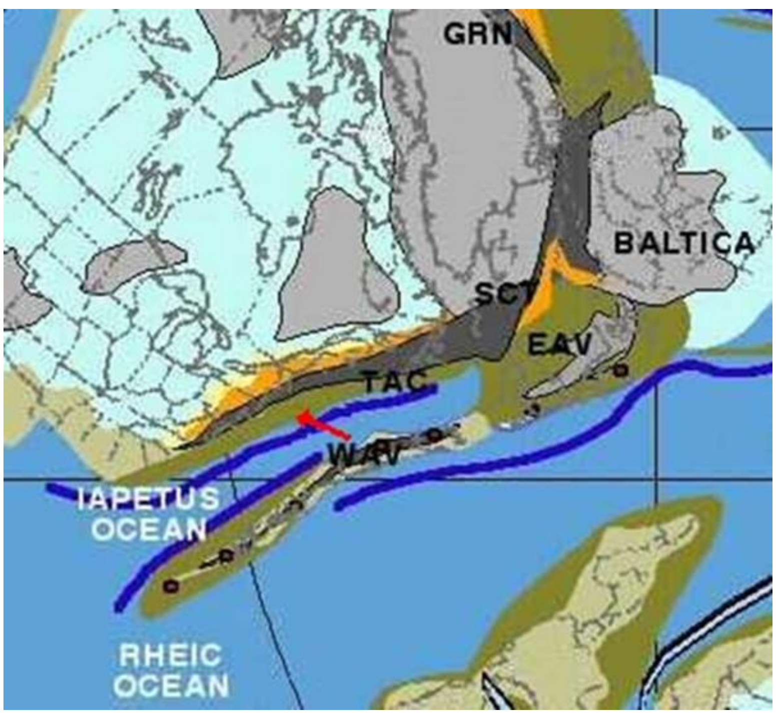


Figure 10. Collision of the Taconic Island arc (TAC) with Laurentia occurred about 470 to 450 Ma. Then about 430 Ma the western and eastern portions of a discontinuous Avalonian terraine and Baltica approached Laurentia in back of a closing Iapetus Ocean as depicted here. Pangea had to await the closure of the Rheic Ocean when Gondwanda joined Laurentia. After Blakey (cpgeosystems.com).

The deep bedrock of eastern Long Island is probably part of Avalonia and the metamorphic influence of Avalonian accretion affected Manhattan area rocks. Figures 9 and 10 depicts the accretion of both the Taconic volcanic arc during the Taconic Orogeny and Avalonia during the Acadian Orogeny. The Accretion of Avalonia during the Acadian Orogeny finally closed the Iapetus Ocean although the final closure of the Rheic Ocean (Fig. 10) had to await the assembly of Pangea when the proto African portion of Gondwanda joined eastern Laurentia during the late Mississippian and the early Alleghanian Orogeny about 320 Ma.

The Break-up of Pangaea

Pangaea remained intact as a supercontinent from about 320 Ma during the late Mississippian until some-time in the Jurassic with the opening of the Atlantic Ocean. But before the Atlantic could open, an extensional tectonic system had to become established. Two competing theories dominate the geologic literature: 1. Active theories typically involving a rising mantle superplume that arched central Pangaea and broke it into continents that slid away from the geoid high to relatively cool geoid lows. 2. Passive theories including a thickened central Pangean continental plate that trapped heat generated beneath it for at least 120 million years until a similar thermally driven geoid high was established. Decompression of the sub-continental-lithospheric mantle (SCLM) under incipient normal faults through central Pangaea forced a drop in the melting point of the SCLM and near eutectic melting of the first magmas of the Central Atlantic Magmatic Province. This passive SCLM source idea for eastern North American members of what would later be called CAMP was first proposed by Puffer (1989) and then Pegram (1990). Later Anderson (1994) developed passive models that would apply as a general theory for continental flood basalt generation that were first specifically applied to eastern North American CAMP basalts by Puffer (1997, 1999, 2001, 2003) and Puffer and Benimoff, (2013), and Benimoff and Puffer (2013). Currently the passive CAMP idea is gaining support in the geologic literature, particularly Merle (in press) at the expense of plume theory although the debate is far from settled.

New York City and Northern New Jersey are located where central Pangaea first underwent rifting, Newark Basin sedimentation, and finally intrusion and extrusion of the first CAMP basalts. CAMP was one of the largest if not the largest of all large igneous provinces (LIPs) on Earth (Fig. 11) and coincides with one of the most extensive mass extinctions on Earth for obvious reasons (Blackburn et al 2013). This places our location at a historically very important place.

Before the extent of CAMP (Figure 11) was published by McHone (2000) and further defined by Marzoli et al., 1999) CAMP was not widely regarded as an important

LIP or anything more than loose collection of independent igneous events. It wasn't until ENA correlations made by Puffer (1984a,b, 1992, 1993, 1994), Puffer et al. (1981, 1996), Puffer and Lechler (1980), Puffer and Philpotts (1988), Olsen et al (2003), DeBoer et al (1988), McHone and Puffer (1996 and 2003); and the first trans-Atlantic correlations by Manspeizer and Puffer (1974a,b, 1976, and 2000), and Manspeizer et al. 1976 and 1989) and then Bertrand et al., (1982) that an early Jurassic Pangean LIP started to become taken seriously. It is now clear (Figure 11) that CAMP basalts covered large portions of Europe, Africa, South America, and North America and emitted enough toxic gas to force one of the most extensive mass extinctions on record (Blackburn et al, 2013).

I have taken part in the debate pertaining to the origin of CAMP throughout the last 40 years since my first involvement with correlations of New Jersey basalts with Moroccan basalts made with Manspeizer in 1973 and still have a few CAMP projects in progress with Jeff Steiner, Karin Block, Alan Benimoff, Renaud Merle, Andrea Marzoli, and Greg McHone. Therefore, this might not be my last GANJ contribution.

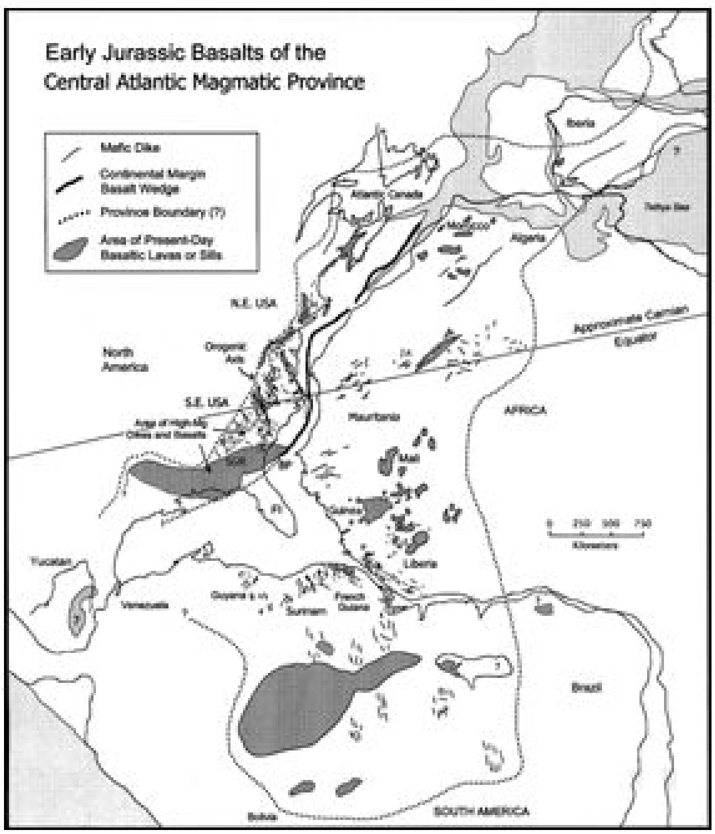


Figure 11. Map of CAMP by McHone (2000).

What follows is a brief summary of what I have learned during the last 40 years that focuses on the origin of CAMP. The following list is a revision of a paper published earlier this year (Puffer and Bemimoff, 2013) and demonstrates the growing strength of arguments in support of a passive non-plume CAMP source over competing plume source models.

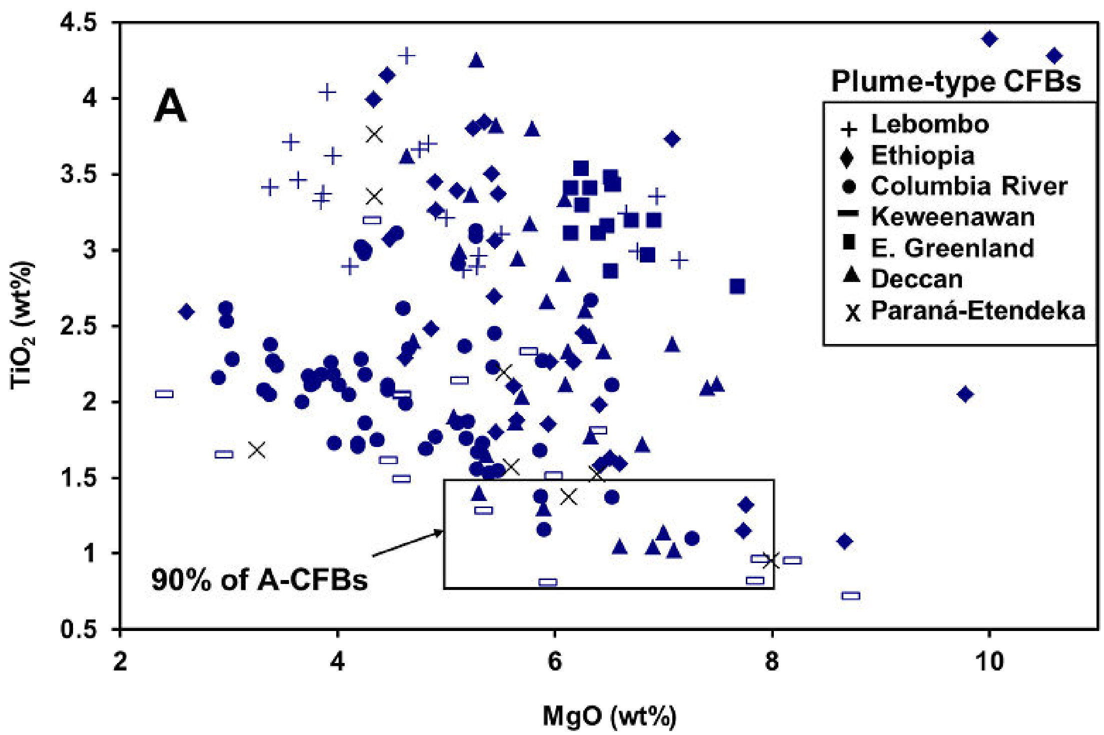
1. Size and shape of the CAMP – CAMP does not include some of the key features of most generally accepted plume generated igneous systems such as a hot-spot track. There are subtle ways of hiding such a track under post-plume deposition or eroding away evidence but there is currently no clear consensus of a CAMP track that we are aware of. This feature is shared by the Siberian LIP that is another candidate for a non-plume origin.

2. Plume generated uplift - Czamanske (1998) argues that the absence of evidence that the Siberian traps were preceded by the topographic uplift expected of a rising plume head is a good reason to reject the application of the plume model. At first glance the CAMP seems to have been preceded by subsidence instead of uplift. However, sediment filled grabens underlying LIPs are interpreted by Hill (1991) and Rainbird and Ernst (2001) as evidence of arching and uplift over a rising mantle plume. They found that plume induced uplift typically results in erosion producing an unconformity together with block faulting and deposition of fluvial sandstones directly underlying flood basalts and show that the effects of uplift typically occur tens of millions of years before magmatism. Each of these plume characteristics applies to the tectonic setting of CAMP. Alternatively, non-plume regional thermal uplift of continental plates is predicted by Anderson (1994) as the result of the accumulation of heat beneath an insulating lithosphere. Erosion and crustal thinning over the resulting geoid high precedes continental break-up and drifting toward relatively cool geoid lows according to King and Anderson (1995).

3. Radiating dyke pattern – Plume-head magmatism is typically intruded though the crust as a network of dykes that radiate away from the center of the plume head (May 1971; Ernst and Buchan, 1997; Hill, 1991; Rainbird and Ernst, 2001). This radiating pattern was used by Wilson (1997) as strong evidence for the occurrence of a superplume under CAMP. However, McHone (2000) argued that CAMP dykes intruded as a series of linear dyke populations intruded as a progressive sequence of distinct dyke trends and compositional types, not as a single magmatic event. More recently Beutela et al. (2005) proposed a rapidly rotating stress field model controlled by movement of North America away from Africa and South America. They proposed that the orientations of the three major Eastern North American CAMP dyke populations (NW, NS, and NE-trending) were controlled by either of two scenarios: 1) The NW dykes are related to the onset of decompression melting in the rift zone between North America and Africa and that the NS and NE dykes were intruded later according to the re-orientation of the rift zones they were associated with. 2) The dyke orientations reflect a changing stress field during the final

stages of rifting between North America and Africa complicated by the initiation of South America's motion. In either case radiation away from a plume center was not the controlling factor.

4. Chemical homogeneity - Despite the huge areal extent of CAMP the initial and most widespread volcanism is remarkably homogenous. Compositional variations due to hydrothermal contamination and alteration as seen in basal zones (Puffer and Laskowich, 2012, Puffer et al 2013) ; post eruptive in-situ fractionation within flow cores (Puffer and Horter, 1993; Puffer and Volkert, 2001); fusion of country rock (Benimoff and Puffer, 2005); complex post intrusive fractionation of CAMP intrusions (Block, 2005; Block, 2013, Steiner et al. 1992); and entrainment of source zone material and accreted pre-eruptive cumulus (a cumulus-transport-deposition CTD model), (Steiner et al. 1992, Steiner et al., 2013a and Steiner et al. 2013b) can be considerable. However, if post eruptive influences and local processes are filtered from the data, the composition of the main ITi CAMP magma type is constrained within a very narrow range on a province – wide basis (Fig. 12b). In contrast, plume generated LIPs are chemically diverse (Fig. 12a) and are characterized by chemical trends, in time and space, away from a central plume head.



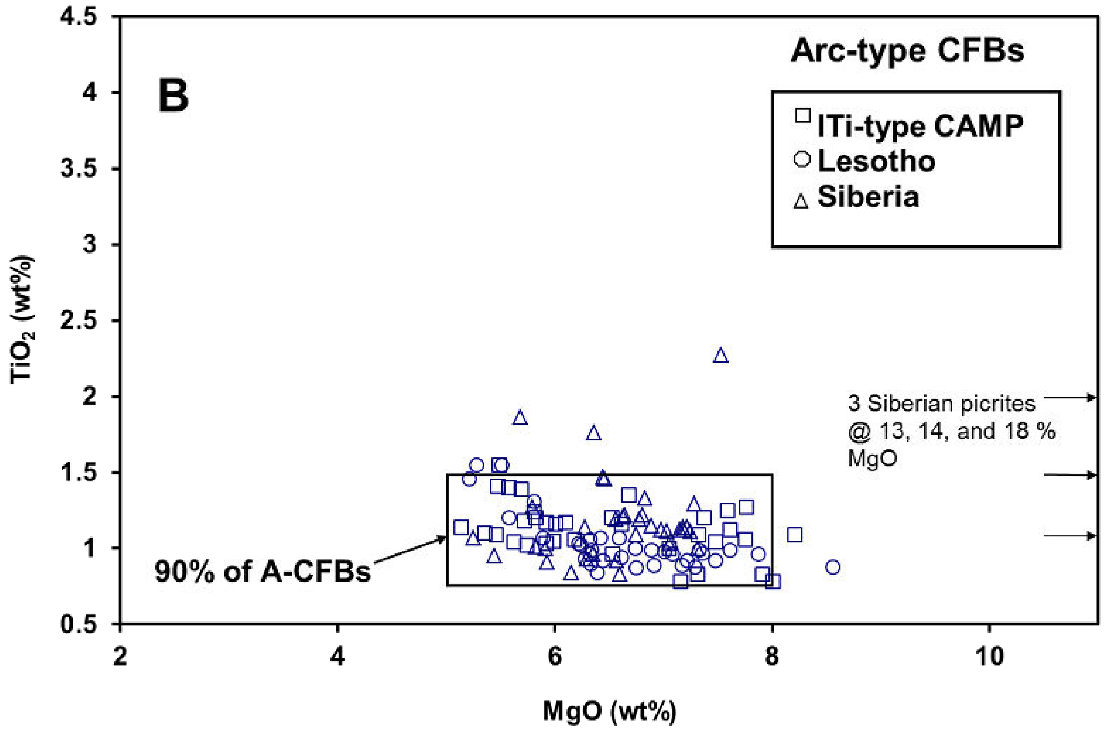


Figure 12. TiO2/MgO content of continental flood basalts after Puffer (2001) from A: probable plume generated provinces and B. provinces that contain a major subduction component and geochemically resemble arc magmatism.

It is also meaningful that CAMP is devoid of the ultramafic and ultra-alkalic rock types that are an integral part of most plume generated LIPs. Superplume LIPs in particular include a variety of such rock types as, for example, the Ontong Java Plateau (Tatsumi et al., 1998). The high temperatures and high degrees of melting required for such magma genesis are consistent with the plume model but are not available to passive processes. Instead restricted composition ranges consistent with near eutectic melting are a characteristic of CAMP.

5. Chemical composition - Plume generated LIPs are characterized by a distinctive geochemical signature that is easily distinguished from MORB or ARC magma. There may be considerable variation within plume systems, depending on size or distance from the plume head. However, in general plume generated LIPs plot on spider diagrams close to the OIB standard of Sun and McDonough (1989) that is generally accepted as typical hot-spot track ocean island basalt. Exceptions are commonly interpreted as having been mixed with varying amounts of lithosphere (Lightfoot et al. 1990, 93). Among several LIPs, mostly CFBs, average CAMP basalt shows the most deviation from OIB (Fig. 13). In

particular, the strong negative Nb anomaly is generally recognized as evidence of a major lithospheric or subduction component. High degrees of mixing are not common among CFBs but are also characteristics of Siberian and Lesotho CFBs. However, the CAMP plot, including its negative Nb anomaly, more closely resembles typical island arc (Arc) as represented by typical andesite from the Andes Mountains (Hickey et al., 1986) than OIB. This degree of lithospheric mixing is not predicted by the classic plume model but is consistent with some passive models. This association is true of the entire CAMP province, not just local portions, and must be an integral part of any genetic model.

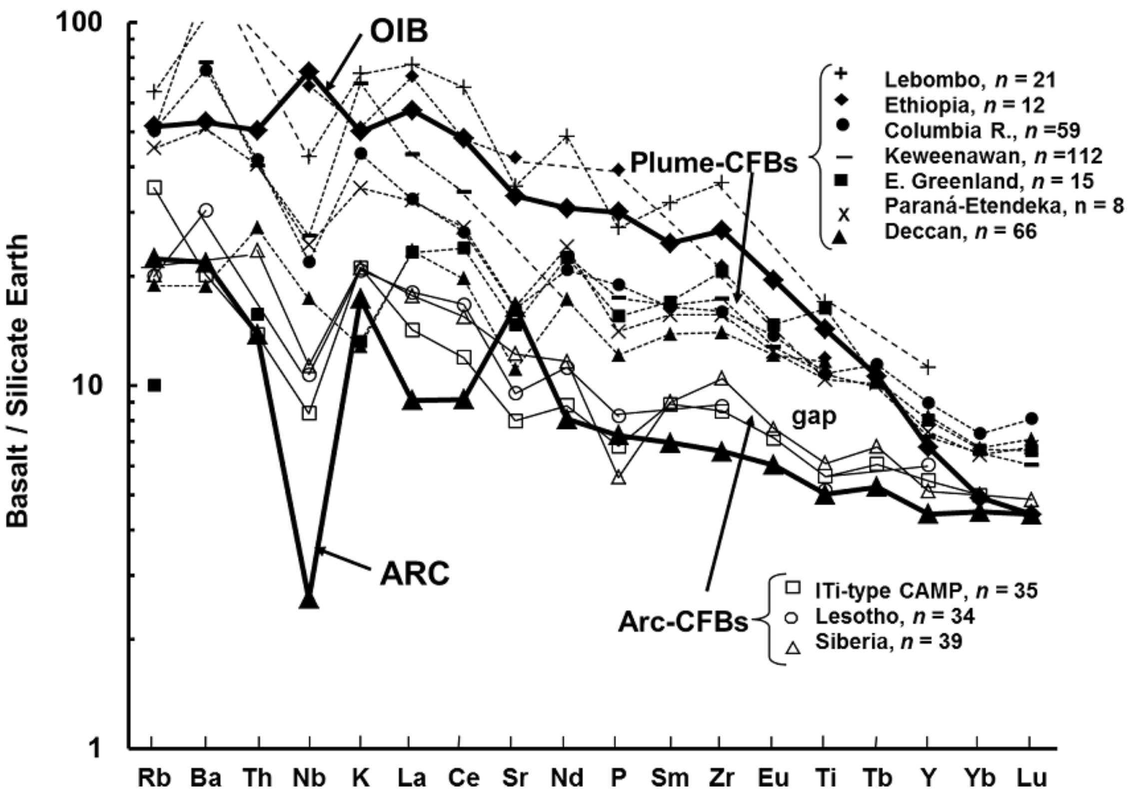


Figure 13. Sun and McDonough (1989) spider diagrams of Plume-type and Arc-type CFBs after Puffer (2001). See Puffer (2001) for sources of data. Note that ITi-CAMP more closely resembles Arc magma than any other province.

6. Mineralogical evidence - Recent evidence of subduction enrichment of CAMP is provided by mineralogical analyses. Dorais and Tubrett (2008) analyzed Cr-rich pyroxenes from ITi (HTQ) CAMP tholeiites and calculated corresponding equilibrium magma compositions with subduction enriched characteristics. They interpreted optical and LA-

ICP-MS analyses of strongly zoned CPX grains as indicating that the cores are early phenocrysts not xenocrysts and were able to calculate equilibrium liquid compositions of the most primitive melt or parental magma. They found that this liquid shows incompatible element enrichment similar to Arc basalt, strongly indicating a subduction zone component in the mantle source. Their conclusions support the Puffer (2003) proposal that the parental CAMP magma bears the signature of a dormant arc mantle source trapped beneath the Pangean suture.

7. Depth of melting - As summarized by Salters et al. (2003) plume models predict that as plume heads impinge on the base of the lithosphere the initial average depth of melting is relatively deep but decreases as the degree of melting increases. They showed, however, that the initial and widespread ITi-type CAMP magma was derived from shallower depths than subsequent LTi-type) CAMP magma. Evidence that the ITi population was intruded before the largely NE trending and olivine normative LTi population includes both cross-cutting field relationships (Ragland, 1991; Ragland et al. 1983; Beutel et al. 2005) and new radiometric evidence (Blackburn et al., 2013).

Salters et al. (2003) use La/Nb and Sr-Nd isotopic data to estimate the lithosphere/asthenospheric component in the magma after Garland et al (1996). Plume derived CFB such as the Parana show a high lithospheric content (high La/Nb) in the early stages then an increasing asthenospheric (plume) component (low La/Nb) at later stages (Garland et al, 1996) consistent with a decreasing depth of melting with time as the lithosphere is removed from the rift zone. However in the case of CAMP the data indicate just the opposite with La/Nb increasing from 8.61/6.90 in the ITi to 4.86/2.17 in the LTi. They also referred to the work of Kelemen and Holbrook (1995) who calibrated seismic velocities as a function of pressure, temperature (depth and degree of melting), and composition particularly silica and magnesium content. The data for CAMP indicate a progressive increase in the average depth of melting, directly inconsistent with a rising plume, but consistent with a passive (non-plume) break-up of Pangea.

8. Temperature of melting - Herzberg and Gazel (2009) calculated mantle potential temperatures for several LIPs including CAMP and found most melted at > 1500 ^{o}C consistent with the melting region of mantle plume heads (Fig. 14). However, CAMP was an exception and melted at < 1500^{o}C. New calculations by Benimoff and Puffer (2013) using PRIMEMELT2 (Herzberg and Asimow, 2008) yield mantle potential temperatures for the mean ITi and LTi primary magma compositions (Salters et al. 2003) of 1394 ° C and 1449° C, respectively. These temperatures are lower than the melting region of the mantle plume model.

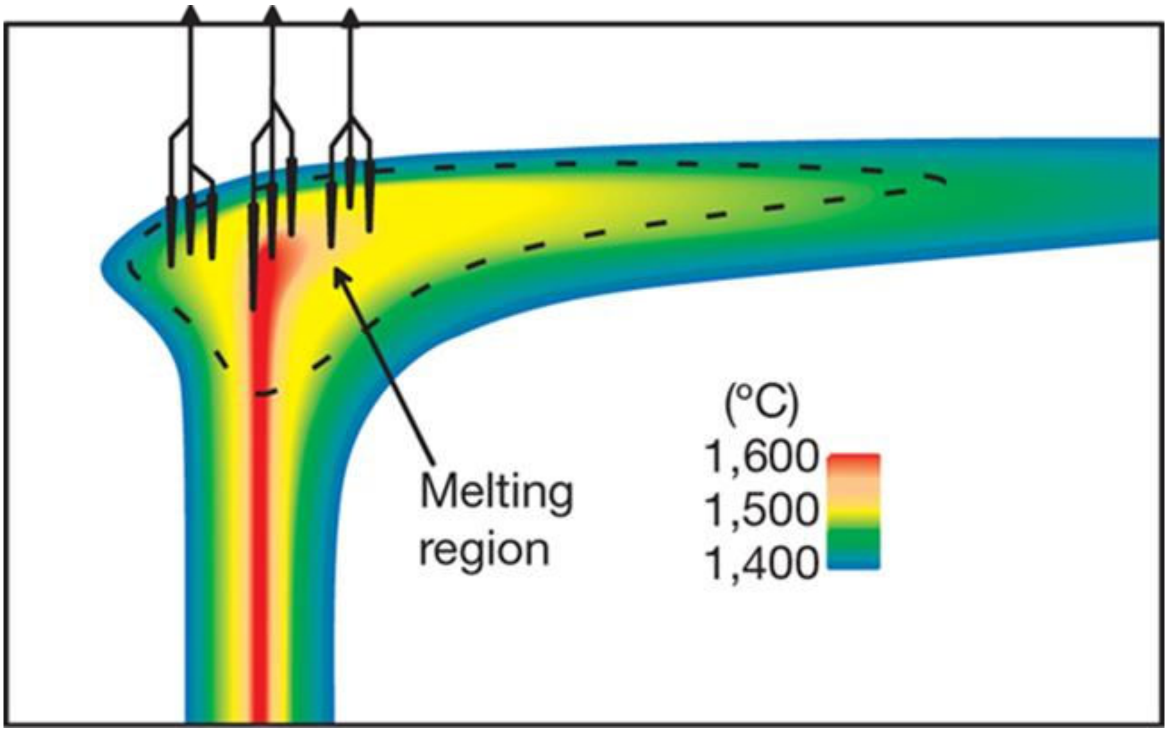


Figure 14. after Herzberg and Gazel (2009): the plume model in which hot primary magmas originate from the axis and cooler magmas originate from the periphery. The model provides an interpretation of primary magmas with highly variable compositions, inferred mantle potential temperatures and melt fractions.

9. Isotopic evidence – The Sr, Nd and Pb isotopic data of Pegram (1990) and the Sr and Nd isotopic data of Puffer (1992) were interpreted by both authors as evidence of eastern North American (CAMP) magma derivation from a subcontinental lithospheric mantle source that was enriched in a subduction component. However, important forthcoming evidence utilizing a very impressive array of new Sr, Nd, Pb, and Os isotopic data has been gathered by Merle et al. (in press) and strongly supports an enriched SCLM source similar to the model proposed by Puffer (2003) that will be discussed in the next and last section of this paper.

10. Brief magmatic duration – The brief duration of the main phase of CAMP magmatism (Marzoli et al., 2011) is consistent with sudden decompression melting triggered by the initial rifting of Pangaea. If the source of CAMP magma was reactivation of approximately the same source responsible for the underlying Paleozoic basaltic andesites (Puffer, 2003) a limited supply of water and other fluxes would have been available. Paleozoic

subduction and arc magmatism during the assembly of Pangaea would have stopped as soon as Pangaea was assembled. The source of metasomatic fluxing and enrichment of the sub-continental lithospheric mantle source of CAMP would have been limited to the portion of the subducting lithospheric slab that had not already undergone Paleozoic dehydration and would have constrained the duration of CAMP magmatism.

Proposed CAMP Source

CAMP magmatism was preceded and stratigraphically overlaps arc magmatism and was extruded out of rifts located close to convergent Paleozoic sutures. Figure 16 is a slightly modified version of a general model proposed by Anderson (1994).

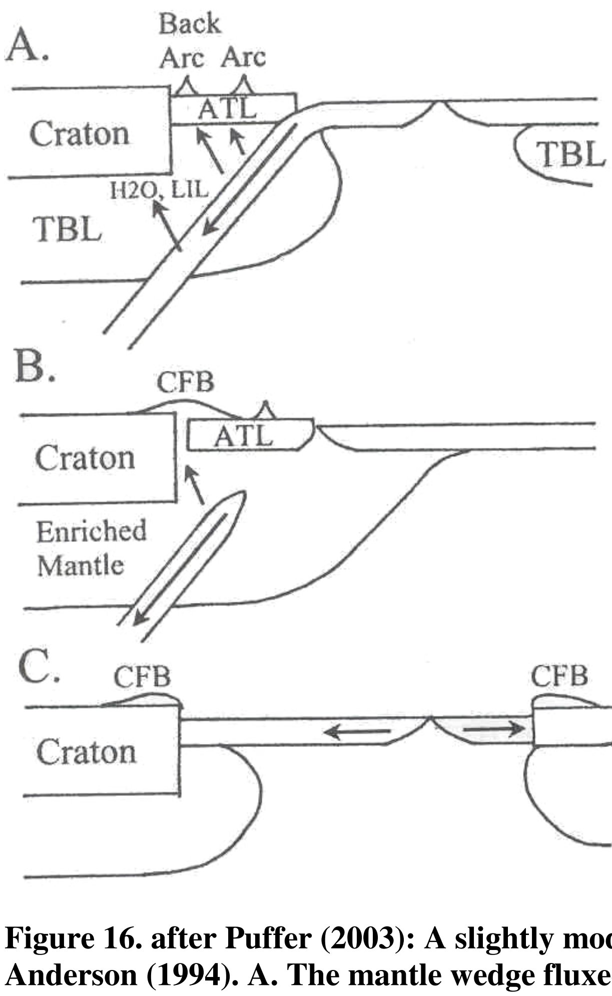


Figure 16. after Puffer (2003): A slightly modified version of a model proposed by Anderson (1994). A. The mantle wedge fluxed and enriched during subduction produces typical Arc and back arc magma. B. When the tectonic setting changes from compression to extension CFB forms as a result of plate pull-apart of the accreted terrain layer (ATL) and lithospheric delamination. C. Resumption of MORB.

Figure 15 includes three essential processes. Figure 17A. - The mantle wedge is fluxed by water and becomes enriched in LILs and generates typical Arc and Back Arc magmas but only a fraction of the available LILs ends up in the volcanics. Figure 17B. - As the tectonic setting changes from compressional to extensional, continental flood basalts (CFB) form as a result of decompression melting and plate pull-apart of an accreted terrain layer (ATL), similar to the "edge-driven" model of King and Anderson (1998). Figure 17C. During seafloor spreading the shallow enriched mantle is displaced and normal depleted basalts (MORB) replace enriched CFBs.

The essential aspects of an edge-driven model involving a delamination process (Elkens-Tanton, 2005) are consistent with the facts on the ground as represented by Figure 7. A cross section through eastern North America was illustrated by Cook et al (1979) with volcanic activity added by Puffer (2003). The sequence of igneous events pertaining to the CAMP magma source begins in the early Paleozoic (Fig. 17) A. The Ammonoosuc – Piedmont Arc is developed over a subducting plate during the early Paleozoic. B. The Ammonoosuc and Piedmont are accreted onto Laurentia while a second Gondwandaland arc (Avalonia) began to migrate toward Laurentia. C. more arc-derived basalts, including the Newbury and Leighton basaltic andesites are extruded during Silurian (Acadian) accretion and subduction of an oceanic plate below the Piedmont. D. Detachment and sinking of a dense subduction slab displaces undepleted asthenosphere into a zone of enrichment above the undetached portion of the oceanic plate; a Back Arc/CFB source comparable to Fig. 16A., B. The depth of melting of enriched mantle increases as the detached slab delaminates and creates topographic subsidence. Increasing temperatures and higher degrees of partial melting are consistent with the conclusions of Salters et al. (2003). As soon as the limited supply of water and other fluxes are depleted CAMP magmatism is terminated accounting for the brief duration of CAMP.

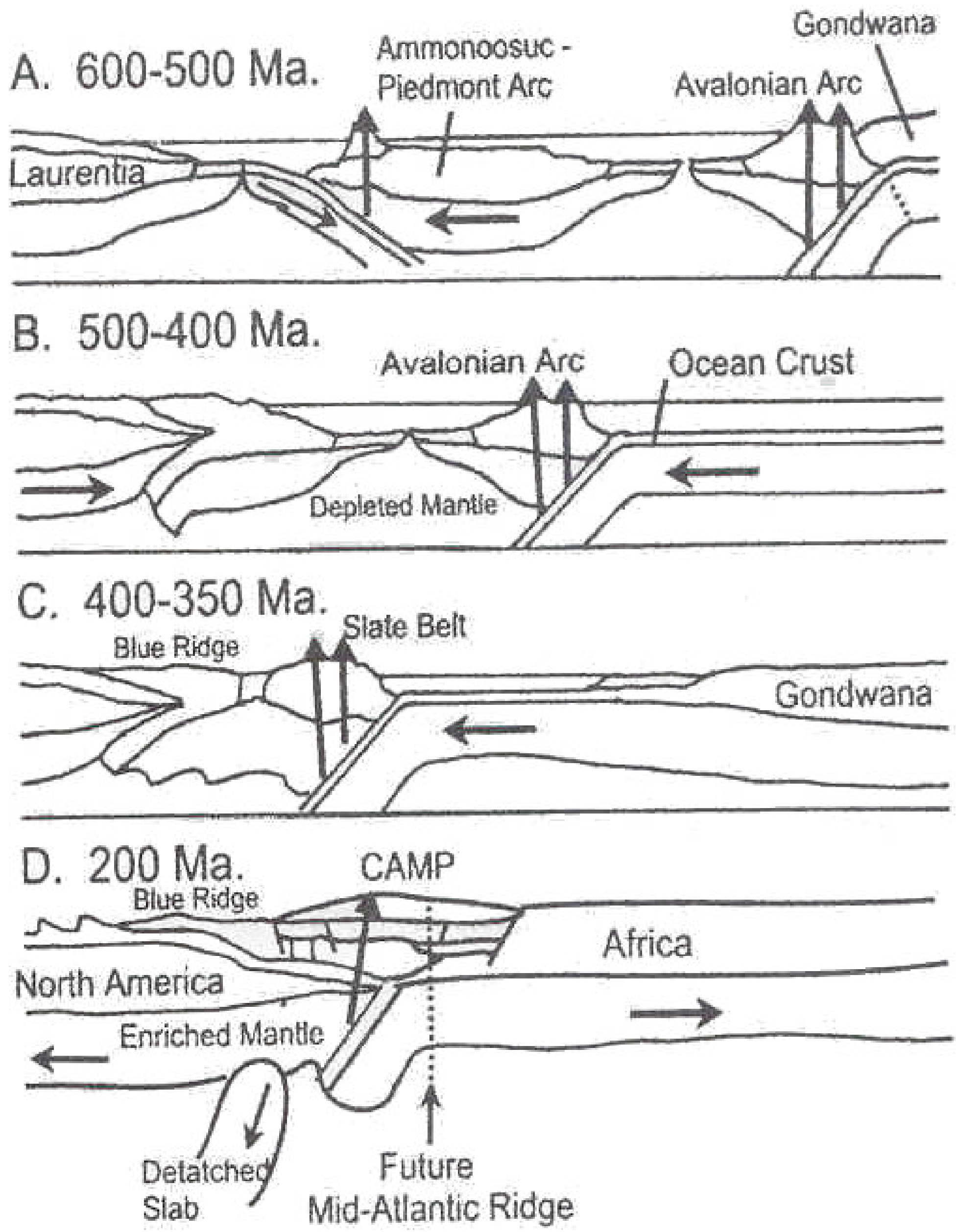


Figure 17. after Puffer (2003): A modified version of a tectonic synthesis by Cook et al (1979). A. Subduction during the early Paleozoic, B. Accretion of island arcs, C. Arc magmatism including the Newbury and Leighton Formations during accretion and subduction below the Piedmont. D. Detachment and sinking of a dense slab displacing undepleted asthenosphere into a zone of enrichment above the undetached portion of the oceanic plate. CAMP magma melts until the limited supply of flux is exhausted and penetrates through Paleozoic allochthons and through Triassic rift basins.

It is important to note that the source of the Acadian Arc volcanics and the early CAMP are virtually the same (Fig. 18) thus explaining their remarkable similarity in chemical composition to ITi-type CAMP (Fig. 18). The Paleozoic arc volcanics of Fig. 18 include the Ammonoosuc Formation (Leo, 1985 and Schumacher,1988), the Partridge Formation (Hollocher, 1993), and the Leighton Formation (Gates and Moench, 1981).

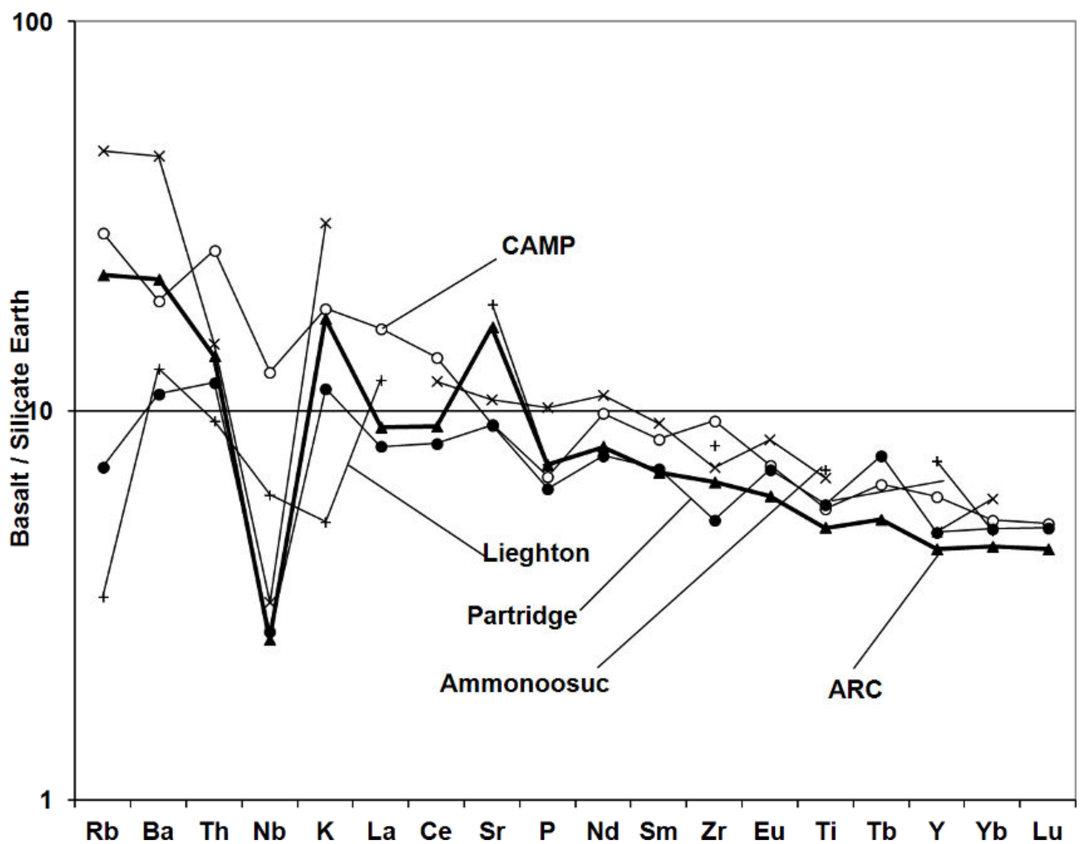


Figure 18. after Puffer (2003). Sun and McDonough (1989) spider diagrams of Paleozoic arc volcanics (Lieghton, Partridge, and Ammonoosuc) stratigraphically beneath CAMP that closely resemble both CAMP and standard Arc magmas; and may share similar source rocks. See Puffer (2003) for sources of data.

A plume, therefore, is not needed as a source of melt nor is it needed as a heat source any more than it is needed to generate MORB. After about 150 million years of thermal insulation the thick Pangean continental plate may have trapped enough heat (as described by Coltice et al., 2009) within the sub-continental lithosphere to approach solidus temperatures. If so, all that would be needed to trigger melting would be tectonic extension away from the thermally uplifted geoid center of Pangea. Gravity is the only force that could have pulled the continents apart and decompression could have triggered CAMP melting until the enriched SCLM fluxes at the magma source were depleted. CAMP was the beginning of the extensional tectonics and associated decompression melting that continues today as MORB.

References Cited

Anderson, D. L., 1994, The sublithospheric mantle as a source of continental flood basalts: The case against the continental lithosphere and plume head reservoirs. Earth Plan. Sci. Let. 123:269-280.

Benimoff, A.I, and Puffer, J.H., 2013, Mantle Potential Temperature Trend for the Central Atlantic Magmatic Province, abstract, Goldschmidt Conference, Florence Italy, Mineralogical Magazine 77(5) p. 686.

Benimoff, A.I. and Puffer, J. H., 2000, Syenitic and trondhjemitic fusion at Mesozoic diabase intrusion contacts with sedimentary rocks of northern New Jersey and Staten Island: Field-trip Guidebook, 35th Annual Meeting of the Northeastern Section, Geological Society of America, New Brunswick, New Jersey, 46 pp.

Benimoff, A.I., Puffer, J.H., 2005. Tri-modal fusion of meta-argillites along margins of early jurassic diabase intrusions, New Jersey and New York. Northeastern Geology and Environmental Science 27, 265-275.

Bertrand, H. Dostal, J. and C. Dupuy, C. 1982, Geochemistry of early Mesozoic tholeiites from Morocco. Earth and Planetary Science Letters, v. 58. P. 225-239.

Beutel, E.K., Nomade, S.; Fronabarger, A.K., and Renne, P.R., 2005, Pangea's complex breakup: A new rapidly changing stress field model. Earth and Planetary Science Letters, v. 236, p. 417-485.

Blakey, R. C., 2008, Gondwana paleogeography from assembly to breakup - a 500 million year odyssey, in Fielding, Christopher R., Frank, Tracy D., and Isbell, John L. (eds), Resolving the Late Paleozoic Ice Age in Time and Space: Geological Society of America, Special Paper 441, p. 1-28.

Blackburn, T.J., Olsen, P., Bowring S.A., Mclean, N., Kent, D., Puffer, J.H., McHone, G., Rasbury, T., and El-Touhami, M., 2013. Zircon U-Pb Geochronology Links the End-

Triassic Extinction with the Central Atlantic Magmatic Province. Science. v. 340, p. 941-945. With supplementary materials pp. 1-15, references, and tables.

Block, K.A., 2006. A Refined Multiple Injections Model for the Palisades Sill, New York and New Jersey, Earth and Environmental Sciences. City University of New York, New York.

Block, K.A., Steiner, J., Puffer, J.H., and Steiner, N., 2013, Unraviling the complex textural heredity of melanogranophyres in the Palisades Sill, NY and NJ: GSA Northeastern Section Meeting, Bretton Woods, New Hampshire, Abstracts with Programs, v. 45, Number 1, p. 127

Cadmus, D.; Hodgson, R.; Gatto, L. M.; and Puffer, J. H., 1996, Geochemical Traverse across Cameron's Line, Boro Hall Park, Bronx, New York, in Hanson, G.N., (editor), Geology of Long Island and Metropolitan New York, Long Island Geologists, SUNY Stony Brook, p. 26-32.

Coffin, M.F. and Eldholm, O., 1992, Volcanism and continental break-up: a global compilation of large igneous provinces. In: B.C. Storey, T. Alabaster and R.J. Pankhurst (Editors), Magmatism and the Causes of Continental Breakup. Special Publication of the Geological Society of London, London, pp. 17-30.

Coltice, N. Bertrand, H. Rey, P. Jourdan, F. Philipps, B.R., and Ricard, Y., 2009, Global warming of the mantle beneath continents back to the Archean. Gondwana Research 15, 254-266.

Cook, J.K., Albaugh, D.S., Brown, L.D., Kaufman, S., Oliver, J.K., and Hatcher, R.D., 1979, Thin-skinned tectonics in the crystalline southern Appalachians, COCORP seismic-reflection profiling of the Blue Ridge and Piedmont. Geology, 7: 563-567.

Czamanske, G.K., Gurevitch, V., Fedorenko, V., and Simonov, O., 1998, Demise of the Siberian plume: palaeogeographic and palaeotectonic reconstruction from the prevolcanic and volcanic record, north-central Siberia. International Geology Review, 40: 95-115.

DeBoer, J. Z.; McHone, J. G.; Puffer, J. H.; Ragland, P. C.; and Whittington, D., l988, Mesozoic and Cenozoic magmatism: in Sheridan, R. E., and Grow, J. A., (editors), The Geology of North America, v. 1-2, The Atlantic Continental Margin, U.S.A: Geological Society of America, p. 217-241.

Deckart, K., Bertrand. H., and Liegeois, J.P., 2005, Geochemistry and Sr, Nd, Pb isotopic composition of the Central Atlantic Magmatic Province (CAMP) in Guyana and Guinea. Lithos, 82: 289-314.

De Min. A., Piccirilio, E.M., Marzoli, A., Bellieni, G., Renne, P.R., Ernesto, M., and Marques, L., 2003, The Central Atlantic Magmatic Province (CAMP) in Brazil: Petrology, Geochemistry, 40Ar/39Ar ages, paleomagnetism and geodynamic implications. In Hames, W.E., McHone, J.G., Renne, P.R., and Ruppel, C. (editors), The Central Atlantic Magmatic Province: Insights from fragments of Pangea, AGU Geophysical Monograph 136: 209-226.

Dorais, M.J., and Tubrett, M., 2008, Identification of a subduction zone component in the Higganum dyke, Central Atlantic Magma Province: A LA-ICPMS study of clinopyroxene with implications for flood basalt petrogenesis. Geochem. Geophysics Geosystems, 9, Q10005, 13 pp. doi:10.1029/2008GC002079.

Elkins-Tanton, L.T., 2005, Continental magmatism caused by lithospheric delamination. In: G.R. Foulger, J.H. Natland, D.C. Presnall and D.L. Anderson (Editors), Plates, Plumes and Paradigms. Special Paper. Geological Society of America, Boulder, Colorado, pp. 449-461.

Ernst, R.E., and Buchan, K.L., 1997, Giant radiating dyke swarms; their use in identifying pre-Mesozoic large igneous provinces and mantle plume, in: Mahoney, J.J., and Coffin, M.F., (Eds.) Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism, Geophysical Monograph, v. 100, pp. 297-333.

Garland, F.E., Turner, S.P., and Hawkesworth, C.J., 1996, Shifts in the source of Parana basalts through time, Lithos 37: 223-243.

Gates, O., and Moench, R.H., 1981, Bimodal Silurian and Lower Devonian volcanic rock assemblage in the Machias-Eastport area, Maine, U.S. Geological Survey Prof. Paper 1184, 32 pp.

GEOROC, Geochemistry of Rocks of the Oceans and Continents. Max Planck Institute for Chemistry, Mainz, Germany. Georoc.mpch-mainz.gwdg.de

Herzberg, C., and Asimow, P.D., 2008, Petrology of some oceanic island basalts: PRIMELT2.XLSsoftware for primary magma calculation. Geochem. Geophys. Geosyst. 9, doi:10.1029/2008GC002057.

Herzberg, C., and Gazel, E., 2009, Petrological evidence for secular cooling in mantle plumes. Nature 458:619-622.

Hickey, R.L., Frey, F.A., and Gerlach, D.C., 1986, Multiple sources for basaltic arc rocks from the southern zone of the Andes: trace element and isotopic evidence for contributions form subducted oceanic crust, mantle, and continental crust. J. Geophy. Res., 91:5963-5983.

Hill, R.I., 1991, Starting plumes and continental break-up. Earth and Planetary Science Letters, v. 104, p. 398-416.

Hollocher, K., 1993, Geochemistry and origin of volcanics in the Ordovician Partridge Formation, Bronson Hill Anticlinorium, West-central Massachusetts, Amer. J. Sci., 293:671-721.

Kelemen, P.B., and Holbrook, W.S., 1995, Origin of thick, high velocity igneous crust along the US East Coast Margin, J. of Geophysical Research, 100:10,077-10,094.

King, S.D., and Anderson, D.L., 1995, An alternative mechanism of flood basalt formation. Earth and Planetary Science Letters, 136: 269-279.

King, S.D., and Anderson, D.L., 1998, Edge-driven convection. Earth and Planetary Science Letters, 160: 289-296.

Leo, R.W., 1985, Trondhjemite and metamorphosed quartz keratophyre tuff of the Ammonoosuc Volcanics (Ordovician), western New Hampshire and adjacent Vermont and Massachusetts, Geol. Soc. Amer. Bull., 96:1493-1507.

Lawver, L.A., and Müller, R.D., 1994, Iceland hotspot track. Geology, 22: 311-314.

Li, Z. X.; Bogdanova, S. V.; Collins, A. S.; Davidson, A.; B. De Waele, R. E. Ernst, I. C. W. Fitzsimons, R. A. Fuck, D. P. Gladkochub, J. Jacobs, K. E. Karlstrom, S. Lul, L.M. Natapov, V. Pease, S. A. Pisarevsky, K. Thrane and V. Vernikovsky, 2008, "Assembly, configuration, and break-up history of Rodinia: A synthesis". Precambrian Research 160: 179–210.

Lightfoot, P.C. et al., 1993, Remobilization of the continental lithosphere by a mantle plume: major-, trace-element, and Sr-, Nd-, and Pb-isotopic evidence from picritic and tholeiitic lavas of the Noril'sk District, Siberian Trap, Russia. Contributions to Mineralogy and Petrology, 114: 171-188.

Lightfoot, P.C., Naldrett, A.J., Gorbachev, N.S., Doherty, W., and Fedorenko, V.A., 1990, Geochemistry of the Siberian Traps of the Noril'sk area, USSR, with implications for the relative contributions of crust and mantle to flood basalt magmatism. Contrib. Mineral. Petrol., 104: 631-644.

Little and Epstein, 1987, Geologic Map of the Newark $1^o x 2^o$ Quadrangle New Jersey, Pennsylvania, and New York. Miscellaneous Investigations Series, 1-1715, Dept. of the Interior, U.S. Geological Survey.

Manspeizer, W.; DeBoer, J. Z; Costain, J. K.; Froelich, A. J.; Coruh, C.; Olsen, P. E.; McHone, J. G.; Puffer, J. H.; and Powell, D., l989, Post-Paleozoic activity through the Appalachians: in Hatcher, R. D., Jr.; W.; Thomas, W. A. and Viele, G. (editors), The Appalachian/Ouachita Orogen in the United States: Geological Society of America, The Geology of North America v. F-2, p. 319-374.

Manspeizer, W.; Puffer, J. H.; and Cousminer, J. H., l976, The separation of Morocco and Eastern Northern America: A Triassic-Jurassic stratigraphic record: Geological Society of America Bulletin, v. 80, p. 901-920.

Manspeizer, W. and Puffer, J. H., 2000, Oldest Atlantic MORB extrusion records early ridge event on the passive margin of Morocco: Geological Society of America, Northeastern Section, New Brunswick, New Jersey, v. 31, p. A-57.

Manspeizer, W., and Puffer, J. H., l976, Subduction rifting and sea floor spreading: A volcanic record in Morocco and Eastern North America: Geological Society of America, Abstracts with Program, Northeastern and Southeastern Sections, Arlington, Virginia, v. 8, p. 224-225.

Manspeizer, W., and Puffer, J. H., l974a, Basalt geochemistry: Sea-Floor spreading, North Africa and North America: EOS, Transactions, American Geophysical Union, v. 55, No. 4, p. 460.

Manspeizer, W., and Puffer, J. H., l974b, Triassic Basalts: Morocco and North America: Geological Society of America, Abstracts with Program, Northeastern Section, Baltimore, Maryland, v. 6, p. 50.

Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesto, M., Bellieni, G., and De Min, A. 1999, Extensive 200 million-year-old continental flood basalts of the central Atlantic magmatic province. Science 284: 616-618.

Marzoli, A., Jourdan F., Puffer J.H., Cupone, T., Tanner L. H., Weems, R.E., Bertrand H., Cirilli, S., Bellieni G., and De Min A., 2011, Timing and duration of the Central Atlantic magmatic province in the Newark and Culpeper basins, eastern U.S.A. , Lithos, v. 122, p. 175-188.

May, P.R., 1971, Pattern of Triassic-Jurassic diabase dikes around the North Atlantic in context of predrift position of the continents. Geological Society of America Bulletin, v. 82, p. 1285-1292.

McHone, J. G., 2000, Non-plume magmatism and tectonics during the opening of the central Atlantic Ocean. Tectonophysics, 316:287-296.

McHone, J.G., and Puffer, J.H., 2003, Flood basalt provinces of the Pangean Atlantic Rift: Regional extent and environmental significance: in LeTourneau, P. M. and Olsen, P. E., (editors), The Great Rift Valleys of Pangea in Eastern North America, Volume 1, Tectonics, Structure, and Volcanism: New York, Columbia University Press, Chapter 10. p. 141-154.

McHone, J.G. and Puffer, J.H., l996, Hettangian Flood Basalts across the Initial Pangaean Rift: in LeTorneau, P.M. and Olsen, P.E. (editors), Aspects of Triassic-Jurassic Rift Basin Geoscience Abstracts: Dinosaur State Park, Rocky Hill CT, State Geological and Natural History Survey of Connecticut Miscellaneous Reports 1., p. 29.

Merguerian, C., 1983, The significance of Cameron's Line in the vicinity of the Hodges Complex – An imbricate thrust model for Western Connecticut. American Journal of Science, v. 283, p. 341-368.

Merle, R., Marzoli, A., Reisberg, L., Bertrand, H., Nemchin, A., ChiaradiaM., Callegaro, S., JourdanF., Bellieni, G., Kontak D., Puffer J., and McHone G. (in press) Geochemical stratigraphy related to mantle source variations of CAMP tholeiites from Eastern North America (ENA) basins: Sr, Nd, Pb and Os isotope systematics.

Olsen, P. E., Kent, D. V., Et-Touhami, M., and Puffer, J. H., 2003, Cyclo- magneto- and bio-stratigraphic constraints on the duration of the CAMP event and its relationship to the Triassic-Jurassic boundary: in Hames, W. E., McHome, J. G., Renne, P. R. and Ruppel, C. (editors) The Central Atlantic Magmatic Province: Insights From Fragments of Pangea: American Geophysical Union Geophysical Monograph 136, p. 7-32.

Pegram, W. J., 1990, Development of continental lithospheric mantle as reflected in the chemistry of the Mesozoic Appalachian tholeiites. U.S.A. Earth Plan. Sci. Lett. 97:316-331.

Plank and Schenck, 1998, in "Delaware Piedmont Geology" Delaware Geologic Survey.

Puffer, J. H., l984a, Early Jurassic eastern North American tholeiites: in Puffer J. H. (editor) Igneous Rocks of the Newark Basin: Petrology, Mineralogy, Ore Deposits, and

Guide to Field Trip: Geological Association of New Jersey, 1st Annual Field Conference, p. 1-15.

Puffer, J. H., l984b, Relationships among ENA tholeiites: in Puffer J. H. (editor) Igneous Rocks of the Newark Basin: Petrology, Mineralogy, Ore Deposits, and Guide to Field Trip: Geological Association of New Jersey, 1st Annual Field Conference, p. 16-44.

Puffer, J. H., l987, The Palisades Sill and Watchung Basalt flows, northern New Jersey: in Roy, D. C., (editor) Geological Society of America Centennial Field Guide - Northeastern Section, p. 91-96.

Puffer, J. H., l992, Eastern North American flood basalts in the context of the incipient breakup of Pangea: in Puffer, J. H., and Ragland, P. C., (editors) Eastern North American Mesozoic Magmatism: Geological Society of America, Special Paper 268, p. 95-119.

Puffer, J. H., l993, Early Jurassic Basalts of the Algarve Basin, Portugal: Carboniferous to Jurassic Pangea, Canadian Society of Petroleum Geologists, Program and Abstracts, Calgary, Canada, p. 254.

Puffer, J. H., l994, Initial and secondary Pangean Basalts: in Beauchamp, B; Embry, A.F.; and Glass, D., (editors), Pangea: Global Environments and Resources: Canadian Society of Petroleum Geologists, Memoir 17, p. 85-95.

Puffer, J.H., l996, Serpentinites of New York City and vicinity: in Benimoff, A.I. and Ohan, A.A., (editors), Field Trip Guide for the 68th Annual Meeting, New York State Geological Association, The College of Staten Island/CUNY, Staten Island, NY, p. 1-52.

Puffer, J.H., l997, High-Field-Strength Element Content of Continental Flood Basalts as a Basis for Determining Magma Source: Geological Society of America, Northeastern Section, King of Prussia, Penn., v. 29.

Puffer, J.H., l999, Tectonic Controls on the Geochemistry of Continental Flood Basalts: EOS, Transactions, American Geophysical Union, Spring Meeting, Boston, Mass., v. 80, No. 17, April 27, 1999 Supplement, p. S-317.

Puffer, J.H., 2001, Contrasting HFSE contents of plume sourced and reactivated arc-sourced continental flood basalts. Geology, v. 29, p. 675-678.

Puffer, J. H., 2002, A late Neoproterozoic, Eastern Laurentian superplume: location, size, chemical composition, and environmental impact. American Journal of Science, v. 302, p. 1-27.

Puffer, J. H., 2003, A reactivated back-arc source for CAMP Magma: in Hames, W. E., McHone, J. G., Renne, P. R., and Ruppel, C. (editors) The Central Atlantic Magmatic Province: Insights From Fragments of Pangea: American Geophysical Union Geophysical Monograph 136, p. 151-162.

Puffer, J. H.; Ageitos, D. M.; Buehler, S. C.; Eicher, J. C.; Kaplan, C. H.; and Seeber, F. C., l994, Geochemistry of the schists of Central Park, New York City: in Hanson, G.N., (editor), Geology of Long Island and Metropolitan New York, Long Island Geologists, SUNY Stony Brook, New York, p 86-92.

Puffer, J.H., and Benimoff, A., 2013, The CAMP Magma Source, LIP of the Month, (R.E. Ernst, editor), Large Igneous Provinces Commission, International Association of Volcanology and Chemistry of the Earth's Interior. Largeigneousprovinces.org.

Puffer, J.H., Benimoff, A.I., and Steiner, J.C., 2010, Geochemical Characterization of New York City Schist Formations., New York State Geological Association, 82nd Annual Meeting, Field Trip Guidebook, p. 163-182.

Puffer, J. H., Block, K.A., and Steiner, J.C., 2009, Transmission of flood basalts through a shallow crustal sill and the correlation of sill layers with extrusive flows: The Palisades Intrusive System and the basalts of the Newark Basin, New Jersey, USA, The Journal of Geology, v. 17, p. 139-155.

Puffer, J. H., DiPlacido, A., Hurtubise, E., and Leavy, B. D., l981. Chemical composition of the igneous flow units of the Culpeper Basin, Virginia: Geological Society of America, Abstracts with Program, Southeastern Section, Hattiesburg, Mississippi, v. 13, p. 33.

Puffer, J. H., and Germine, M., l994, The Staten Island Meta-Peridotite: in Benimoff, A.I., (editor), Geology of Staten Island, New York, Field Guide and Proceedings, Geological Association of New Jersey, p. 1-25.

Puffer, J. H. and Horter, D. L., l993, Origin of pegmatitic segregation veins within flood basalt: Geological Society of America Bulletin, v. 105, no. 6, p. 738-748.

Puffer, J. H., Hurtubise, D. O., Geiger, F. J., and Lechler, P. l981, Chemical composition and stratigraphic correlation of Mesozoic basalt units of the Newark Basin, New Jersey and the Hartford Basin, Connecticut: Geological Society of America Bulletin, v. 92, part 1, p. 155-159, part 11, p. 515-553.

Puffer, J. H., and Hush, J., l996, Early Jurassic diabase sheets and basalt flows, Newark Basin, New Jersey: An updated geological summary and field guide: in Benimoff, A.I. and Ohan, A.A., (editors), Field Trip Guide for the 68th Annual Meeting, New York State

Geological Association, The College of Staten Island/CUNY, Staten Island, NY, p. 157-176.

Puffer, J.H., and Laskowich, C., 2012, Volcanic diapirs in the Orange Mountain flood basalt: New Jersey, USA. Journal of Volcanology and Geothermal Research, v. 237-238, p. 1-9.

Puffer, J. H., and Lechler, P. l980, Geochemical cross-sections through the Watchung Basalts of New Jersey: Geological Society of America Bulletin, v. 91, part 1, p. 7-10, part 11, p. 156-191.

Puffer, J. H., Pestana, E. M., and Theokritoff, G., l983, Geochemical characteristics of rift related volcanic rocks in the Appalachian Orogen: Geological Society of America, Abstracts with Program, Northeastern Section, Kiamesha Lake, New York, v. 15, No. 3, p. 184.

Puffer, J. H., and Philpotts, A. R., l988, Eastern North American quartz tholeiites: geochemistry and petrology, in Manspeizer, W. (editor) Triassic-Jurassic Rifting, Continental Breakup and the Origin of the Atlantic Ocean, Developments in Geotectonics, v. 22, Elsevier Scientific Publishers, Amsterdam, p. 579-606.

Puffer J.H., and Volkert, R. A., 2001, Pegmatoid and gabbroid layers in Jurassic Preakness and Hook Mountain Basalts, Newark Basin, New Jersey: The Journal of Geology, v. 109, p. 585-601.

Ragland, P.C., 1991, Mesozoic igneous rocks, In Horton, J.W., and Zullo, V.A. (Eds.). The Geology of the Carolinas. Carolina Geological Society Fifteenth Anniversary Volume, p. 171-190.

Ragland, P.C., Hatcher, R.D., and Whittington, D., 1983, Juxtaposed Mesozoic diabase dike sets from the Carolinas; a preliminary assessment. Geology 11:394-399.

Rogers, J.J.W., 1996, A history the Continents in the past 3 billion years. The Journal of Geology, v. 104, p. 91-107.

Roser, B.P. and Korsch, R.J., 1986, Determination of tectonic setting of sandstone-mudstone suites using content and ratio. The Journal of Geology, v. 94, p. 635-650.

Rowley, D.B., and Kidd, W.S.F., 1981, Stratigraphic relationships and detrital composition of the Medial Ordovician flysch of western New England: Implications for the tectonic evolution of the Taconic …The Journal of Geology, v. 89, p. 199-218.

Salters, V. J., Ragland, P., Hames, W., Milla, and K., Ruppel, C., 2003, Temporal chemical variations within lowermost Jurassic tholeiitic magmas of the Central Atlantic Magmatic Province, in The Central Atlantic Magmatic Province: Insights From Fragments of Pangea, Geophys. Monogr. Ser., vol. 136, edited by W. Hames et al., pp. 163–177, AGU, Washington, D. C., doi:10.1029/136GM09.

Schuberth, C.J., 1968, The Geology of New York City and Environs. American Museum of Natural History, Natural History Press, 304 pp.

Schumacher, J.C, 1988. Stratigraphy and geochemistry of the Ammonoosuc Volcanics, central Massachusetts and southwestern New Hampshire. American Journal of Science, 288, 619-663.

Scotese, C.R. "Rodinia". Paleomap Project, Scotese.com

Sears, J.W.and Price, R.A. (2000). "New look at the Siberian connection: No SWEAT". Geology 28 (5): 423–426.

Steiner, J.C., Walker, R.J., Warner, R.D., Olson, T.R., 1992. A cumulus-transport-deposition model for the differentiation of the Palisades sill. Geological Society of America Special Paper 268, 193-217.

Steiner, J.C., Block, K.A., Steiner, N.C., Puffer, J.H., and Sviridov, L., 2013a, Unraveling Pangaea Flood Basalts from the botton up: The Orange Mountain Basalt mixed lava. Geological Association of New Jersey Proceedings Volume (this guidebook).

Steiner, J., Sviridov, L., Puffer, J.H., Block, K.A., and Steiner, N., 2013b, The Orange Mountain Flow, New Jersey: A stratigraphically zoned decompressed-melt composite basalt: GSA Northeastern Section Meeting, Bretton Woods, New Hampshire, Abstracts with Programs, v. 45, Number 1, p. 127.

Sun, S., and McDonough, W.F., 1989, Chemical and isotopic systematic of oceanic basalts, Implications for mantle composition and processes. In Magmatism in the Ocean Basins, edited by Saunders, A.D. and Narry, M.J., Geological Society Special Publication 42:313-345.

Tatsumi, Y., Shinjoe, H., Ishizuka, H., Sager, W. W., and Klaus A., 1998, Geochemical evidence for a mid-Cretaceous superplume. Geology. 26:151-154.

Wakabayashi, J. and Dilek, Y., 2003, What constitutes 'emplacement' of an ophiolite?" Mechanisms and relationship to subduction initiation and formation of metamorphic soles.

In DILEK, Y. & ROBINSON P. T. (eds) Ophiolites in Earth History. Geological Society, London, Special Publications, v. 218; p. 427-447

Weigand, P.W., and Ragland, P.C., 1970, Geochemistry of Mesozoic dolerite dikes form eastern North America, Contrib. to Min. Pet, 29:195-214.

Wilson, M., 1997, Thermal evolution of the central Atlantic passive margins: continental break-up above a Mesozoic super-plume. J. Geol. Soc. London 154:491–495.

THE MANHATTAN NEW YORK SERPENTINITE SUITE, MINERALOGY, GEOCHEMISTRY, AND PETROGENESIS

Mark Germine and John H. Puffer

Dept. of Earth & Environmental Sciences, Rutgers University, Newark, New Jersey 07102

Abstract

A rare sample of Manhattan Serpentinite from the Kung collection of the American Museum on Natural History in New York City was analyzed chemically, mineralogically, and petrographically at Rutgers University. Mineralogical analysis indicates the sample is composed of lizardite serpentine, anthophyllite, chlorite, actinolite, calcite, olivine, and magnetite. Pseudomorphous replacement of most of the original olivine by lizardite has the typical core and band structure of a serpentinized peridotite. Chemical analysis indicates a high Cr and Ni content consistent with a meta-peridotite protolith interpretation. High MnO and CaO suggest hydrothermal alteration.

Similar serpentinites typically occur as ophiolites and are abducted into plate sutures. Our data supports Brock and Brock's (2001) placement of the Cameron's Line plate suture between the Manhattan Schist and the Hartland Formation along the Hudson River through the Staten Island, Castle Point, and Manhattan serpentinite occurrences.

Introduction

An occurrence of serpentinite located in Manhattan (the Manhattan Serpentinite, Figure 1) was first described by Gale (1842) as exposed along Tenth Avenue from 59^{th} Street north to 63^{rd} Street. The serpentinite is currently buried under urban infrastructure and large buildings typical of mid-town Manhattan, but according to Gale (1843) it "… occupied several conical hills and was of variable character." The Manhattan occurrence was previously known as "radiated asbestos rock" until an acquaintance of Gail by the name of Dr. Torrey sent a sample "… to Prof. Thomson of Glasgow, who analyzed it and pronounced it anthophyllite; but as it contained a much larger proportion of water than had usually been found in this mineral. Dr. Torrey proposed to prefix the term hydrous anthophyllite, which has been generally adopted." (Gale,1843).

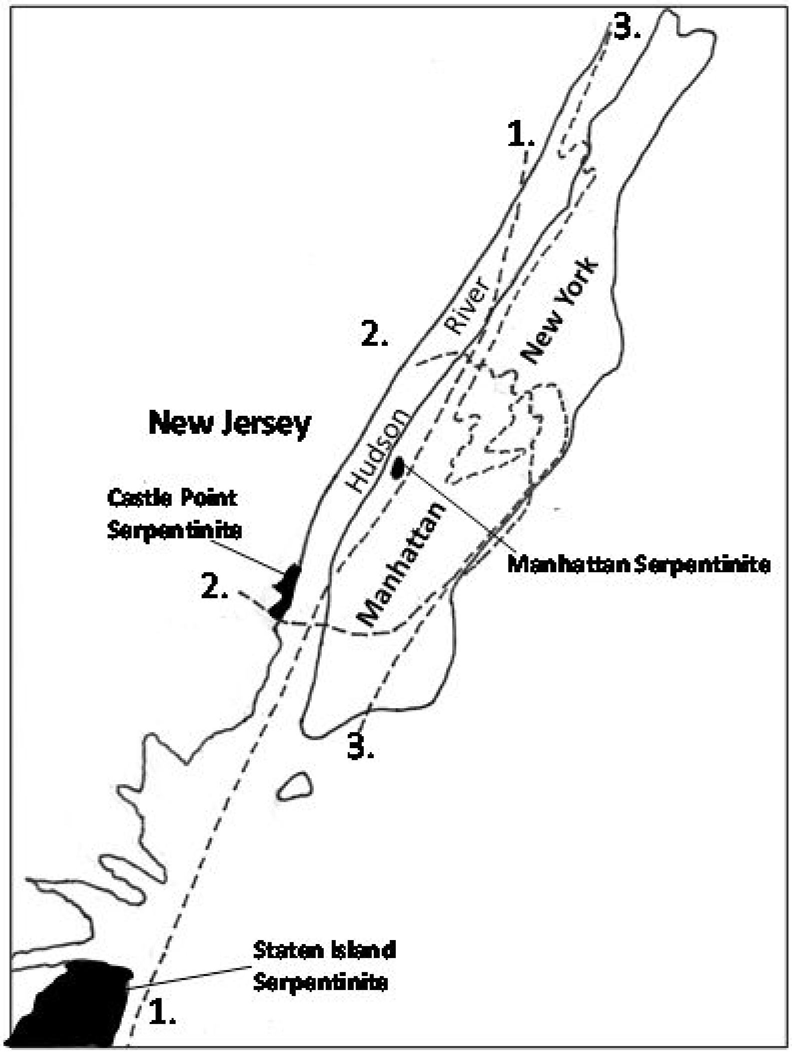


Figure 1: Map of the Manhattan, New York area including the location of serpentinite occurrences and the position of the Manhattan Schist - Hartland terrain suture (Cameron's Line) according to 1. Brock and Brock (2001), 2. Baskerville (1994), and 3. Merguerian and Merguerian (2004).

The first map of The Manhattan Serpentinite was published by Julien (1903, Figure 2a). The serpentinite appears on his map as a northeast trending lens that grades northward into a north trending chlorite schist, which combine to consist of a lens about 0.4 km long and 0.15 km wide. It is intersected by 58th street between Tenth and Eleventh Ave. Manhattan, New York. It also appears on a detailed 1:24,000 geologic map of Manhattan by Baskerville (1994) as a lens shaped body 0.6 km long and 0.5 km wide. The Manhattan Serpentinite can be subdivided into a western suite dominated by serpentine including "talcose, ophicalcit, and chloritic" facies and an eastern suite dominated by anthophylite including "actinolite, tremolite, and talcose" facies (Fig. 2b).

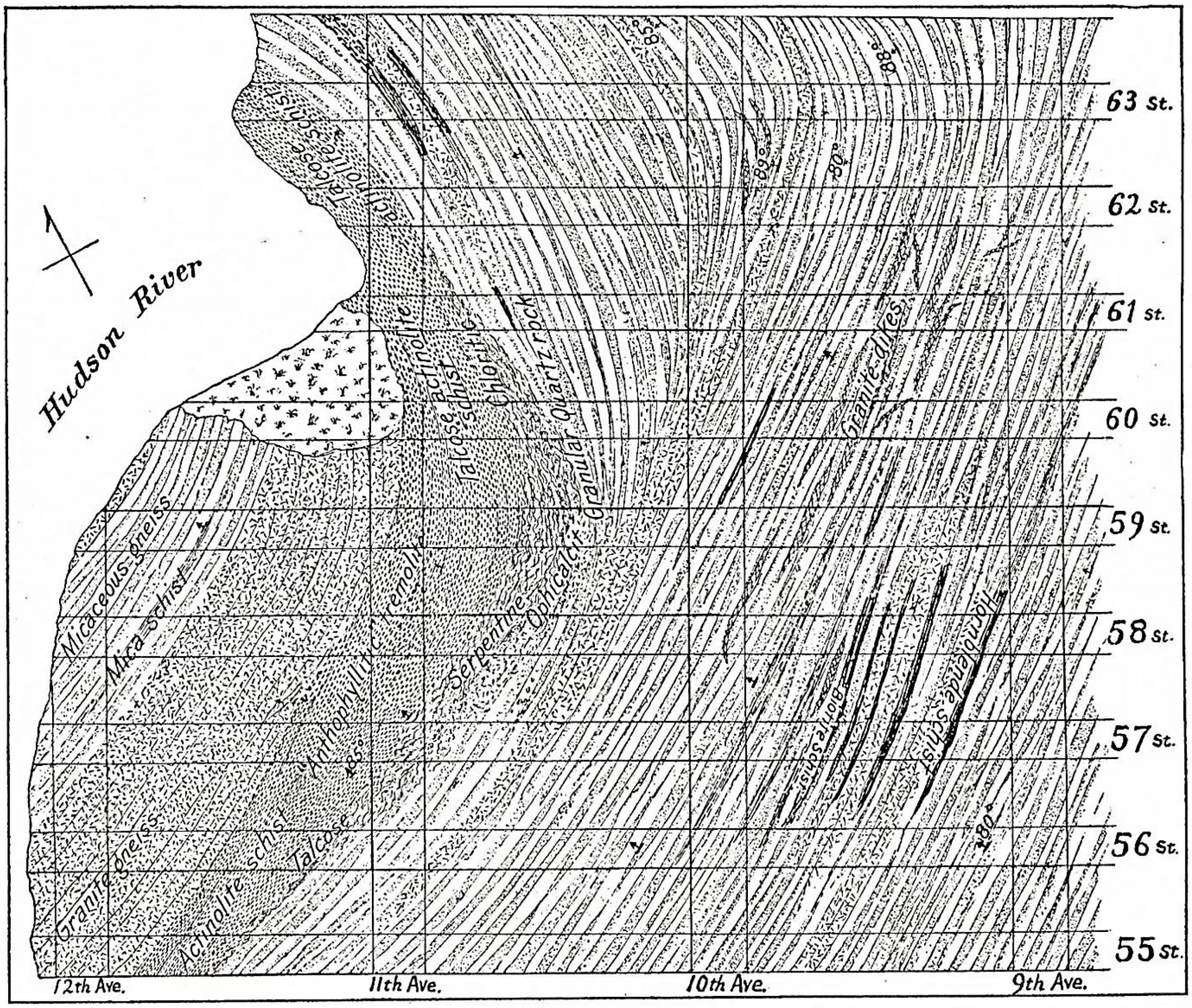


Figure 2a: Map of the region of the Manhattan Serpentinite suite showing lithologies as determined by Julien (1903). Manhattan streets and avenues are labeled by Julien (1903).

Geologic Setting

The bedrock geology of Manhattan, New York is not well constrained. There is a general consensus that Manhattan Island consists largely of Manhattan Schist and Hartland Formation with relatively minor distributions of Inwood Marble, Walloomsac Formation, and Fordham Gneiss.

However, there is no consensus regarding the age of the Manhattan Schist or the Hartland Formation (Puffer et al,

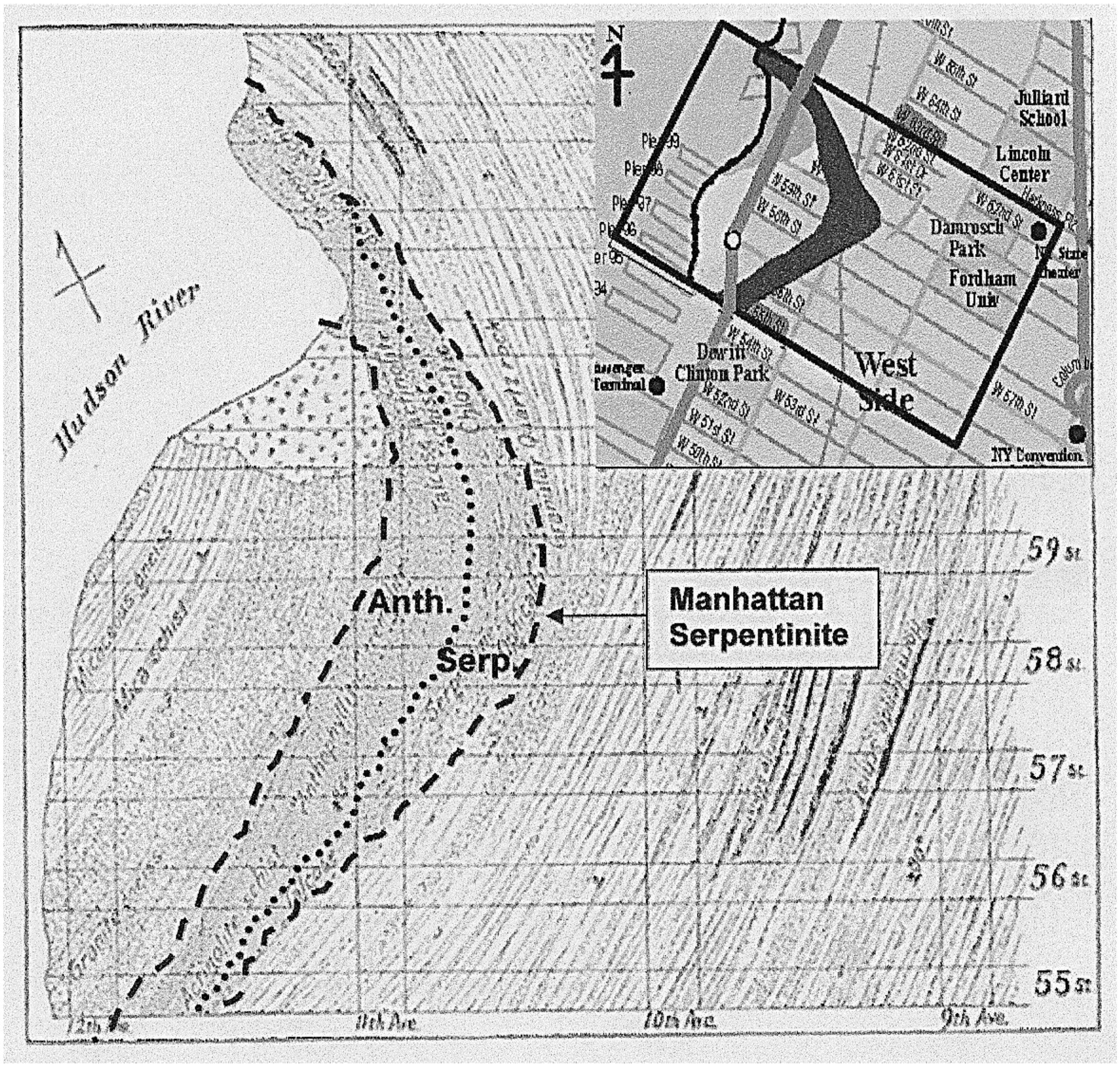


Figure 2b: The map of Julien (1903) subdivided into a suite dominated by serpentine labeled (Serp.) including "talcose serpentine, ophicalcit, and chloritic" facies and a suite dominated by anthophyllite labeled (Anth.) including "anthophyllite, actinolite, tremolite, and talcose" facies. Current street location map insert is added for clarity. The campus of Fordham Univ. is located one block east of the serpentinite.

2009). The Hartland Formation is described by Baskerville (1994), Merguerian and Merguerian (2004) and by Hall (1968,1976, 1980) as Early Cambrian to Middle Ordovician; but is subdivided into "True" Pellam Bay-type Hartland of Middle to late Ordovician age and Bronx Zoo-type Hartland of Late Neoproterozoic age by Brock and Brock (2001). The Manhattan Schist is described by Baskerville (1994) as Early Cambrian; as Cambro/Ordovician by Merguerian and Merguerian (2004) and Hall (1968, 1976, 1980), and as Late Neoproterozoic by Brock and Brock (2001).

There is also a complete lack of consensus regarding the map distribution of the Hartland and Manhattan formations throughout Manhattan. Mapping difficulties are largely due to a complete overlap in the mineralogy and texture of the two formations. Both are mica schists containing overlapping concentrations of accessory minerals such as garnet, amphiboles, and oxides. However, each of several competing maps published since 1950 indicates a Hartland host rock for the Manhattan Serpentinite.

The data that we will present is consistent with an ophiolitic plate suture interpretation in which case the rocks to the east of the Manhattan Serpentinite are most likely Manhattan Schist while the rocks to the west are Hartland Formation.

Materials and Methods

A sample of the Manhattan Serpentinite was obtained from the Kunz collection of the American Museum of Natural History in New York City. The sample was labeled "hydrous anthophyllite." Another sample from labeled "ophicalcite" was also obtained, but, as it appeared to be metasedimentary, was not included in our treatment of the Manhattan Serpentinite, and will only be briefly described here.

The "hydrous anthophyllite" sample was actually serpentinite with some actinolite content. The sample was a dark green hand-sized rock that was fine-grained, of granular texture, with no distinct textural orientation.

Another sample typical of serpentinite from Hoboken, New Jersey was collected at a location west of the Manhattan Serpentinite, on the opposite side of the Hudson River, at the eastern boundary of the Stevens College of Engineering campus. The Hoboken serpentinite body is identical to and presumably part of the Staten Island serpentinite that is generally interpreted as a Taconic metaperidotite (Germine, 1981a,b; Puffer and Germine, 1994). The Hoboken sample serves as a comparator for chemical analysis.

Thin-section analysis was done using a petrographic microscope, or polarized light microscopy (PLM) at magnifications up to 1000X in both plane and cross-polarized light. PLM analysis was also performed on each sample of crushed rock. The sample remaining after thin-sectioning was used for quantitative chemical analysis, x-ray diffraction, and electron microprobe. The sample was too small relative to the grain size for quantitative petrographic analyses of mineral constituents.

For chemical analyses (Table 1), split, powdered samples (100 mg) were dissolved by fusion with LiBO2 (500 mg) in graphite crucibles. Fusion was performed in a muffle furnace (30 minutes at 1050 C^o). Resulting glass beads were dissolved in 2M HNO_3 in teflon beakers and then transferred to 100 ml volumetric flasks diluted with more 2M HNO_3. The sample solutions were analyzed with an inductively coupled plasma atomic emission spectrometer (ICP-AES) at the Rutgers University geochemistry lab in New Brunswick, New Jersey. The spectrometer was calibrated with basalt standard IZ (Rutgers house standard), and with USGS standards PC1 (peridotite), AGV1 (andesite), and G-2 (granite).

A polished thin section of the Manhattan Serpentinite was carbon coated and analyzed with a JEOL 753 microprobe operated using a 15Kv, 20A, ca. 1 micrometer beam, equipped with transmitting light optics, with a 30 second count time and standards described by Germine (1987). Two analyses were done on each of the three most common silicate minerals identified in thin section. The same highly polished section was sampled in an area that was clearly serpentine and imaged by SEM using back scattered electron imaging and analyzed using selected area electron microscopy.

Transmission electron microscopy (TEM) was performed by suspending a ground sample in double distilled water and depositing it onto a copper TEM grid. This analysis was done strictly for content of asbestos.

Results

Thin section analysis showed minerals in the following order of concentration: 1) Serpentine (non-fibrous), 2) anthophyllite (non-fibrous), 3) chlorite, 4) calcite, 5) olivine (highly altered), 6) opaques, mostly small grains of magnetite. Actinolite asbestos was not seen in the thin section but was seen in the crushed rock under PLM and TEM, as we will later discuss. Serpentitine was seen replacing olivine, and appeared granular. There was pseudomorphous replacement of olivine by serpentine which had the typical core and band structure of a serpentinized ultramafic rock, indicating that the serpentinite had formed from an ultramfic rock, most likely a peridotite, as is seen in the Staten Island and Hoboken serpentinites. Relict olivine was too highly altered to determine fosterite/fayalite percentages, but it was likely on the high fosterite end as there was little relict magnetite in the rock. Chlorite was bladed and cut across by serpentine. Calcite appeared as thin veins. Chromite was not detected in thin section or backscattered electron imaging. Chemical analyses by microprobe of serpentine, anthophyllite, and chlorite are shown in Table 2. The microprobe data is completely consistent with our mineralogical identifications based on PLM and SEM observations.

Table 1: Chemical Analyses of Serpentinite and Schist Samples from New York City and Hoboken

Location	Manhattan 58Th Street 10th Ave.	Hoboken Castle Pt.	Manhattan 58Th Street 10th Ave.	Manhattan Central Park Northern	Manhattan Central Park Southern	Staten Island
Sample #	M-1	H-1		average 19	average 20	average 16
Reference*	1	1	2	3	4	4
SiO_2	34.31	35.29	44.43	59.21	59.31	41.36
TiO_2	0.04	0		1.3	1.23	0.01
Al_2O_3	1.98	n.a.		17.51	17.32	0.41
FeOt	6.51	5.09	9.37	7.35	7.42	7.21
MnO	1.38	0.08	1.38	0.11	0.11	0.1
MgO	30.44	40	28.8	3.52	3.54	37.41
CaO	7.92	1.71	5.06	1.44	1.14	0.23
Na_2O	0.06	0.08		1.92	1.57	0.01
K_2O	0.06	0.08		3.97	4.56	0
P_2O_5	0	0.01		0.18	0.19	0
CO_2**	6.22	1.34				
H_2O^+***	10.15	13.33	8.58	3.01	3.16	13.11
Total	99.07	97.01	97.62	99.52	99.55	99.85
Cr (ppm)	808	639		105	121	1479
Ni (ppm)	958	1153		38	47	2419

* 1 = new data; 2 = Newland, 1901; 3= Puffer et al. 1994; 4 = Puffer and Germine, 1994
** Calculated CO_2 assuming all CaO occures as calcium carbonate
*** Calculated H_20 assuming all MgO occures as serpentinite, except for Newland (1901) data

TEM analysis of the ground sample showed that serpentine was lizardite with no chrysotile detected. About 2% of the sample was composed of actinolite asbestos (Figure 3) based on both TEM and PLM examinations of the crushed rock, with identification confirmed using electron diffraction and X-ray fluorescence. In polarized light the actinolite was of medium green color with typical dark grey to yellow birefringence and maximum extinction angle averaging about $15^{O,}$ and with no pseudo-orthorhombic fibers with diffuse extinction to indicate fibril structure. The gravel-sized fragment of "ophicalcite" was found to be a coarse grained rock comprised of apple green serpentine, calcite, and magnetite.

The bulk chemical analysis of the sample of Manhattan Serpentinite (Table 1) indicates a high CaO content consistent with the calcite and actinolite observed in thin section. The relatively high nickel content and also high chromium content supports its identification as a meta-peridotite. The anomalously high manganese content is most likely of hydrothermal origin or was residue of weathering, as such was not found in the major primary minerals. Both the historical analysis (Newland, 1901) and our new analysis from the same location both had 1.38% MnO, favoring a hydrothermal origin (Table 2).

It is also important to note that the Nickel content of the Manhattan sample is approximately the same as the Nickel content of the Hoboken serpentinite (Table 1).

The Newland (1901) analysis of a sample of the Manhattan Serpentinite was analyzed by Dr. Thomson of Edinburgh (Table 1.) The results compare quite closely to our new data (Table 1.)

Table 2: Chemical analyses of minerals (each is a mean of two analyses)

	Serpentine	Anthophyllite/Talc	Clinochlore
SiO_2	41.96	56.04	33.16
Al_2O_3	0.00	0.00	15.19
FeO	9.28	8.41	3.82
MgO	36.38	27.99	34.08
CaO	0.03	0.35	0.00
Na_2O	0.00	0.00	0.00
TiO_2	0.00	0.00	0.02
Total	87.65	92.79	86.27

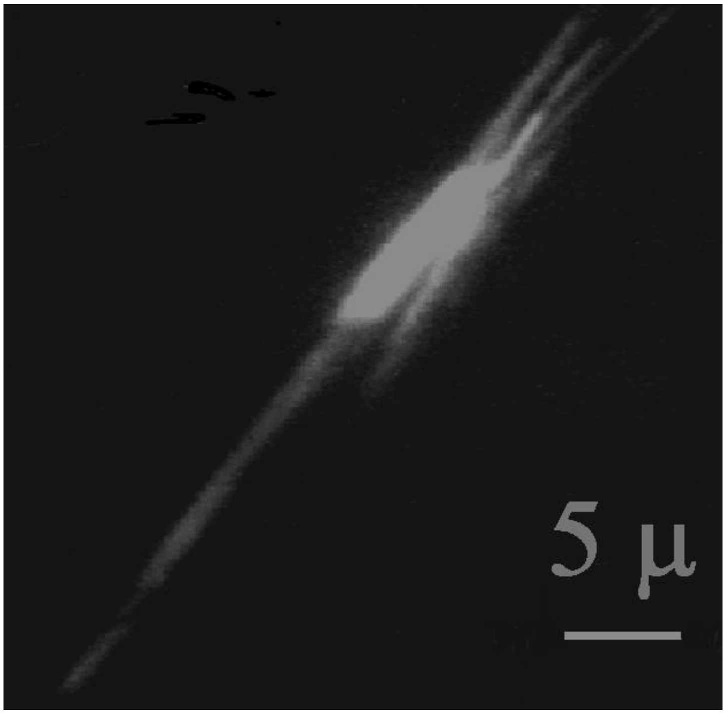


Figure 3: Oil immersion PLM photomicrograph of an aggregate of actinolite asbestos fibers from crushed Manhattan Serpentinite under crossed polarized light.

Geologic Implication

The core and band texture of olivine replacement indicate that the serpeninite is derived from an ultramafic rock and not a sedimentary rock. This is confirmed by the relative chromium and nickel content, which sharply separate ultramafic from metasedimentary serpentines (Faust and Fahey, 1962). There was apparently a high degree of metasomatism, much of which is seen at the contact of serpentinite with wall rock of varying compositions, but might also involve hydrothermal metasomatism, perhaps related to the unlabeled body of pegmatite which occurs at the northern end of the suite of rocks (Fig. 2a) between 60th and 61st Street and 11th and 12th Ave.

The Manhattan Serpentinite mapped by Julien (1903) is quite varied including serpentinite, "ophicalcite," anthophyllite, talcose actinolite schist, hydrous anthophyllite, and talcose schist. The hydrous anthophyllite facies has been analysed in detail here and found to be a highly altered oceanic metaperidotite or metadunite. Although now widely considered to be a serpentinite of lower oceanic crust derivation, this is the first actual demonstration that this is the case, and earlier authors generally considered it a metasedimentary rock derived by alteration of the actinolite schist found on Manhattan Island (Dana, 1858).

The "ophicalcite" sample was likely derived from the actinolite schist facies, with actinolite altered such that the magnesium silicate component was hydrated into serpentine, and the remaining calcium and iron formed the calcite and magnetite as a result of metesomatism. The talcose actinolite schist and talcose schist are likely also members of the actinolite schist facies, although it is difficult to reconstruct the sequence based on our sampling.

Despite the geologic consensus for a Hartland host rock for the Manhattan Serpentinite there is an absence of any published geochemical supporting evidence. Each published map of Manhattan has been accomplished without any geochemical basis despite the overlap in mineralogy and texture among Manhattan schist and Hartland formations. The establishment of a geochemical distinction has been attempted by Puffer et al. (1994) and Puffer et al. (2010). A widespread sampling of Manhattan Island, approximately equally divided between exposures mapped as Hartland and exposures mapped as Manhattan, were chemically analyzed and found to plot as a single cluster of data points on each of several geochemical variation diagrams. The sample data cluster closely overlapped with a cluster of data based on Martinsburg shale analyses. Puffer el al. (2010) conclude that the close resemblance of all schist samples from Manhattan with the Martinsburg Formation supports the interpretation that each analyzed schist sample from Manhattan is consistent with a Manhattan Schist interpretation. Most of the 35 samples from widespread Manhattan locations plot within the “Active Continental Margin” field of the K_2O/Na_2O vs SiO_2 variation diagram of Roser and Korsch (1986) which agrees with most interpretations of the source of the Manhattan Schist protolith. In addition, McBride (1962) found that the chief source for the chemically very similar Martinsburg Formation was sedimentary and low-grade metamorphic rock together with some granitic plutonic rock. McBride also found paleocurrent evidence indicating Martinsburg sediments were carried down the sub-sea slope of “Appalachia”, or the eastern portion of the Laurentian craton. In contrast, Hartland Formation samples collected at undisputed Hartland locations outside of Manhattan (including Pelham Bay, Bronx and north-west Brooklyn New York) typically plot on in the Oceanic Island Arc Margin field of Roser and Korsch (1986). These data (Puffer el al., 2010) support the consensus interpretation of the Manhattan Schist as a continental margin derived meta-shale derived from a continental provenance in contrast to Hartland Formation generally interpreted as a calc-alkaline deep marine arc derived meta-sediment. The chemical composition of an arc derived sediment clearly differs from that of continental derived sediment such as Martinsburg shale.

The occurrence of an ultramafic serpentinite body, therefore, suggests that at least the western edge of central Manhattan near the Manhattan Serpentinite, together with the serpentinite exposed across the Hudson River at Castle Point, Hoboken, New Jersey may be on a suture separating Hartland Formation on the west from the Manhattan Schist that probably makes up most of Manhattan Island. The placement of such a suture would agree with mapping by Brock and Brock (2001) who has proposed a suture along the Hudson River at the base of the Hartland Formation, from the Staten Island Serpentinite northward through the Castle Point Serpentinite of Hoboken, New Jersey curving slightly eastward to include the Manhattan Serpentinite and then continuing northward along the Hudson. This also implies that the currently unexposed lense of mica schist located west of the Manhattan Serpentinite (Figure 1) together with Ordovician Schist exposures along the New Jersey side of the Hudson are Hartland Formation.

Similar serpentinite occurrences are typically interpreted as defining plate sutures as for example virtually all of the widespread serpenitinite bodies of California that mineralogically and texturally closely resemble the Hoboken and Manhattan Serpentinites (Coleman, 2000).

The anthophyllite asbestos of the western Manhattan Serpentinite is probably not unlike the anthophyllite occurrence in Staten Island that we have described (Germine and Puffer, 1981a,b) that was likely the deposit mined by Johns in their first asbestos mine over a century ago. Although appearing like anthophyllite in thin section, this anthophyllite asbestos is finely laminated with talc, forming the principle cleavage faces on the fibers. Serpentine is also present in the mined anthophyllite rock as documented by XRD data (Puffer and Germine, 1994).

Acknowledgments

We thank Joe Peters of the American Museum of Natural History (retired) for providing samples of Manhattan Serpentinite.

References

Baskerville, C., 1994, Bedrock and Engineering Geologic Maps of New York County and Parts of Kings and Queens Counties, New York, and Parts of Bergen and Hudson Counties, New Jersey, United States Geological Survey, Map I-2306.

Brock, P.J.C., and Brock, P.W.G., 2001, Geologic Map of New York City, *www.geo.sunysb.edu/reports/ny-city/full-map.pdf*

Coleman, R.G., 2000, Prospecting for ophiolites along the California continental coast. in Dilek, Y., Moores, E., Elthon, D., and Nicola, A. (eds) Ophiolies and Oceanic Crust: New insights from field studies and the Ocean Drilling Program: Boulder Colorado, Geol. Soc. Amer, Special Paper 349,p. 351-364.

Dana, J.D., 1853, Manual of Mineralogy: Including Mines, Rocks, Reduction of Ores, and the Application of the Science to the Arts. Seventh edition.

Faust, G.T. and Fahey, J.J. 1962, The Serpentine Group Minerals. USGS Professional Paper 384 – A. Washington, US Government Printing Office.

Gale, 1843, Diary of a geological survey of the Island of New York ***In*** Mather, W.W., Geology of New York, pt 1, p. 581-604, Carroll and Cook, Printers to the Assembly, Albany, New York.

Germine, M., 1981, Asbestoform serpentine and amphibole group minerals in the northern New Jersey area. MS thesis, Rutgers University, Newark, 240 pp.

Germine, M., and Puffer, J.H., l981, Distribution of asbestos in the bedrock of the northern New Jersey area: Environmental Geology, v. 3, p. 337-351.

Germine M., 1987, Asbestos in play sand. New England Journal of Medicine 316, 882.

Hall, L.M., 1968, Times and origin and deformation of bedrock in the Manhattan prong; In Zen, E-an, White, W.S., Hadley, J.B., and Thompson, J.B., eds., Studies of Appalachisn geology: Northern and maritime: Interscience Publishers, New York, p. 117-127.

Hall, L.M., 1976, Preliminary correlation of rocks in southwestern Connecticut: Geol. Soc. Amer. Memoir 148, p. 337-349.

Hall, L.M., 1980, Basement-cover relations in western Connecticut and southeastern New York: in Wones D.R. editor, Proceedings, The Caledonides in the USA: Virginia Polytechnic Institute and State University Memoir 2, p. 229-306.

Julien, A.A., 1903, Genesis of the amphibole schists and serpentinites of Manhattan Island, New York, Geol. Soc. Amer. Bull., v. 1., p. 421-494.

Langer, A.; and Bowes, D., 1969, Polyphase deformation in the Manhattan Formation, Manhattan Island, New York City, p. 361-377 in Larsen, L. H.; Prinz, M.; and Manson, V., eds., Igneous (sic) and metamorphic geology: Boulder, CO, Geological Society of America Memoir 115, x p.

Newland, D.H., 1901, The serpentines of Manhattan Island and their Accompanying Minerals: The School of Mines Quarterly, Columbia University, New York City, v. 22, p. 307-317 and 399-401.

Puffer, J. H., and Germine, M., l994, The Staten Island Meta-Peridotite: *in* Benimoff, A.I., (editor), Geology of Staten Island, New York, Field Guide and Proceedings, Geological Association of New Jersey, p. 1-25.

Puffer, J.H.; Benimoff, A.; and Steiner, J.C., 2009, Geochemical characterization of the Manhattan Schist and its distribution throughout Manhattan, New York. Geol. Soc. America, (abstract) Northeastern Section, Portland, Maine.

Puffer, J.H., Benimoff, A.I., and Steiner, J.C., 2010, Geochemical Characterization of New York City Schist Formations., New York State Geological Association, 82nd Annual Meeting, Field Trip Guidebook, p. 163-182..

Puffer, J. H.; Ageitos, D. M.; Buehler, S. C.; Eicher, J. C.; Kaplan, C. H.; and Seeber, F. C., l994, Geochemistry of the schists of Central Park, New York City: in Hanson, G.N., (editor), Geology of Long Island and Metropolitan New York, Long Island Geologists, SUNY Stony Brook, New York, p 86-92.

Merrill, F. J. H.; Darton, N. H.; Hollick, Arthur; Salisbury, R. D.; Dodge, R. E.; Willis, Bailey; and Pressey, H. A., 1902, Description of the New York City district: United States Geological Survey Geologic Atlas of the United States, New York City Folio, No. 83, 19 p. (Includes colored geologic map on a scale of l:62,500).

Merguerian, Charles; and Merguerian, Mickey, 2004, Geology of Central Park – From rocks to ice: *in* Hanson, G. N., *chm*., Eleventh Annual Conference on Geology of Long Island and Metropolitan New York, 17 April 2004, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 24 p.

McBride E.F., 1962, Flysch and associated beds of the Martinsburg Formation (Ordovician), central Appalachians. Journal of Sedimentary Research, v. 32, p. 39-91.

Roser, BP and Korsch, RJ., 1986, Determination of tectonic setting ofsandstone-mudstone suites using SiO2 content and K2O/Na2O ratio. TheJournal of Geology, v. 94, pp. 635-650.

ORANGE MOUNTAIN BASALT, SECOND LAVA FLOW (OMB2): OBSERVATIONS (PARTICULARLY PAHOEHOE STRUCTURES AND PREHNITE DISTRIBUTION) AT LOWER NEW STREET QUARRY, PATERSON, N.J.

Chris Laskowich
14 Old Rifle Camp Road, West Paterson, NJ 07424

FORWARD

The following observations were made at the behest of professor Alan Benimoff (Staten Island, NY) and professor John Puffer (Rutgers, NJ). The ORANGE MOUNTAIN BASALT or OMB (P.E.Olsen, 1980) had been called the FIRST WATCHUNG BASALT.

This chapter focuses on geologic observations made at the Lower New Street Quarry, Paterson, NJ located at 100 New St, Paterson, New Jersey, opposite St Bonaventure Church adjacent to Route 80 east, in Passaic County, Paterson Quadrangle

Although Paul Olsen's drill core data had established that there were three lava flow units (Olsen, 1980?) that made up the Orange Mountain Basalt or OMB, there is no clear demarcation in the Paterson area that one can recognize as the start of a third lava flow.

The Paterson area has exposed basalt in building excavations, but has rapidly buried them, walled over road cuts, turned streams into concrete culverts, and put off-limits the gated condominiums (UBC quarry, West Paterson, and Eagle Rock Ave quarry, West Orange). Homeowners and time have also covered bare basalt with topsoil and plants. Recent economic hardship and fear of litigation or theft has closed off permission to private property. It was only through the efforts of hobbyists, academics, quarry people, town mayors, and homeowners that make accessible today's (disappearing) rock exposures. Unless there is more recognition at the town, state, and federal level for preserving exposed rock for tomorrow's science students, the remaining sites for geology study will be lost.

INTRODUCTION

This author observed a slate-smooth surface of basalt, flat to tilting northward up to 15 degrees in the southwest wall of Lower New Street quarry, July 2011. The presence of a shrinkage-cooling joint system, perpendicular and immediately below this smooth lava surface proves that this is PAHOHOE LAVA. Other authors (Manspeizer, 1980) have said that there is pahoehoe (subaerial) lava in the upper or Second Lava Flow of the OMB (Orange Mountain Basalt) at the Lower New Street Quarry. In the diagrams on page 322, Manspeizer called the large holes (that are still present) pahoehoe toes, or rather the lava that drained out of the pahoehoe toe had left hollows.

However Swanson (1973, page, 617, par. 3) notes that "probably 25 to 50 percent of the cavities…" of the Kilauea, Hawaii, "developed by degassing of amoeboid shelly pahoehoe", "not by draining of lava out of the toe." Although this pahoehoe is the "smooth-surfaced type (p619), the lava was not completely degassed. There is the probability that some of these large hollows, lined with green prehnite, were the result of, or aided by, gas expanding along the flow axis, as well as lava draining out of a pahoehoe toe. The 2011 pahoehoe of Lower New Street quarry is within 30 meters (~100feet) of subaqueous pillow lava (to the east, and within 10 meters of lower elevation).

Collecting green prehnite, zeolites and Lower Jurassic dinosaur tracks since 1973 in the Paterson area, has given this author a prejudiced viewpoint that has led to errors, but also discoveries particularly volcanic diapirs (Puffer and Laskowich, 2012). Due to trespassing and insurance constraints, the knowledge of basalt, in quarries and elsewhere, has been limited to few observers, mostly crystal collectors. I first collected prehnite in West Paterson about a mile from my home, and visited Upper and Lower New Street quarries in the 1960's and early 1970's. I had always ignored distinctions between pillow and pahoehoe, and just called any bulbous mass "pillow lava". Recent observations of Lower New Street quarry began in March 2011, when hobbyists started selling prehnite from the poison-ivy-covered quarry cliff. They had managed to pry new prehnite from the west quarry wall, adjacent to route 80, that had not seen any blasting since 1936. Until this time, this author had noticed little if ANY evidence of pahoehoe lava, ropy, stringy, or smooth-surfaced, above the first or lowest lava of the OMB.

QUESTION: Is the new pahoehoe lava at Lower New Street a portion of a Third Lava Flow unit, as postulated by others? The recently worked (fifteen meter wide) basalt cliff wall poses other questions. Exactly how and when did the conditions arise for the SUBAERIAL (below open air) pahoehoe lava and breccia, AND SUBAQUEOUS (underwater) pillow lava, and how did their associated mineral assemblages occur, all WITHIN 30 METERS of each other? In other words, how are pillow and pahoehoe lavas affected by the presence or absence of water before and after burial?

Chiseling has clearly uncovered the Lower New Street smooth layer of pahoehoe lava, whose surface is perpendicular to the small (~7-30cm) vertical joints below, like the start of columnar joints (looking like a micro-colonnade). Only two loose pieces of basalt were found to have a distinct ropy surface, below a cliff by the old north gate. Other writers since 1980 have taken the proof of their pahoehoe findings elsewhere as a reason to declare a third lava flow. I myself am skeptical of declaring a Third Flow in the Paterson-Passaic County area. I do not have drill core information with dating.

Lava History – Pauses in the Lava Flood of OMB

A northward flood of lava of about 60 meters high (Lewis,1915? Mason, 1960?) was to have emplaced the first flow of the Orange Mountain Basalt (formerly the First Watchung Basalt), which was almost completely subaerial at the time, 201.5 Ma. (Note that there were shallow water pillows at the Passaic Formation contact at Little Falls). Proof of this are the earliest Jurassic dinosaur tracks found directly below the lowest lava at Great Notch, on either side of Rt. 46 (Little Falls and West Paterson, Passaic County). Prior to first lava flow, the Newark Basin was regularly a vast (playa) lake, perhaps an outwash plain, underlain here by conglomerate, fining upwards to sand and silt just below the basalt contact. Note that there was (extremely amygdular) shallow water pillow lava up to about 3 meters high at the Little Falls (MSU), directly above the sandstone. One author (Mason? Schaller, 1932?) proposed wet sediments as the cause of the pillow masses.

About four decades after the first hypotheses about flood lavas, new quarrying showed breaks or pauses in what was thought to be a continuous, one direction flood (Figure 1).

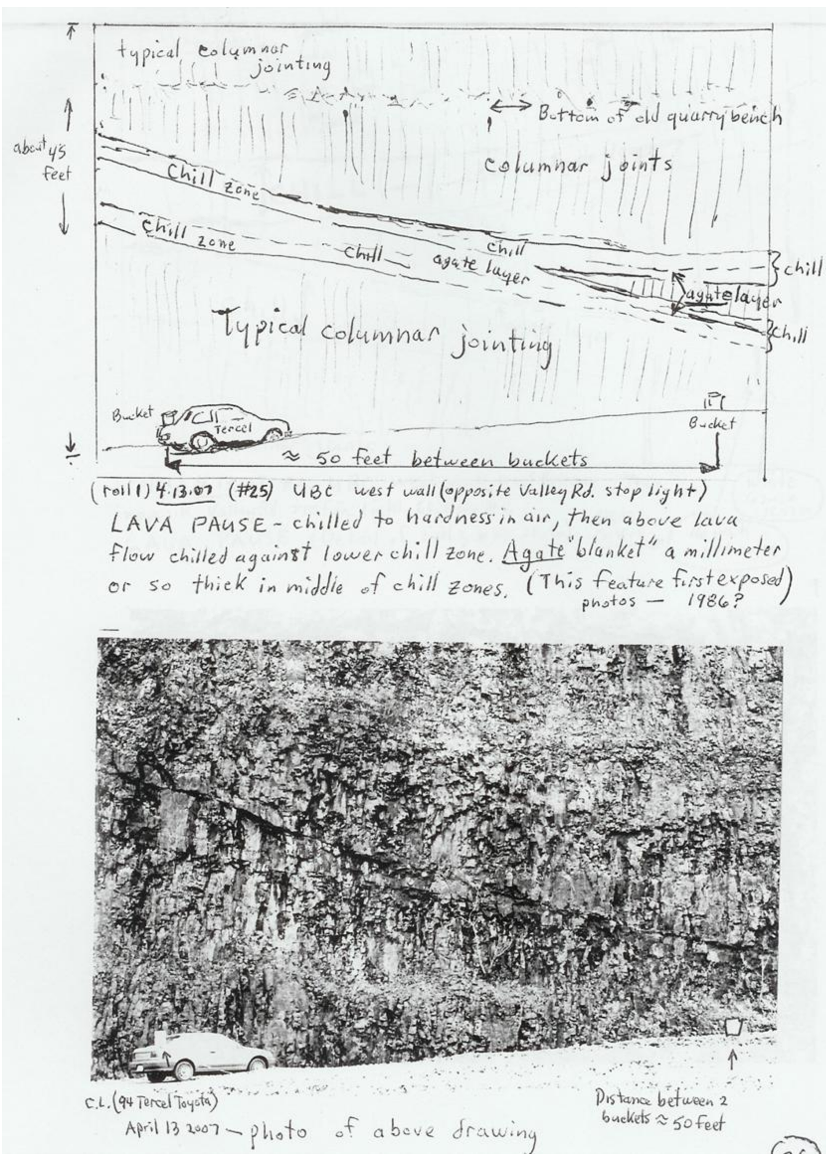


Figure 1. Photograph and interpretive sketch of "lava pause".

The UBC (Union Building & Construction Corp) quarry, by route 46, West Paterson (renamed Woodland Park, 2008), has shown breaks in the lava "flood". There is a LAVA PAUSE, a (2/3 meter thick) chilled surface, at the west wall of UBC, which can still be seen with binoculars from the highest point of the remaining NE quarry wall, viewed above the condominiums from Rifle Camp Park. Just above this lava pause is another 2/3-meter thick chilled border, when the lava resumed, with an unusual sheet of agate in the middle, conforming to the surface shape, which at one point buckles upward. (See LAVA PAUSE UBC figure)

At route 46, Great Notch, or at New Street, Paterson, lava pauses or lava interruptions may be interpreted as separate Lava Flow Units, but not having seen the drill data with other surface correlations, I cannot judge where a Third Lava Flow Unit is supposed to be.

Prehnite, Quartz, and Zeolite Distribution in Subaerial Pahoehoe and Subaqueous Pillow Lava Flows

There is an attempt to identify subaerial pahoehoe or subaqueous pillow lava by its particular set of associated minerals, and their relative paucity or abundance. It seems clear that without the source of a water-saturated palagonite (hydrated volcanic glass), or some H_2O affected basalt, the water-rich zeolites like stilbite or heulandite would not grow. Crystal collecting hobbyists had known that there were certain zones that had more or less orange stilbite, or had only white pectolite (no OH). Prehnite $(Ca_2Al(AlSi_3O_{10})(OH)_2$ and pectolite always seemed to be at a higher stratum, towards pahoehoe, and away from stilbite $(NaCa_2Al_5Si_{13}O_{36}\cdot 14H_2O)$ and heulandite $(Na,Ca)_{2\text{-}3}\ Al_3(Al,Si)_2Si_{13}O_{36}\cdot 12H_2O$ in pillow lava. Prehnite was sparse where zeolites were present. Prehnite had differences in the shape, thickness, color or surface crenulations (the tiny rectangle or crescent surfaces of the grape-like (botryoidal) prehnite masses) depending on location. (see prehnite examples)

The LOWEST strata in the UPPER New Street quarry, against the highest cliff with the condominium apartments on top, is the amygdaloidal basalt from TOP of the First Lava Flow (now almost buried, can be seen near Mountain Ave, by Dixon and Carlyle Aves). Above this is massive basalt, mostly without columnar joints, and a 4-meter wide pillow shape (really pahoehoe?) with black glassy (tachylyte) breccia imbedded in a white matrix (datolite? Quartz?), and amethyst and clear quartz pockets in seams between pillows. The mineral collectors of the 1986-87 lower blasting, at Upper New Street quarry gate, remember the near absence of stilbite. It was not until later blasts, at a higher south area, that a great mass of stilbite, and very little other crystals, was found. Within 30 meters away, at a higher lava level, there is no stilbite, but much pectolite (no H_2O), apophyllite $KCa_4(Si_4O_{10})_2(OH,F)\cdot 8H_2O$ and thaumasite $(Ca_3Si(CO_3)(SO_4)(OH)_6\cdot 12H_2O)$ within a dozen meters of each other. Just above this at the uppermost strata of pillows in Upper New Street, and corresponding to Lower New Street areas of its western side beside route 80, there is prehnite, pectolite, and a little chabazite, like the #27 Hugo Ave property (Strictly off limits to all but a professor, and only by written permission).

There are a number of structures in basalt at certain depths within a lava flow that one must be aware of before associating a mineral suite with a particular basalt structure. (Figure 2).

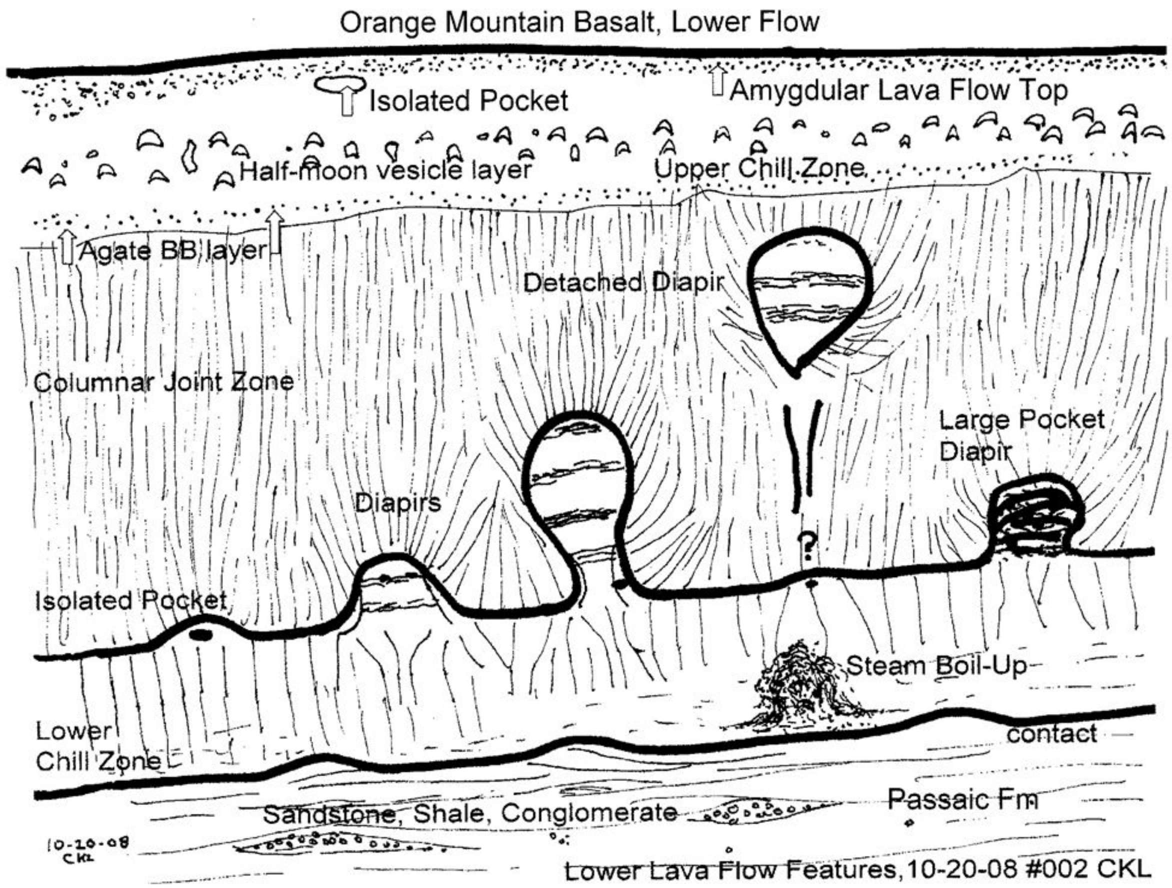


Figure 2. Idealized sketch of volcanic structures found in the lower flow (OMB1) of the Orange Mountain basalt.

At the bottom of the First (lowest) Lava Flow, just above the Passaic Formation sandstone, “Steam Boil-ups” (resembling spiracles) rise a few meters into the lava due to superheated water vapor. Volcanic Diapirs (above the lower colonnade, and within the columnar jointed Entablature), and similarly formed Isolated Pockets were emplaced before crystal mush and basalt glass developed the columnar joints. Agate BB and prehnite Half-moon Vesicle horizons (at the top of the flow, or “upper colonnade”) segregated their differing compositions and were emplaced during the liquid to plastic lava states (Figure 2.).

Well after the first OMB flow (some hundreds of years?), after a weathered surface developed on its amygdaloidal crust, the Second OMB Lava entered into a Newark Basin (Figure 3) that had sunk in its NW corner, becoming the basin for local "Lake Paterson", filled with brackish saline waters (with sodium and calcium salts). Lava entering water at whatever depth created pillow lava. At issue here is the timing of when the lava no longer was pouring into water, as lava displaced the water, or the water level had dropped, to allow for pahoehoe toes and flows on "dry land". There is no amygdular flow top or eroded weathered surface to mark the end of the pillow lava, and the start of subaerial pahoehoe.

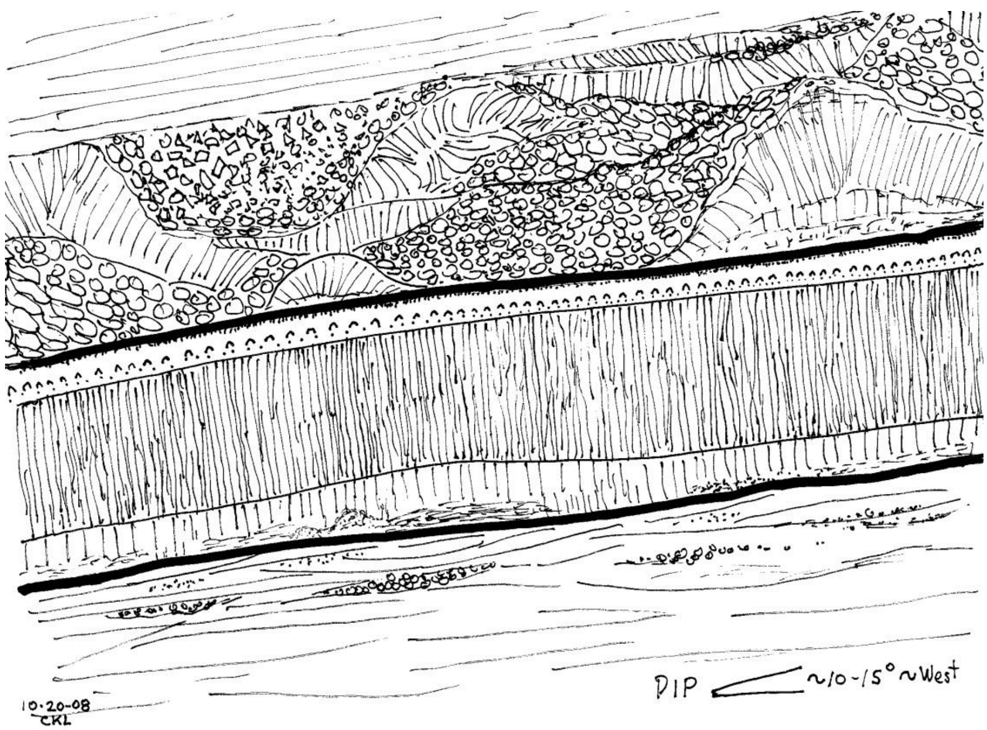


Figure 3. Idealized sketch of volcanic structures found in the second flow (OMB2) and first flow (OMB1) of the Orange Mountain basalt.

Pillow Lava

Lava entering water of any depth forms bulbous masses from approximately 1/3 meter to 2 meters in length, resembling sacks or sandbags, piled one atop the other. The bottom of each following pillow conforms to the top of the previous pillow. The outer margin of a tongue or toe of lava enters shallow or deep water, or wet swampy sediment, and acquires a dark glassy crust. In the lowest pillows of the east wall of Lower New Street (Figure 4) this crust has a black glassy sheen when fresh. According to MacDonald (1953) the cross sections of each pillow have a radial joint structure, and the length of pillows are seldom more than three or four times their diameter. There is a black glassy completely covering the pillow. At New Street, zeolites occur within the spaces between the pillows, but the best, most well-formed crystals are formed in "center-of-pillow pockets". These center-of-pillow pockets are vesicles entirely within the pillow, and in unusually large pillows there can be as many as four hollows, shaped like bread loaves, stacked one atop the other.

Figure 4. Pillow basalt, Lower New Street quarry.

Pahoehoe Lava

Lava in open air, exiting a flow lobe, develops lava toes, or pahoehoe lava, smooth or iconically having a ropy or stringy surface. Unfortunately, until the discovery of the smooth surface of pahoehoe lava at Lower New Street, there had been no examples of ANY pahoehoe this writer knew of WITHIN any local New Jersey exposure. Consequently, I did not look for them, or notice them if present. Three decades of observation at the sandstone-lava contact at UBC quarry, West Paterson, had shown only a few clear examples of stringy-surface pahoehoe at the very base of the First Lava Flow.

There is a small but accessible exposure of pahoehoe lava toes at McBride Ave, between Henderson and Rockland Aves, Paterson, which appears contemporaneous with Lower New Street, and is just north and downhill of the quarry. Very large ellipsoidal basalt masses with relatively small (compared to pillows) and flattened center-of-lava toe vesicles are behind the Lukoil (former Shell) gas station. These pahoehoe toes are exactly similar in shape to the pillow lava buds, the bottoms of which conform to the previous shape of round pahoehoe below. The crust or outer rind of one pahoehoe toe contains lava drips and fractured sand and gravel-sized lava chips adhering to its surface. (see photos 7363,7364).

These same lava drops and drips, looking like rusty dark melted tar, on the pale cracked ellipsoid surface found north of UPPER New Street quarry, and the pahoehoe at #35 Wilson Ave, West Paterson (Figure 7) and elsewhere, convinces this writer that pahoehoe covers most of the pillow lava at New Street.

Figure 5. Photo 7363 illustrating lava drips. Lukoil gas station, corner of McBride Ave and Rockland Ave, Paterson, NJ, due north of New Street quarries.

Figure 6. Photo 7364 illustrating fractured sand and gravel-sized lava chips adhering to subaerial flow surface. Lukoil Gas station, Rockland Ave and McBride Ave, north of New Street quarries.

Figure 7. Pahoehoe ellipsoidal bodies, 100 meters south of Upper New Street Quarry, 35 Wilson Ave, off New Street, West Paterson.

Palagonite

Palagonite is defined as the yellow-orange (Fe) alteration product of basalt glass and water. It can occur from direct contact of molten lava into water as with pillow lava (or steam above the water table, as from a geyser?). The most prominent examples of this rust color seem to be within areas that are pahoehoe (Figure 8).

Figure 8. Palagonite in stream bed at McBride Ave and Browertown Road. Smooth pahoehoe surface.

A yellow orange color is prominent within the west wall breccia at Lower New Street, above the smooth pahoehoe surface, which surface is very dull, hard, and a rust brown color. The stream at McBride Ave and Browertown Road (Figure 8) or the PNC bank parking lot beside New Street, or the lot at 3 Garret Mountain Plaza has examples, also appearing to be pahoehoe.

Lower New Street Quarry: Observations:

Professor Warren Manspeizer of Rutgers (Newark, NJ) last wrote of pahoehoe lava toes, and pillow lava at Lower New Street Quarry, in the 1980 New York State Geological Association "Field Studies of New Jersey Geology and Guide to Field Trips (pages 313-350, Fig. 12, p.322). Citing Macdonald (1953) and Swanson (1973), Manspeizer sees pahoehoe in two places within the south wall, though these places are surrounded by pillow lava in his Figure 12 (Figure 9).

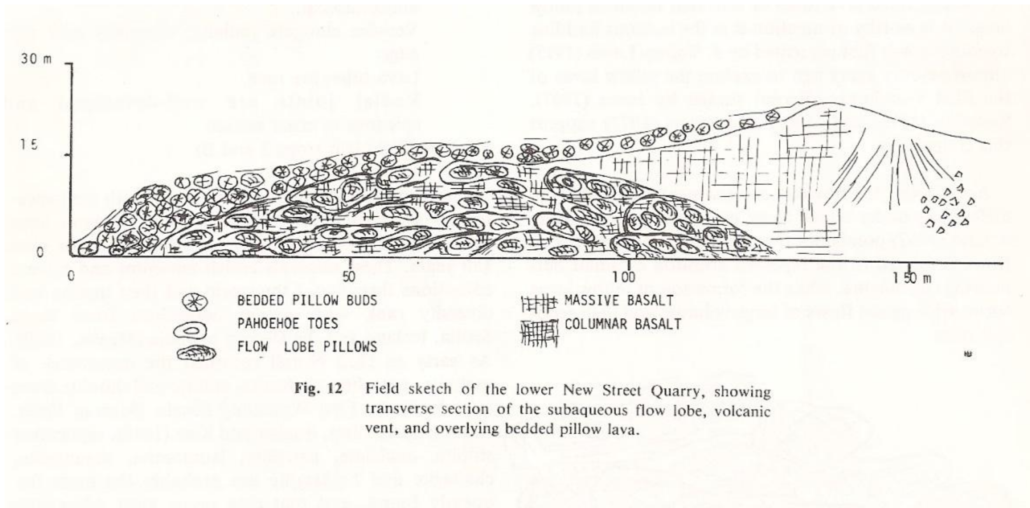


Figure 9. Interpretation of volcanic structures at the Lower New Street Quarry by Manspeizer (1980).

My interpretation (Figure 10) has subaerial, massive, and columnar basalt, or pahoehoe lava, for most of the upper east wall, and the entire south to southwest wall, except for the lowest meter above the quarry floor. Today, perhaps unlike 1980, one may view the cliff walls here free from the most obstructive thick poison ivy vines. Though trees obstruct photos now, a limber graduate student may climb the wall for close inspection, almost to the top, just south of the one remaining telephone pole and its hanging cable.

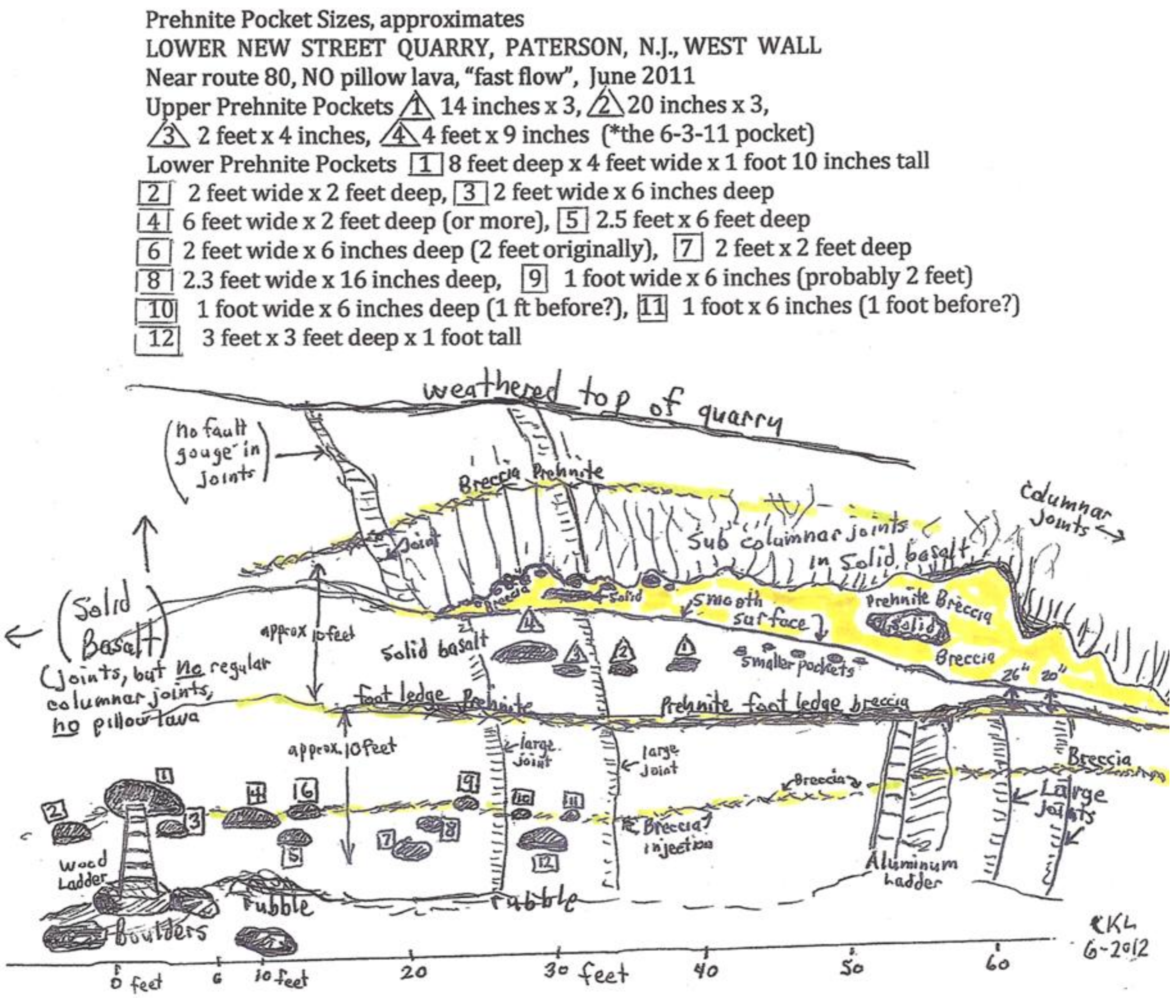


Figure 10. Southwest wall ofLower New St quarry, nearest route 80. Prehnite pockets drawing, of 4 Upper pockets, 12 Lower pockets, Pahoehoe "smooth" layer with ("micro") columnar joints, and large breccia area above. Note boulders below left ladder are not pockets.

John Sinkankas was an avid zeolite collector born in Paterson, who later became the famous author of a book on Beryls. He is quoted as describing "very fine specimens" of prehnite as coming from Lower New Street Quarry in his 1964 book "Mineralogy" (page 545). Images on library searches for Schaller (1932) show prehnite balls, hemispheres and "scepters" or "fingers". Some collectors refer to the fingers as "arrowheads" or "snakeheads". Prehnite had covered anhydrite or glauberite crystals, assumed their shape, and left hollows when the Calcium and Sodium sulphates dissolved away. The prehnite fingers after glauberite and anhydrite (Figure 11) occurred in Upper and Lower New Street quarries, north to Prospect Park, and south to Great

Notch, Rt. 46, West Paterson. (Note that West Paterson changed its name in 2008 to Woodland Park)

Figure 11. Prehnite, reportedly from Lower pocket #12 (Figure 10), Eric Stanchich specimen #2, collected 2004 (Eric communication).

Lower New St is listed by mindat.org as having been a working quarry from 1900 to 1936. The Upper New St quarry was worked from 1893 to 1925. In Upper New Street quarry between Mountain Ave and New Street there had been no blasting, and no minerals to be found in chiseled-smooth walls, until minor quarrying about 1986-87. Condominiums off Mountain Ave now fill the top of Garret Mountain, where one can see columnar fans and pahoehoe at the end of Amethyst Lane. Long after the last brief blasting, collectors still pry down into the quarry floor pillow lava below, after having dug past the grass and rubble. (You would need at least an 8-ton jack and wrecking bars, etc.).

The latest collecting of minerals on the SW wall near Rt. 80, started about 2004 at Lower New Street (#100? New St, the old “Burger’s Quarry”), followed by the finds in January (?) 2011. This has been strictly sledgehammer, with many broken and bent pry bars and chisels, and a few discarded hydraulic jacks. I have collected and observed about 50 times, and almost monthly photographed the activity here from April 2011 to June 2013 (for example Figure 12).

Figure 12. Lava tube (Lower pocket #1), interpreted as lava drained from a large pahoehoe toe exposed in the quarry face at Lower New Street. Possibility of some degassing that aided expansion.

THE FOOT LEDGE – The foot ledge (Figure 10) is a place where people could stand, and chisel up to the area below the next highest level, the Smooth Surface pahoehoe, and the large breccia (yellow) area above that. The

Figure 13. "Smooth Layer" (Figure 10) of pahoehoe, southwest wall of Lower New Street Quarry.

Foot Ledge is an area of horizontal prehnite veins which occasionally opened up into collectable vesicles. The prehnite here was a gemmy green translucent kind of the finest quality, with fine mm crescent faces. Trying to remove the overlying basalt from the foot ledge exposed the LARGE UPPER POCKETS 1,2,3,4.

LARGE LOWER and UPPER POCKETS - There were 12 lower prehnite pockets (Drawing) present, though a few have since been buried or destroyed. All but one was found decades ago. The last of these lower pockets (#12) was exposed in 2004 (ES). Four upper pockets, of prehnite and minor calcite and chalcopyrite, were then uncovered (2010-2011) within several months of each other, above the "foot ledge". Upper pocket #3 is now destroyed, and upper pocket #4 (four feet wide) is nearly gone. The Large Upper and Large Lower pockets contained the unweathered, "gemmy" and thicker light green prehnite. The most valuable-per-weight prehnite came from the #4 Upper pocket, opened June 3, 2011 (AG). The prehnite had small (1-2 mm) rectangular faces, grouped in a circular pattern, the size of coins, looking like a miniature seating plan for a round stadium.

Only 3 of the large Lower pockets had a general north-south direction for their longest axis. The large Upper pockets, and the rest of the lower pockets had no preferred direction, but most had flat bottoms and arched rounded roofs.

SMOOTH PAHOEHOE - Above the Large Lower and Upper Pockets was found a "smooth layer" which is a pahoehoe lava surface (Figure 14). This smooth, not ropy, surface was not available to be viewed until 2011, when prehnite collectors uncovered it with the help of ladders.

Figure 14. Smooth pahoehoe layer.

The majority of mass of weathered basalt, and of prehnite, was excavated here. There is a "micro-columnar" joint surface below the smooth pahoehoe layer (Figure 15).

Figure 15. Micro-columnar joint surface below the smooth pahoehoe layer.

This is conclusive proof of subaerial, chilled-to-solid in-open-air basalt. The pahoehoe lava formed above and below this smooth surface.

LARGE BRECCIA AREA - The large breccia layer is above the Smooth Pahoehoe surface. The weathered basalt clasts appear to be angular and solid. There are NO amygdules or vesicles within each clast. The basalt clasts are several cm to a meter in length, and are shoe leather brown on the outside. Sometimes the BB-sized to pea-sized prehnite balls have grown on the brown basalt clasts, and have left a dimpled pattern of round indentations on its surface. The mechanically broken basalt has mostly weathered to a yellow-orange inside, and each clast is surrounded with what can be described as "black prehnite". Blue-green prehnite, in larger seams, grows directly away from the darker prehnite pocket walls wherever there is a hollow. Where there is no green prehnite there is still a dark or black prehnite seam separating the weathered basalt pieces. One large meter long clast is of fresher dark basalt which has not weathered to yellow orange inside.

There are smaller Breccia Layers above and below the Large Breccia Area, which contain prehnite seams and pockets. There are about five breccia layers in the southwest wall of New Street quarry, though the lowest, beside the Large Lower Pockets is periodically buried by collector debris, chiseled from above.

LARGE BRECCIA AREA PREHNITE POCKETS - These prehnite pocket hollows, like a crystal-lined geode, are of TWO distinct shapes:

1 – ANGULAR PREHNITE POCKETS – Within the Large Breccia Area are many prehnite pockets whose walls are angular, and have the shape left in between the individual clasts of breccia (Figure 16). These breccia clasts look like broken pieces of solid pahoehoe, pushed along by the lava above the SMOOTH Surfaced pahoehoe. These pocket hollows have cross-sections that look like triangular or trapezoid holes, 3 to 30 cm across the largest dimension.

Figure 16. Green Prehnite pocket, in seams below the "smooth surface" of pahoehoe.

The longest Round-Walled prehnite pocket dimension had no preferred compass direction. The Angular Pockets are between mechanically broken basalt clasts, which are now almost all weathered to a yellow-orange clay color. Most of the original green to blue-green prehnite has weathered to a dull, powdery luster, or has rotted to tan or creamy yellow-brown clay. A few intact unweathered pockets, that escaped poison ivy roots and weak acids from plant decay, contain pristine prehnite as small balls, or coatings, rarely larger than one cm thick, and short finger shapes. Oxalic acid and "iron-out" soakings helped bring back green color to yellowish "rusted" pieces. Chiseling deeper into the walls brought less weathered specimens. There was very little calcite, mostly half a cm, and minor to rare chalcopyrite, though if found, it was mostly in a seam behind the prehnite of the round-walled pockets at the top of the Large Breccia Area, described next.

2 – ROUND-WALLED PREHNITE POCKETS – Within the Large Breccia Area were less common, and much larger, Round-Walled prehnite pockets whose walls are distinctly rounded or smooth, with prehnite balls or fingers (Figure 17).

Figure 17. Round-Walled prehnite pocket.

The prehnite coating is thicker and greener in these Round-Walled pockets. The largest round–walled prehnite pocket (Dec 12, 2012) was about 1.5 meters long, up to 40 cm high, located just above the Smooth Pahoehoe surface. This one largest Round-Walled pocket had a roughly north-south long axis, though all other Round-Walled pockets had no preferred orientation. Most of the larger Round-Walled pockets, 15-30 cm or more wide, were at the top of the Large Breccia Area, below the next pahoehoe flow. Besides the minor to rare chalcopyrite, Phillipsite (a zeolite) was found covering a seam behind the roof of one of these prehnite pockets, and in joints of a mm or less, from the basalt above and below the Foot Ledge, and in solid basalt above the Large Breccia Area

QUESTION- How did a pillow lava area, created in an area of some DEEP lake water depth, have, in the same quarry, an open-to-the-air lava flow that could produce a pahoehoe chilled surface? Don Bello, a graduate student of Rutgers (1975), wrote a paper that cited depth of water as the reason why there were NO amygdules, vesicles, or bubbles of any kind in Prospect Park quarry pillow lava (about2 km north). The absence of gas bubbles (amygdules or vesicles) may mean that the pillows there, and at New Street, were formed in up to 200 meters of water depth. Manspeizer (page 321) makes note of the absence of rubble in Paterson pillows to suggest a deep basin also, in most of the quarry area. However, below the largest present cliff face in the Upper New Street quarry, one can see very large ellipsoidal lava with black breccia, up to a few cm or more, within a white to light gray matrix (carbonate? datolite?) between the pillows (the minerals here are quartz, calcite and anhydrite casts). This is in contrast to the very shallow water pillow lava buried at Montclair State College (University today, in the old Houdaille quarry). The maximum water depth may only have been a few meters there, and therefore the pillows were EXTREMELY amygdular. Any glassy black crust was so thin and fragile that it crumbled and washed away after a few months. The Orange Mountain Basalt of the first lava flow unit lay upon sandstone, whose surface was covered by dinosaur and reptile tracks. (It appears that the water was a leftover remnant of drying river ponds following the drainage of "Lake Paterson" (See "mega-ripple marks, UBC quarry, NE wall", Spirit River, and Spirit Lake).

CONCLUSIONS - First, Hawaii is not New Jersey. Observations Orange Mountain Basalt do not easily follow Kilauea lava observations. Second, just like Kilauea, New Jersey regularly erupts in spasms of blasting and excavating. It is a good bet that the Third Lava Flow is present in the area, just not as clearly demarcated as it is in the southern OMB.

Questions about the timing of lake water depth or the likelihood of geyser-induced lava alteration (creating a prehnite or zeolite dominant zone) will have to wait for more precise data.

Lava Transition Between Pillow Lava and Pahoehoe

There must be an intermediate zone of lava between pillow lava and pahoehoe, places where water level fluctuated. There was dramatic evidence of a rapid change of Newark Basin water level at the northeast wall of UBC quarry, West Paterson (now called Woodland Park since 2008). Several centimeters below the first and lowest lava of the OMB, in the Passaic formation red sandstone, were the largest ripple marks seen at this horizon by this author in 35 years. They were about 40 cm apart, indicating a sudden drainage of the Basin to the west. The drying sediments were then covered with reptile, insect and dinosaur tracks from the start of the Jurassic period in New Jersey.

Besides water level change during basin deformation and magma inflation/deflation, the simple filling of the basin with lava or landslide sediments, or a glacial ice avalanche must be considered (evidence of vegetation or ice rafting, UBC quarry). Geysers or torrential rains may have changed the viscosity of the lava and created an intermediate broad area of local ponds beside dry pahoehoe, and there are questions of timing, as the final lava source here may have changed location, or direction. (Quarried away at Mountain Ave and Boulder run, and below the flag tower and memorial in Garret Mtn Reservation, is a basalt that looks like diabase due to the unusually large plagioclase crystal lathes)

Third Lava Flow in the Orange Mountain Basalt

This author acknowledges the obvious pahoehoe ("smooth surface") in the southwest vicinity of Lower New Street quarry, but fails to see any clear separation between PILLOW LAVA zones in the Second Lava Flow unit and PAHOEHOE LAVA, from Browertown Road and locations uphill and east. Warren Cummings (May-June 1987, Rocks & Minerals) and Olsen's drill core data insist upon THREE separate lava flows, each separated by reddish color weathered sediment. No evidence of such a separation could be found. The pahoehoe lava ½ km north (Lukoil Gas station, McBride and Henderson Ave, and beside Rockland Ave) appears to be the same flow as Lower New Street. The halfmoon vesicle area ½ km west (McBride Ave south of Glover Ave bridge) MAY constitute the halfmoon vesicle (upper part) of the Third Lava Flow, or just an up-block of the Second Lava Flow, west of a normal fault. This author will make no distinction based on the data observed in this very urban and poorly exposed area.

MAP LOCATIONS:

NOTE- West Paterson or WP, is now called Woodland Park. Be sure to write and ask permission. I suggest that you carry a large notebook, NOT a crowbar when first visiting. People here are used to rock collectors, but come in broad daylight appropriately dressed ask permission to private property.

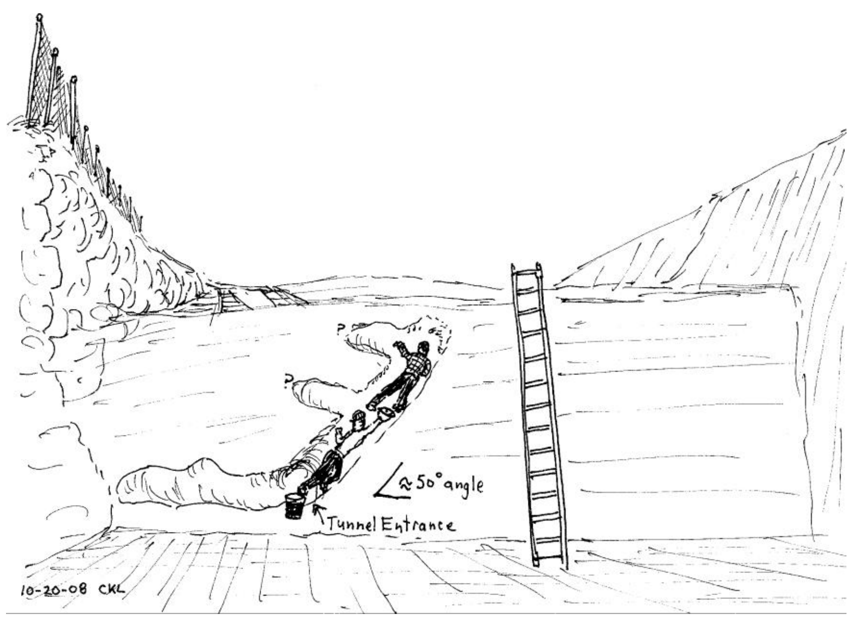


Figure 18. McBride Ave and Browertown Road, recycling center. The new brick building was the site of lava tube filled with prehnite. CKL and John B, 1986 (Google West Paterson pumping station prehnite). The stream here has pahoehoe surfaces and prehnite pipe vesicles, and a walk down Browertown Road has basalt faces past the trees. Uphill is the old Morris Canal walkway, and Virbickas Drive.

*Mount Pleasant Ave, just beyond concrete stream culvert opposite Virbickas Drive, prehnite Halfmoon vesicles. 7-13-2013 CKL (my first collectible prehnite~ 1973, botryoidal and separate hemispheres)

*20 Virbickas Drive, WP, driveway cliff, three 2 x 3/4 inch vesicles, one atop the other, and prehnite with anhydrite casts in backyard basalt exposures. Virbickas Drive was created by destroying the stream that was here along the pahoehoe and solid basalt ravine. It was covered over to make Virbickas Drive and the home sites. 7-13-2013 CKL

*35 Virbickas Drive, WP, off Mount Pleasant Ave, WP, just downhill of this driveway are three faint sausage-shaped vesicles, 3x1 inch, one atop the other, in neighbors driveway near sidewalk. 7-13-2013 CKL.

Figure 19. 145 Meriline Ave, WP, off Overmount Ave WP, lava drips on pahoehoe, uphill from driveway, between north side of house and Ave, 6-26-2013 CKL

*Opposite 42 Winding Way, WP, off Rolling Views Drive, off Overmount Ave, about 30 feet to right of parking lot, lava drips, lava chips (figure) and prehnite vesicle, above columnar basalt, 6-27-2013 CKL. Note-When blasting for these home foundations (about 2002), there were many pieces of prehnite and pectolite (my notes say the matrix was pillow lava, but most likely it was pahoehoe). This area is adjacent to the Westmount Country Club, beside the #724, #730 Rifle camp Rd localities.

Figure 20. Robs Way, WP, lava drip.

*35 Wilson Ave, WP, top of hill, REACHED ONLY off New St, pahoehoe flow, very near and south of UPPER New St quarry.

Figure 21. 27 Hugo Ave, WP, backyard cliff of Mr. Rausch, (NO TRESPASSING) 1973-2013 CKL. This is on the other side of the south wall of UPPER New St. quarry. Pillow buds and pahoehoe, prehnite. Note, In the Upper New St quarry, prehnite and chabazite was found bordering #27 Hugo Ave, in Pillow lava, between and in the centers of pillows. The lower part of the #27 Hugo Ave appears wholly to be pahoehoe. The pillow lava of #27 is above the pahoehoe, stratigraphically on the same level as the afore mentioned Upper New St quarry pillows which are a few meters below the cliff top, and within 10 meters distant of the #27 cliff.

*40 Hugo Ave, WP, June 2013, opposite the #27 house is a massive, non-columnar, small cliff of pahoehoe, exactly the same character as the pahoehoe north side of the PNC bank parking lot, which is the other side of the south wall of LOWER New St quarry,

*PNC bank, opposite Hugo Ave, on New St, parking lot entrance #1 Garret Mountain Plaza, WP, pahoehoe massive, non-columnar small cliff. Also, along New St, within the parking lot, are pahoehoe toes. Note that this parking lot, made in the 1970s when route 80 was being made, contained prehnite.

*#3 Garret Mountain Plaza, beside Squirrelwood Road/Rifle Camp Road, WP. Pahoehoe toes and flows.

Westmount Country Club, parking lot entrance

*#730 Rifle Camp Road, brothers Chris and Nagy Abdullah, pillow lava, very weathered, behind private home in 45 x 3 meter tall cliff. 6-29-13 CKL

*#724 Rifle Camp Road, pahoehoe(?), glaciated, weathered, driveway entrance, agate nodule, vesicles, anhydrite casts. NOTE this solid flow is on top of the #730 cliff. 6-29-13 CKL

*#494 Rifle Camp Road, earlier 1990's visit of cliff behind home, pillow lava, heulandite between pillows, and CONTACT with First Lava Flow amygdular flow top at far right (north) near the ground, glaciated corner. Now thickly covered with cliff vines and invisible. 6-30-2013, CKL.

Figure 22. Lukoil gas station, between Henderson and Rockland Streets, corners of McBride Avenue. Definitely pahoehoe, though ellipsoidal shapes that conform exactly like bedded pillows makes the distinction impossible from a distance. The discovery of a lava drip surface on a pahoehoe surface on Rockland Ave, and the presence of atrophied, comparatively tiny amounts of stilbite, and few other minerals (trace of chabazite, datolite, smoky quartz) also point to a surface that was subaerial when created.

Figure 23. Upper New Street upper east wall, note large elongated flow lobes interpreted as pahoehoe subaerial structures.

Figure 24. #27 Hugo Ave., West Paterson. Beside south wall of Upper New Street quarry, Paterson Pahoehoe flow lobe with small vesicle (at ruler, lower left).

Pahoehoe had less firm ellipsoidal walls than pillows and would push unto neighboring pahoehoe toes with hot flexible walls (MacDonald, 1953), leaving less space between toes.

Degassing of pahoehoe means less center-of-ellipse vesicle cavities, or very flattened pockets in the centers. Palagonite is yellow brown smooth surface3 between pahoehoe toes. The top surface of a toe had been steem rolled over, like a “tank tread” (MacDonald, 1953; Swanson, 1973).

Acknowledgments

Any value by these observations was made possible by Professor John H. Puffer. Any mistakes in observations or conclusions are entirely my own.

References

MANSPEIZER, W. (1980) Rift tectonics inferred from volcanic and clastic structures. In Manspeizer (editor) Field studies of New Jersey geology and guide to field trips. *52nd Annual Meeting of the New York State Geological Association*, Rutgers University, Newark New Jersey p. 314-350.

Olsen, P.E., 1980. The latest Triassic and early Jurassic formations of the Newark basin (eastern North America, Newark supergroup) : Stratigraphy, structure, and correlation. New Jersey Academy of Science Bull. 10 :40-77.

PUFFER, J.H. and LASKOWICH, C. (2012) Volcanic diapirs in the Orange Mountain flood basalt: New Jersey, USA. Journal of Volcanology and Geothermal Research, 237-238, 1-9.

SCHALLER, W.T. (1932) The crystal cavities of the New Jersey zeolite region. U.S. Dept of the Interior Geological Survey Bulletin, 832, 90 pp.

MACDONALD, G.A. (1953) Pahoehoe, aa, and block lava. *American Journal of Science*, **251**, 169-191.

SINKANKAS, J. (1964) Mineralogy for Amateurs. Von Nostrand Reinhold Company, New York, 585 pp.

SWANSON, D.A. (1973) Pahoehoe flows from the 1969–1971 Mauna Ulu eruption, Kilauea volcano, Hawaii. Geological Society of America Bulletin, **24**, 615-626.

THE LOWER NEW STREET QUARRY, PATERSON, NEW JERSEY: A RE-INTERPRETATION

John H. Puffer and Chris Laskowich

Dept. of Earth & Environmental Sciences, Rutgers University, Newark, New Jersey 07102, jpuffer@andromeda.rutgers.edu

Abstract

The second flow of the Orange Mountain basalt (OMB2) is exposed at the abandoned Lower New Street trap-rock quarry, Paterson New Jersey. Structures typical of subaqueous flood basalts, particularly flow lobes and pillows are exposed along the base of the quarry in the OMB2 flow. Several structures commonly found in subaerial flood basalts including flat pahoehoe surfaces, pahoehoe toes, collapsed and open lava tubes, large lower flow vesicles, and massive to columnar joint systems are exposed along the central and upper quarry walls and throughout a large portion of the Upper New Street Quarry. The secondary mineralization of the OMB2 flow is characterized by zeolites including apophyllite, chabazite, heulandite, pectolite, natrolite, and stilbite with less common to rare, analcime, babingtonite, laumontite, mesolite, pumpellyite, stellerite, and gmelinite. These zeolites and datolite are much more commonly found in the pillowed (subaqueous) portions of the OMB2 flow at both the Lower and Upper New Street quarries than in the OMB1 or OMB3 flows. However, the distribution of prehnite is just the opposite, more likely to occur within subaerial flow structures where it is by far the dominant secondary mineral, particularly within OMB1 diapirs, and the subaerial portion of OMB2 at the Lower and Upper New Street Quarries. This discrepancy may be due to the chemical effects of primary salt water contamination on the mineralization of sodic zeolites in the OMB2 flow.

Introduction

The Lower New Street Quarry (Fig. 1) is located in a wooded lot at 100 New Street, Paterson, New Jersey adjacent to Route 80 east, in Passaic County, and is mapped within the Paterson Quadrangle. It is one of several trap-rock quarries cut into the Orange Mountain basalt of New Jersey. High quality specimens of prehnite, analcime, chabazite, datolite, heulandite, pectolite, natrolite, stilbite, and amethyst have been found in at Lower New Street and in the adjacent Upper New Street quarry located on the east side of New Street. This secondary mineral assemblage in the context of Paterson area trap-rock quarries has been described by Fenner (1910), Schaller (1932), Drake, (1943), Mason (1960), Sassen (1978), Peters et al. (1980), Peters (1984), Cummings (1985, 1987), Kent and Butkowski (2000), Imbriacco (2009, 2010) Sinkankas, J. (1964), Puffer and Student (1992), Puffer and Laskowich (2012), and Laskowich and Puffer (in prep.). One purpose of this chapter is to summarize some new observations pertaining to the distribution of these secondary minerals. Details of these observations appear in the following chapter by Laskowich (this guidebook). This chapter also includes the proposal that a transition from a lower OMB2 subaqueous environment to an upper OMB2 subaerial environment is reflected by a consistent change in the volcanic structures exposed at the Lower New Street quarry.

Geologic Setting

The trap-rock quarries of Lower and Upper New Street expose Orange Mountain basalt consisting of three flows (OMB1, OMB2, and OMB3) from the base to the top of the formation. The first flow is a 60 to 70 m thick subaerial flow, the second flow is about 40 m thick unit that near Paterson is alternately pahoehoe and pillowed. The third flow is subaerial and about 60 m thick. The three flows may be locally discontinuous throughout parts their entire geographic distribution but wherever drill cores through the flows have been logged three flows have been reported. The three flows are separated by scoraceous flow tops and thin discontinuous beds of intertrappen red-bed sediment.

Fig. 1. The geologic setting of the Lower New Street quarry. Jo (Orange Mountain Basalt), Jf (Feltville Formation), JTrpsc (Passaic Formation), Jps (Preakness Basalt), Jt (Towacco Formation) after Drake et al. (1996). West Paterson has been renamed Woodland Park.

The Orange Mountain Basalt together with the overlying Preakness and Hook Mountain flows are part of the Central Atlantic Magmatic Province (CAMP) that is distributed across eastern North America, northeastern South America, northwestern Africa, and southern Europe (Marzoli et al. 2011). High precision age dating (Blackburn et al. 2013) indicates that the Orange Mountain basalt extruded 201.56 Ma and defines the end of Triassic extinction at the Triassic-Jurassic boundary. Recent isotopic evidence (Merle et al. in press) indicates that the Orange Mountain Basalt originated from a subduction-enriched mantle source as originally proposed by Puffer (2003).

The Lower New Street Quarry

a. Subaqueous pillowed OMB2 at base of quarry

At the base of the Lower New Street quarry, in a trench along the south end of the quarry wall, excellent exposures of pillow basalt provide evidence of subaqueous extrusion. Pillows are an important characteristic of the OMB2 flow wherever it has been described. Most of the pillows are large (about one meter across) and are coated with a dark green palagonite rind. Subtle differences in shape and distribution have enabled Manspeizer (1980) to distinguish between pillows, flow lobe pillows, and bedded pillow buds although some of the distinctions among sub-types are based on observation made at other quarries including the Upper New Street quarry that was cut into the OMB2 flow.

b. Subaerial pahoehoe OMB2 on quarry wall

Flat pahoehoe surfaces, pahoehoe toes, collapsed and open lava tubes, large lower flow vesicles, and massive to columnar joint systems are exposed along the quarry wall of the Lower New Street quarry. In contrast to the pillows observed in the trench at the base of the quarry the elongate ellipsoidal structures exposed on the quarry wall are here interpreted as subaerial pahoehoe toes. The criteria for distinction between pillows and pahoehoe toes was presented by Manspeizer (1980) as first established by Macdonald (1953):

Pahoehoe tows

Major axis of the ellipsoid 3 or 4 times the cross sectional axis.

Concentric structures in cross section.

Moderately to highly vesicular or amygdaloidal.

Vesicles elongate tangentially to edge or not at all.

Lava tubes are common, resulting in central cavities.

Radial joints are poorly developed or absent.

Pillows

Major axis of ellipsoid less than 3 or 4 times the cross sectional axis.

Radial structures well developed.

Moderately to poorly vesicular or amygdaloidal.

Vesicles elongate radially, especially near the edge.

Lava tubes are rare.

Radial joints are well-developed and conspicuous in cross section.

These criteria continue to be generally accepted among volcanologists. Although not all of the ellipsoid dimensions of the pahoehoe toes exposed on the quarry wall appear to be more than 3 times the cross section axis, the criteria is based on the maximum dimension of the cross section axis which is not typically exposed in outcrop. It is, however, apparent that lava tubes are common across the quarry face. Each of these tubes have been lined to varying degrees with prehnite. Most of these tubes have collapsed or partially collapsed under the weight of late OMB3 flow inflation resulting in horizontal layers of breccia cemented with prehnite.

At a central location on the south-west quarry wall a smooth flat surface dipping northward about 15 degrees is interpreted as a subaerial pahoehoe surface. Similar surfaces are not commonly found throughout the OMB1 and OMB3 flows despite their generally recognized acceptance as subaerial flood basalt flows. The pahoehoe surface exposed here marks the transition of a subaerial flow lobe before it was buried by a thick layer of massive tholeiitic basalt.

Some columnar cooling joints are apparent in the upper quarry wall together with large vesicles that are a characteristic of OMB1, again, generally accepted as subaerial.

Secondary Mineralization

In general, the most prehnite that we have found among Orange Mountain basalt exposures throughout New Jersey is contained within subaerial structures including diapirs, large partially filled vesicles, half-moon vesicles, and vesicular flow-tops (Puffer and Laskowich, 2012). In contrast, the most productive zeolite collecting is largely confined to the pillows of the OMB2 flow with some notable exceptions. The prehnite to zeolites abundance ratio throughout the Lower New Street quarry above the pillow layer is typical of Orange Mountain subaerial exposures elsewhere and is quite high. There is no definitive explanation for this. However, the zeolites found in the

Orange Mountain basalt are much more highly hydrated than prehnite and in most cases are sodic in contrast to prehnite which contains calcium as the only significant octahedral cation. Perhaps preferential salt water contamination of the pillowed layers during extrusion is a controlling factor. Geochemical evidence (Puffer and Student, 1992; and Tollo and Gottfried, 1992) indicates that the pillowed portions of OMB2 contain up to 5.34 percent Na_2O compared to a typical OMB concentration of only 2.4 percent.

Conclusions

1. Large portions of the Upper and Lower New Street quarries that have been interpreted as subaqueous pillow basalt are re-interpreted as subaerial pahoehoe flows. Pillow basalt is confined to exposures at both quarries that stratigraphically underlie the subaerial portion of OMB2.

2. Most zeolite mineralization is confined to the pillowed portion of OMB2 at the Upper and Lower New Street quarries.

3. Most prehnite mineralization is confined to the subaerial, pahoehoe portion of OMB2 at the Upper and Lower New Street quarries and throughout OMB1 and OMB3 throughout New Jersey.

4. Zeolite concentrations in subaqueous portions of OMB2 are consistent with sodium contamination of basalt from brackish water sources.

References

BLACKBURN, T.J.; OLSEN, PAUL; BOWRING S.A., MCLEAN, NOAH; KENT, DENNIS; PUFFER, J.H.; MCHONE, GREG; RASBURY, TROY, AND EL-TOUHAMI, MOHAMMED. (2013) High-precision U-Pb zircon geochronologic constraints on the End-Triassic Mass Extinction, Central Atlantic Flood Basalt volcanism and the late Triassic Astronomical Time Scale. Science.

CUMMINGS W.L. (1985), Mineralization at the Millington quarry, New Jersey. *Rocks and Minerals*, **60**, 213-218.

CUMMINGS W.L. (1987) Mineralization at the Fanwood & Summit Quarries, New Jersey. *Rocks and Minerals*, **62,** 150-159.

DRAKE, H.Y. (1943) The quarry at Upper Montclair, N.J. *Rocks and Minerals*, **18**, 332-333.

DRAKE, A.A., JR., VOLKERT, R. A., MONTEVERDE, D.H., HERMAN, G. C., HOUGHTON, H. F., PARKER, R. A., DALTON R. F., 1996. Bedrock geologic map of Northern New Jersey: U.S. Geol. Survey Miscellaneous Series Map 1-2540-A, scale 1:100,000.

FENNER, C.N. (1910) The Watchung basalt and the paragenesis of its zeolites and other secondary minerals. *New York Acad. Sci. Annals*, **20,** 93-187.

IMBRIACCO, F.A. (2009), The Braen Quarry, Haledon, Passaic County, New Jersey. *Mineralogical Record*, **40**, 511-524.

IMBRIACCO, F.A. (2010), The Fanwood Quarry, Somerset County, New Jersey. *Mineralogical Record*, **41**, 161-174.

KENT, B.P. and BUTKOWSKI, B. (2000) Mineral of the Millington Quarry, Somerset County, New Jersey. *Mineralogical Record*, **31,** 399-411.

LASKOWICH, CHRIS and PUFFER, JOHN H. (submitted) Prehnite and zeolites in the volcanic structures of the Orange Mountain Basalt, Paterson, New Jersey. The Mineralogical Record.

MACDONALD, G.A. (1953) Pahoehoe, aa, and block lava. *American Journal of Science*, **251**, 169-191.

MANSPEIZER, W. (1980) Rift tectonics inferred from volcanic and clastic structures. In Manspeizer (editor) Field studies of New Jersey geology and guide to field trips. *52nd Annual Meeting of the New York State Geological Association*, Rutgers University, Newark New Jersey p. 314-350.

MARZOLI, A., JOURDAN F., PUFFER J.H., CUPONE, T., TANNER L. H., WEEMS, R.E., BERTRAND H., CIRILLI, S., BELLIENI G., and DE MIN A. (2011) Timing and duration of the Central Atlantic magmatic province in the Newark and Culpeper basins, eastern U.S.A. *Lithos*, **122**, 175-188.

MASON, B.H. (1960) Trap rock minerals of New Jersey. *New Jersey Geological Survey* Bulletin 64.

MERLE, RENAUD; MARZOLI, ANDREA; REISBERG, LAURIE; BERTRAND, HERVÉ; NEMCHIN, ALEXANDER; CHIARADIA, MASSIMO; CALLEGARO, SARA; JOURDAN, FRED; BELLIENI, GIULIANO; KONTAK, DAN; PUFFER, JOHN; AND MCHONE, J. GREGORY (in press)), Sr, Nd, Pb and Os isotope systematics of CAMP tholeiites from Eastern North America (ENA): Evidence of a subduction-enriched mantle source, Journal of Petrology

OLSEN P. E, SCHLISCHE R. W, FEDOSH M. S. (1996) 580 ky duration of the Early Jurassic flood basalt event in eastern North America estimated using Milankovitch cyclostratigraphy. in Morales, M. (ed.) The Continental Jurassic, Museum of Northern Arizona Bulletin, **60**, 11-22.

PETERS, J.J. (1984) Triassic traprock minerals of New Jersey. *Rocks and Minerals*, **59**, 157-183.

PETERS, T.A., PETERS, J.J. and WEBER, J. (1980) Famous mineral localities: Paterson, New Jersey. *Mineralogical Record*, **9**, 157-179.

PUFFER, J. H., (2003), A reactivated back-arc source for CAMP Magma: in Hames, W. E., McHome, J. G., Renne, P. R., and Ruppel, C. (editors) The Central Atlantic Magmatic Province: Insights From Fragments of Pangea: American Geophysical Union Geophysical Monograph 136, p. 151-162.

PUFFER, J. H., and STUDENT, J.J. (l992) The volcanic structure and eruptive style of the Watchung Basalts, New Jersey*: in* Puffer, J. H. and Ragland, P. C., (editors) Eastern North American Mesozoic Magmatism: *Geological Society of America, Special Paper* **268**, 261-279.

PUFFER, J.H. and LASKOWICH, C. (2012) Volcanic diapirs in the Orange Mountain flood basalt: New Jersey, USA. *Journal of Volcanology and Geothermal Research*, **237-238**, 1-9.

SASSEN, R. (1978) Natrolite and associated secondary minerals at the Chimney Rock Quarry, Bound Brook, New Jersey. *Mineralogical Record,* **9**, 25-31.

TOLLO R.P. AND GOTTFRIED, DAVID, (1992),Petrochemistry of Jurassic basalt from eight cores, Newark Basin, New Jersey: Implications for the volcanic petrogenesis of the Newark Supergroup: in Puffer, J. H. and Ragland, P. C., (editors) Eastern North American Mesozoic Magmatism: Geological Society of America, Special Paper 268, p. 233-259.

SCHALLER, W.T. (1932) The crystal cavities of the New Jersey zeolite region. *U.S. Dept of the Interior Geological Survey Bulletin,* **832**, 90 pp.

SINKANKAS, J. (1964) Mineralogy for Amateurs. Von Nostrand Reinhold Company, New York, 585 pp.

OVERVIEW OF THE STATEN ISLAND SERPENTINITE

Alan I. Benimoff[1] and John H. Puffer[2]

1. Department of Engineering Science and Physics, College of Staten Island, Staten Island, NY 10314

2. Dept. of Earth & Environmental Sciences, Rutgers University, Newark NJ 07102

Introduction

The Staten Island serpentinite is a lens shaped NE-SW trending body, having a long dimension of 12 km and a width of 4.7 km. The ridge of serpentinite, makes up the bedrock in the northeastern section of Staten Island, and reaches an elevation of approximately 135 meters above sea level.

The serpentinite body is part of a string of similar ultramafic bodies, extending throughout the Appalachians, from Alabama to Newfoundland (Figure 1). The serpentinite displays a sheared contact with the Hartland formation along its eastern margin (Lyttle and Epstein, 1987) and is uncomfortably overlain by the Triassic age Stockton formation of the Newark super group at the western margin. In places, the western contact is faulted. The southern and eastern margins of the serpentinite are overlain by the Raritan formation of cretaceous age. Pleistocene glacial deposits overlay most of the serpentinite. In cross section the serpentinite body is a wedge shaped pod, extending downward approximately 1.3 km (Yersak, 1977). The serpentinite is situated on Cameron's Line at the base of the Hartland Formation (Lyttle and Epstein, 1987). Hollick (1909) suggested that the Staten Island Serpentinite is a fault bounded horst block. Crosby (1914), Miller (1970) share that interpretation.

The Staten Island Serpentinite is part of a discontinuous chain (Figure 1) of ultramafic bodies that extends from Alabama to Québec. The Staten Island body is the largest of four lenticular masses exposed in the New York City area that includes exposures at Hoboken, New Jersey, Western Manhattan, and Easton Bronx. It is a wide lens shape (Figure 2) that trends Northeast – Southwest and comprises the bedrock of northern Staten Island, although the Western boundary is not exposed.

There is general agreement that the Staten Island Serpentinite is positioned on Cameron's line which defines the tectonic boundary of the western part of the Appalachian core zone. Lyttle and Epstein (1987) stratigraphically place (Figure 2) the Staten Island meta-peridotite and other related serpentinite bodies on Cameron's line conformably above member C of the Manhattan Schist but suggest that most of the peridotite lies east of Cameron's line at the base of the Hartland terrain.

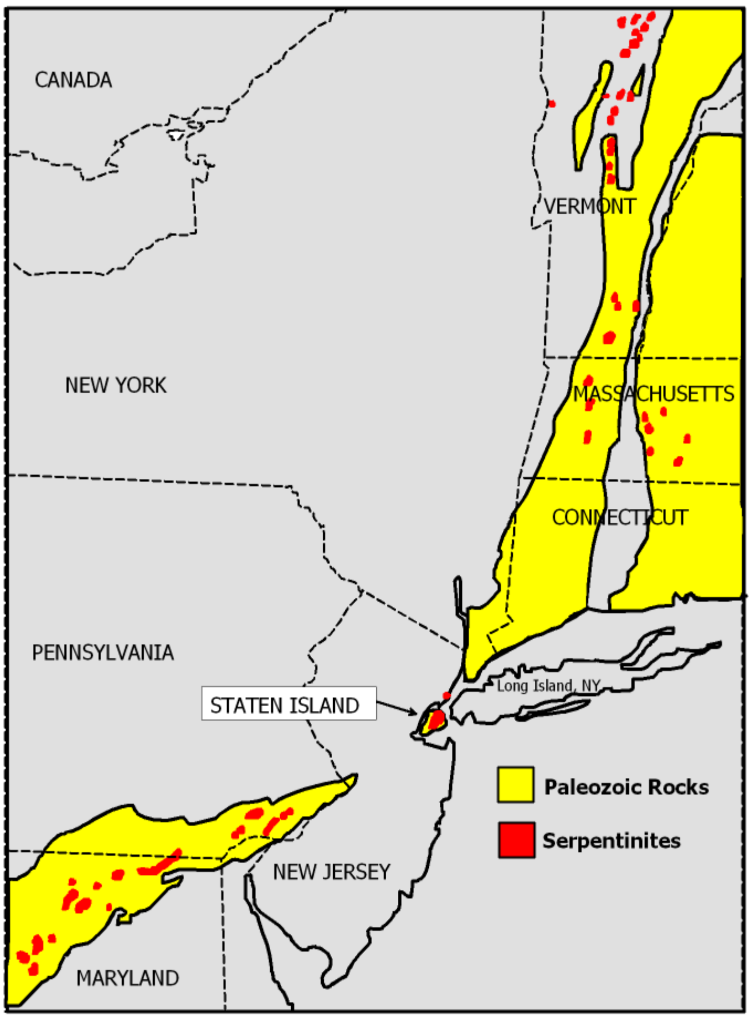


Figure 1: Serpentinite occurrences in the central and northern Appalachians appearing on the USGS "Tectonic map of the United States (modified from Puffer, 1996)

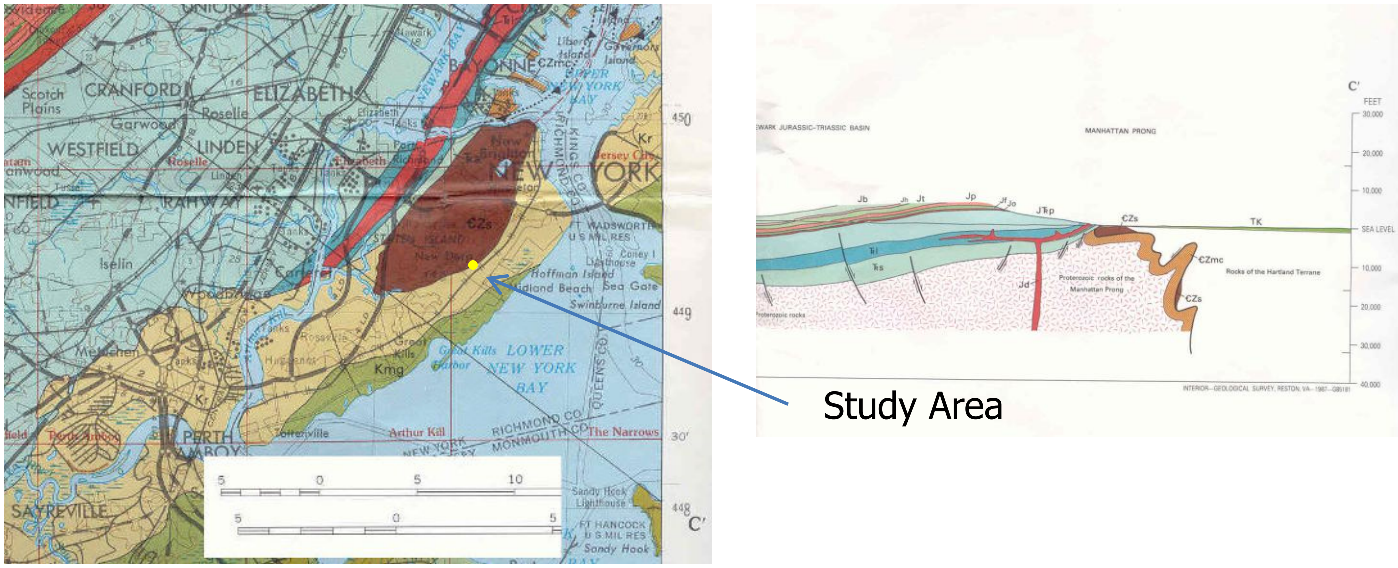


Figure 2: Map and Cross section from Lyttle and Epstein, 1987. Study area is from Benimoff and Lupulescu, 2008).

Petrology

Germine, 1981, Germine, M., and Puffer, J. H., l981 and Puffer, J. H., and Germine, M., l994 methodically examined samples of the Staten Island Serpentinite from 27 localities. They determined that about 66% of the serpentinite is lizardite and 27% chrysotile. Other predominate minerals are olivine, chromite, and magnetite together with minor talc, anthophyllite, relic pyroxene, chlorite, and magnesite. They concluded that the protoliths of the serpentinite body were harzburgite and dunite.

The Staten Island serpentinite has been divided into two zones by Behm, (1954): a highly sheared outer serpentinite characterized by an abundance of talc, anthophyllite, and magnetite, and a relatively massive, under formed inner zone composed largely of partially serpentenite peridotite.

Although now largely a serpentinite, the protolith was a peridotite that was serpentinized before or during Taconic tectonic emplacement. If the protolith was an ophiolite most hydration to serpentine was probably introduced by heated deep marine water circulation near a spreading center. Most samples of peridotites dredged from the ocean floor are largely hydrated to serpentine and contain over 10% H_2O.

Clues as to the original protolith are found in some of the olivine rich samples, particularly from the North – Central portion of the ultramafic body. Unaltered pyroxene is rarely observed in any of the rock but phenocrysts of pyroxene that have been partially or completely altered to inter growths of chlorite, talc and oxide are common in some of the massive serpentinite. These altered pyroxene phenocrysts make up about 15% of subsamples and indicate that such rock was a harzburgite. Most samples of massive serpentinite where primary igneous textures are preserved, however, do not contain evidence of pyroxene and are probably dunite.

Ophiolite Emplacement

Most of the original olivine has been altered to serpentine but some samples contain as much as 50% olivine. The average olivine content of the Staten Island serpentinite is about 5% but it is absent from most samples. Where present, olivine typically occurs as relic anhedral micro – islands surrounded by serpentine that has replaced most of the individual grains or as larger grains thing by olivine. Further details of the petrology of the serpentinite are given in Behm (1954); Germine and Puffer (1981); and Puffer (1996).

Puffer (1996) compares two mechanisms of serpentinite emplacement: Obduction of an ophiolite-suite member or a metamorphosed olivine cumulate zone in a layered gabbro magma chamber. Puffer (1996) supports the obducted ophiolite member since the serpentinite is associated with the Harland schist. Puffer (1996) concludes that the mode of emplacement of the New York area serpentinites is controversial but most evidence tends to favor Taconic obduction of the base of the Iapetus ophiolite sequence. Thus would force the placement of the New York area serpentinites into the Taconic suture zone (Cameron's line) between the Hartland terrain and Manhattan C terrain.

There is general agreement that the chemistry of olivine and spinel reflect the magmatic conditions of origin of highly serpentinized peridotite (Dick and Bullen 1984; Arai 1994; Kametesky et al., 2001: Metsger et al., 2002.

Recently Benimoff and Lupulescu (2008) sampled serpentinite samples from an excavation (Figure 2) for a shopping center in the Staten Island Serpentinite (N 40.5813° and W 74.1123°). The average composition of the serpentinite at this location is SiO_2 34.96, Al_2O_3 0.21, CaO 0.04, MgO 41.41, Na_2O<0.01, K_2O 0.03, Fe_2O_3 7.66, MnO 0.01, TiO_2 0.02, Cr_2O_3 0.44, and LOI 15.57 sum 100.36 wt %. They reported Cr-spinel grains disseminated in the serpentinite; the grains are fractured and some are zoned with a Cr-rich core and Fe-rich rim. Electron microprobe analyses were used to compute the following empirical formulas for core $(Fe^{+2}_{0.70}\,Mg_{0.28}\,Mn_{0.02})_{\Sigma=1.00}\,(Cr_{1.47}\,Al_{0.39}\,Fe^{+3}_{0.14})_{\Sigma=2.00}\,O_4$ and rim $(Fe^{+2}_{0.88}Mg_{0.11}Mn_{0.01})_{\Sigma=1.00}\,(Cr_{0.7028}\,Al_{0.01}\,Fe^{+3}_{1.28})_{\Sigma=1.99}\,O_4$ respectively. Cr numbers range from 94-99 in the rim to 79-87 in the core and the Mg numbers from 9-11 in the rim to 25-30 in the core indicating a probable dunite-harzburgite derivation. The core of the spinels analyzed in their study plot at the margin of the fore-arc peridotite region of Coish and Gardner (2004) in the $(Cr/Cr+Al)_{sp}$ vs. ($Mg/Mg+Fe)_{sp}$ diagram.

Recent work by Moores, Kellogg and Dilek (2000) describe a conflict in many ophiolite complexes that they call the "Ophiolite conundrum". The conflict is between "(1) structural and stratigraphic evidence for sea-floor spreading in a non–island arc environment and (2) geochemical evidence for derivation of magmas from highly depleted mantle similar to that found at present over subduction zones (suprasubduction zone settings)." Furthermore, oceanic paleogeography of the pre-suture ocean basin can be complex because dismembered ophiolitic rocks are associated with both MORB and arc-like igneous rocks (Tankut, et al. 1998). Ophiolite complexes can be divided into either Tethyan or Cordilleran (Moores et al. 2000; Wakabayashi and Dilek, 2003).

Coish and Gardner (2004) studied olivine samples from the meta-peridotite of the Vermont Appalachians in order to evaluate whether they were indeed parts of ophiolites, and if so in what tectonic environment they might have formed. They concluded through remnant olivine and chromite chemistry, that the peridotites probably formed in the fore-arc of an early Ordovician subduction zone. In their study they plotted Fo compositions of Olivine against Cr/(Cr+Al)sp. It is clear that their Fo compositions fall mainly within the mantle array. They concluded that this represents conditions before serpentinization and regional deformation. Furthermore they state that "the small Fo range is typical of residual peridotite, particularly harzburgite and dunite, and unlike cumulate rocks which tend to show lower Fo contents"(Arai, 1994). Their geochemical analyses on Olivine and spinel support the hypothesis that their peridotites formed as highly-depleted mantle residues and they probably formed in a fore-arc, suprasubduction zone during the early Paleozoic. The data suggest that this serpentinite body probably formed in the same way as that described by Coish and Gardner (2004) for the serpentinite in the Vermont Appalachians namely in a fore-arc suprasubduction zone (Figure 3).

However, the occurrence of a suprasubduction zone peridotite in the Northern USA Appalachians (Coish and Gardner, 2004) is not clear evidence that the Staten Island serpentinite is a Cordilleran type. Puffer (Chapter 1, this guidebook) presents evidence that the Staten Island ophiolite resembles the Wakabayashi and Dilek (2003) interpretation of a Tethyan ophiolite more closely than a Cordilleran type. Evidence includes the fact that the Hartland occurs above the Staten Island ophiolite (Figures 2 and 3). If the Hartland is interpreted as an accretionary complex is should instead exist beneath the ophiolite (Figure 4) to fit the Cordilleran description. Puffer (Chapter 1) also points out that the petrologic characteristics of undisputed accretionary complexes such as the Franciscan Formation of California are much different than Hartland rock. However, the issue is probably not settled.

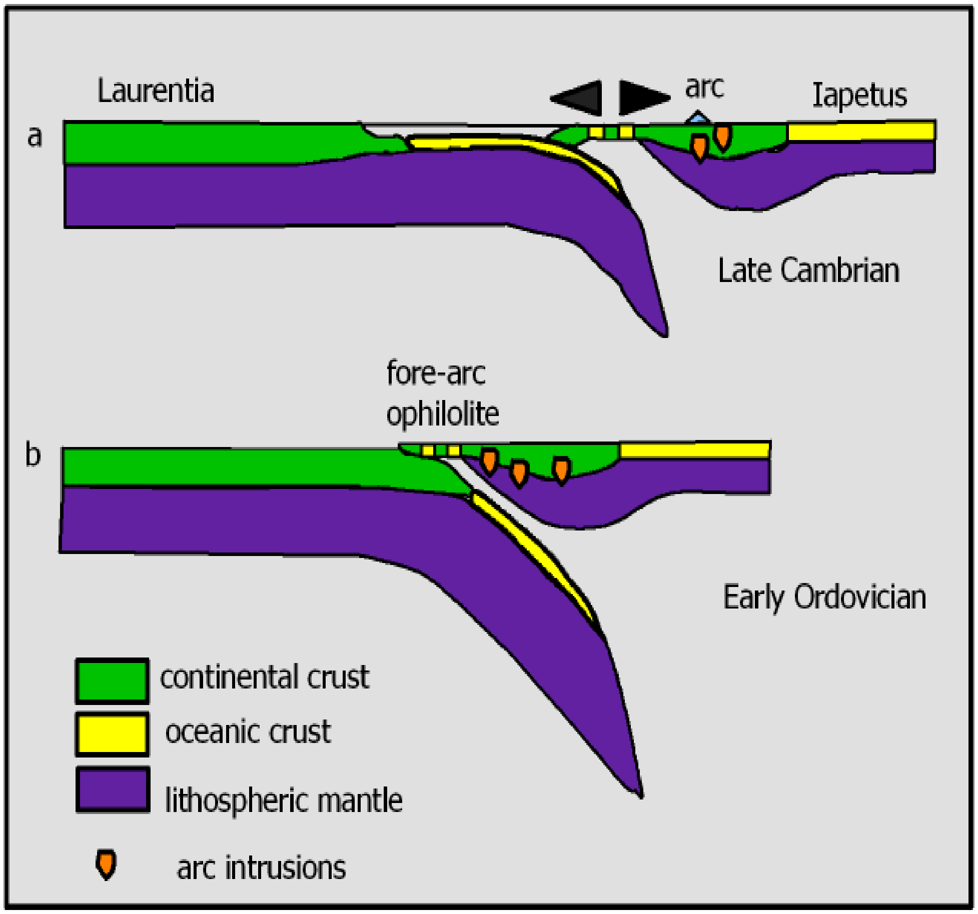


Figure 3: Modified from Coish and Gardner, 2004.

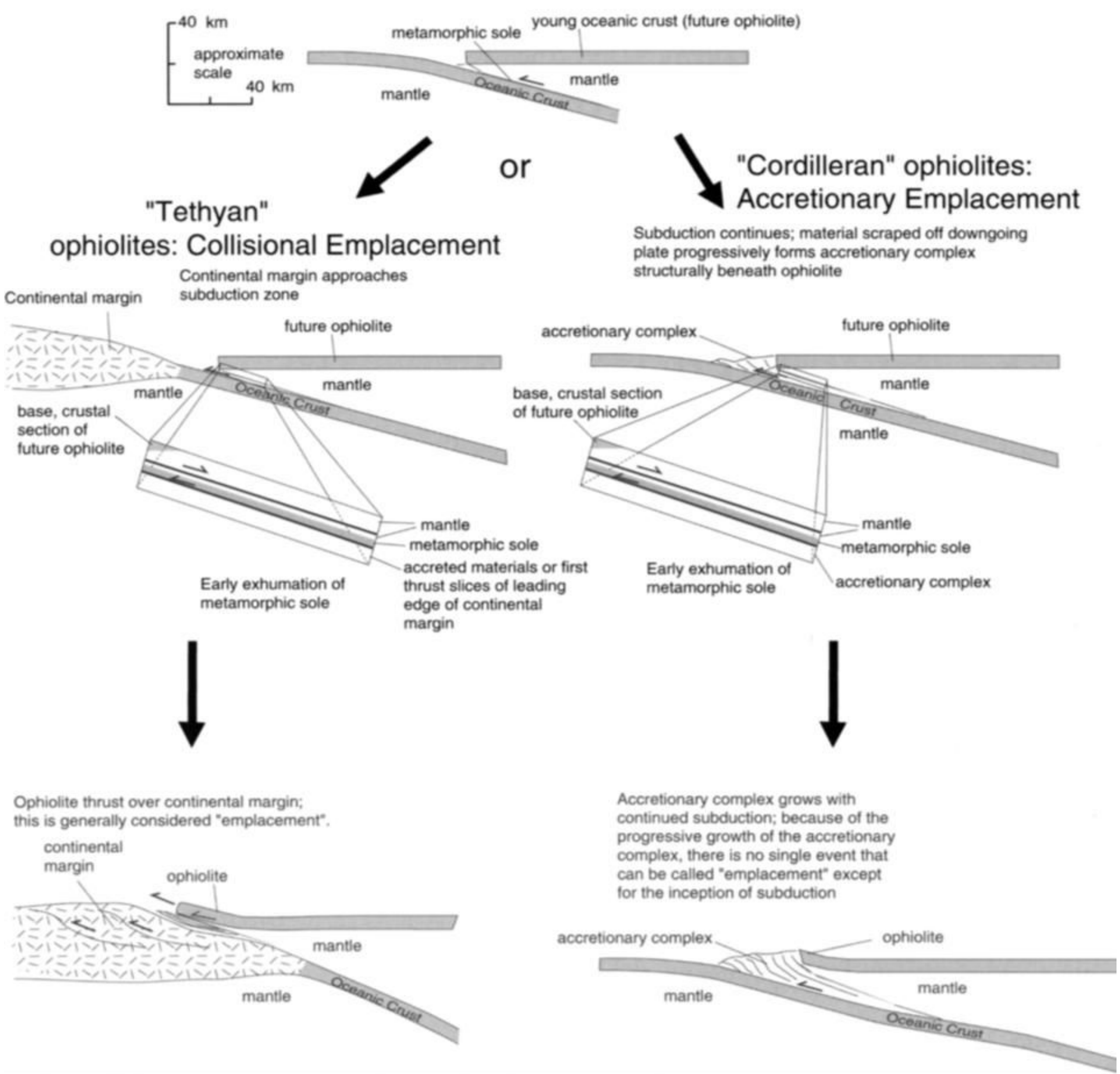


Figure 4. after Wakabashi and Dilek (2003): Emplacement of Tethyan and Cordilleran ophiolites. It should be noted that if a continental margin is attached to the plate subducting beneath a Cordilleran ophiolite, such an ophiolite may eventually be thrust over a continental margin, 'converting' it to a Tethyan-type ophiolite.

References

Arai S.(1994) Characterization of spinel peridotites by Olivine-Spinel compositional relationships; review and interpretation. Chemical geology, 113, 191-293.

Behm, J.J, (1954) The petrology of the Serpentinite of Richmond County (Staten Island). N.Y. Proceedings of the Staten Island Institute of arts and Sciences, V 16, p1-39.

Benimoff, A. I and Lupelscu M. (2008) Zoned accessory Cr-spinel in the Staten Island serpentinite from a new Richmond road outcrop in Staten Island, NY GSA abstracts with programs, 40, No. 2 p 21.

Coish R.A. and Gardner P.(2004) Suprasubduction zone peridotite in the Northern USA Appalachians: Evidence from mineral Composition. Mineral. Mag. Vol. 64(4) 699-708.

Crosby(1914) W.O. (1914) Physiographic relations of serpentine with special reference to the serpentine rock of Staten Island. Journal of Geology 22, No. 6, 582-592

Dick H.J.B and Fisher R.L. (1984) Mineralogical studies of the residues of mantle melting ; Abyssal and alpine peridotites. In J. Korbprobst, ed. Kimberlites II: The mantle and crust mantle relationships. 295-308. Elsevier, Amsterdam.

Dick H.J.B and Bullen T. (1984) Chromian spinel as a petrogenetic indicator in abyssal and Alpine –Type peridotites and spatially associated lavas. Contributions to Mineralogy and Petrology 86, 54-76.

Germine, 1982, Asbestiform serpentine and amphibole group minerals in the northern New Jersey area: Newark, New Jersey. Rutgers University, Master’s thesis, 239 pp.

Germine, M., and Puffer, J. H., l981, Distribution of asbestos in the bedrock of the northern New Jersey area: Environmental Geology, v. 3, p. 337-351.

Hollick C.A. (1909) notes in connection with specimens recently obtained from

serpentinites of Staten Island N.Y. New York Academy of Sciences Annals, V19, p 315-317.

Kametsky, V.S.Crawford, A.J.and Meffre,S.(2001) factors controlling chemistry of magmatic spinel: an empirical study of associated Olivine, Cr-spinel and melt inclusions from primitive rocks. Journal of Petrology, 42, 655-671

Lyttle, P and Epstein, J.(1987) Geologic Map of the Newark 1° x 2°Quadrangle, New Jersey, Pennsylvania and New York. USGS map I-1715.

Metsger, E.P., Miller, R.B. and Harper, G.D.(2002)Geochemistry and tectonic setting of the ophiolitic Ingalls Complex, North Cascades, Washington: Implications for correlations of Jurassic Cordilleran ophiolites. Journal of Geology 110, , 543-560.

Miller, W.H. (1970) Structural Geology and Tectonism of the Staten Island Serpentine,; Brooklyn College masters Thesis 67pages.

Moores, E.M., Kellogg L.H and Dilek Y(2000) Tethyan ophiolites, mantle convection, and tectonic historical contingency": A resolution of the "Ophiolite conundrum in Dilek Y, Moores E.M., Elthon D, and Nicolas A eds. Ophiolites and Oceanic Crust: New Insights from Field Studies and the Oceanic drilling program: Boulder Colorado, Geological society of America Special Paper 349, p 3-12.

Puffer, J. H. (1996) ed *in* Benimoff, A.I., Serpentinites of New York City and Vicinity, *in* Field trip Guide for the 68th Annual Meeting of the New York State Geological association, p.157-176

Puffer, J. H., and Germine, M., l994, The Staten Island Meta-Peridotite: *in* Benimoff, A.I., (editor), Geology of Staten Island, New York, Field Guide and Proceedings, Geological Association of New Jersey, p. 1-25.

Tankut, A., Dilek. Y and Önen, (1998) Petrology and geochemistry of the neo-Tethyan volcanism as revealed by the Ankara mélange, Turkey Journal of Vulcanology and Geothermal Research 85, 265-284

Yersak, T.E(177) Gravity Study of Staten Island and vicinity, Rutgers University, New Brunswick, NJ Masters Thesis.

Wakabayashi, J. and Dilek, Y., 2003, What constitutes 'emplacement' of an ophiolite?" Mechanisms and relationship to subduction initiation and formation of metamorphic soles. In DILEK, Y. & ROBINSON P. T. (eds) Ophiolites in Earth History. Geological Society, London, Special Publications, v. 218; p. 427-447.

UNRAVELING PANGEA FLOOD BASALTS FROM THE BOTTOM UP: THE ORANGE MOUNTAIN BASALT MIXED LAVA

Jeffrey C. Steiner[1], Karin A. Block[1*], Nicholas C. Steiner[1*], John H. Puffer[2], Lev Sviridov[3]

[1]Department of Earth and Atmospheric Sciences, The City College of New York, New York, NY 10031
[2]Department of Earth and Environmental Sciences, Rutgers University, Newark, NJ, 07102
[3]CUNY Energy Institute, The City College of New York, New York, NY 10031

Abstract

An investigation of the transformations in mineralogy that occur within the Orange Mountain Basalt at Tilcon traprock quarry, Clifton, New Jersey defines the presence of five distinct facies, four of which are considered primary layering and the fifth a deformed diapir. A plot of the gamma ordering for unit cells sampled at intervals of ten meters places the boundaries at 15, 45, 80 (diaper), and 110 meters. As representative of the layering, a detailed examination of the plagioclase composition across the second boundary delineates facies 2 as a sodic labradorite facies, An50, with a sanidine component consistent with an origin at 1 kbar over a temperature range of 1000^o to 1100^{o}C. The overlying calcic labradorite facies averages An69 with minimal sanidine involvement. The distinctive mixed lava sequence is consistent with cumulus-transport-deposition theory for the emplacement of horizons within the Palisades Sill of New York and New Jersey, leading to the suggestion that a variable chemistry with Sill may have its source in the welding and annealing of similar mixed-basalt aggregates, or packets, within magma Pulse 1 of the Palisades.

Introduction

The Palisades Sill-Watchung Flow system provides a remarkable opportunity to investigate the evolution of a flood basalt system in the step from a shallow subsurface chamber to an eruptive surface flow. The Palisades Sill is a complex structure that extends in the subsurface from the Hudson River in the east to the Gettysburg Sheet approximately 250 miles to the west (Figure 1). It is widely considered to have formed through the interaction of a mantle-derived melt with deeply buried remnants of a supra-subduction zone complex formed at the suture of the North American Plate and African Plates. This melting of Pangea granulites produced a variety of continental flood basalts (Pangean CFBs). The initial fraction comprises high Ti (TiO_2) quartz normative tholeiite (HTQ type of Weigand and Ragland, 1970) and a later fraction that evolved a low Ti, or LTQ variety. The present eruptives, the Orange Mountain Basalt (OMB) of the Watchung Basalts therefore represent the more primitive of the rifting paradigm (see Puffer, 1992 & 2002) that invaded sedimentary strata of the Newark Supergroup as part of the late Triassic/early Jurassic Central Atlantic Magmatic Province (CAMP; Marzoli, et al., 1999).

Recent work by Puffer and others (2003) proposes that the Palisades is comprised of three discrete magma pulses that successively gave rise to the Orange Mountain Basalt, the Preakness Basalt, and the Hook Mountain Basalt of the Watchung Series, respectively. In this view, basal Pulse 1 of the Palisades Sill of New York and New Jersey is viewed as a remnant of a through-going eruptive set that gave rise to the lowermost Watchung, the OMB. This raises issues of similarity in composition, modal assembly and the significance of layering in the intrusion as applies to the internal structure of the Palisades Sill. A focal point of that work is an extension of cumulus-transport-deposition model (CTD; Steiner and others, 1992) that proposes that the famous Olivine Zone of the Palisades (Hyalosiderite Dolerite, Walker 1969) represents in part an accreted pre-eruptive cumulus with the corollary that significant cryptically layered portions of the lower Palisades should be viewed as potential pre- and syn-eruptive accumulations. This runs counter to the historical emphasis given to *in situ* post-intrusion crystal segregation episodes (see for example, Shirley,1987&1988) . The CTD model postulates that the Palisades has compiled facies that represent disaggregated portions of subterranean magma chambers: stacked sills and lenses comparable to those outlined by Shervais and others, 2006.

The present study examines the OMB with the intent of identifying possible cryptic layering of the sort postulated for the CTD model. The present work uses the micro-chemistry and structure of the OMB labradorite suite to define discrete plagioclase populations in flow-aligned facies within the basalt. The presence of layering bears directly on the theory that a largely coeval emplacement occurred in Pulse 1 magma of the Palisades Sill.

The OMB (Figure 1) is exposed at the UBC/Clifton Tilcon Quarry, West Paterson, New Jersey Jersey. A set of 13 samples at 10 meter intervals beginning from within approximately 5 meters of the basal contact (not exposed).

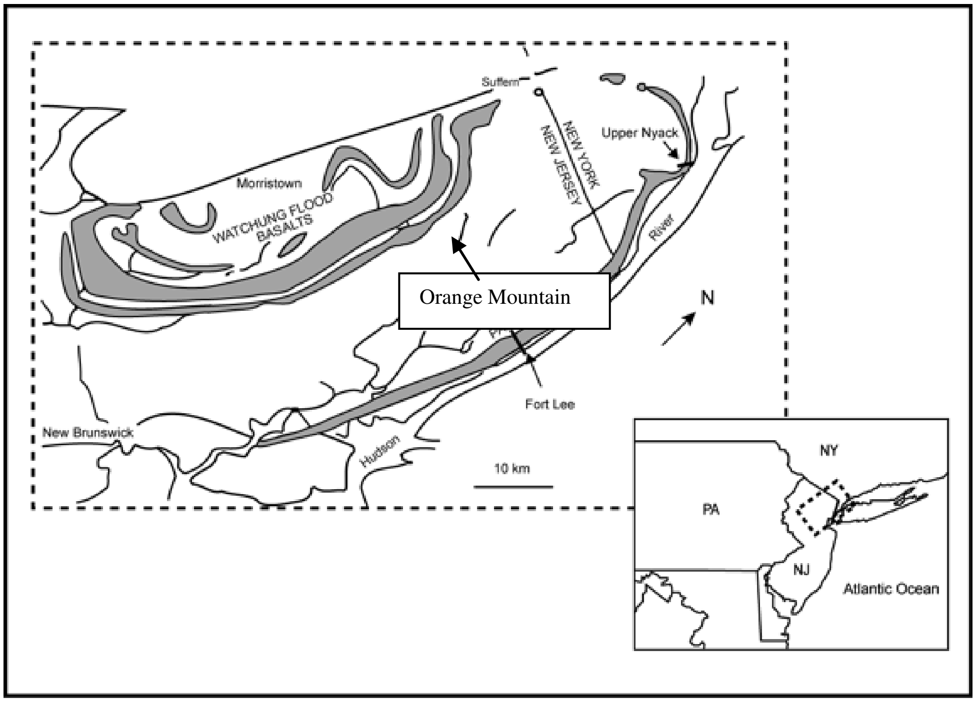


Figure 1. *Arcuate exposure of the Palisades Sill (ca. 199 – 201 Na) along the Hudson River and the Watchung Pangea Continental Flood Basalts; the Orange Mountain Basalt defines the eastern margin of the Watchungs;*

Figure 2. *A north-south running section through OMB exposed at the* UBC/Clifton Tilcon Quarry, *New Jersey; samples are at 10 m intervals; Om4 and Om5 are at the boundary between Ca-rich and Ca-poor labradorite facies; the prominent white layer is interpreted as a sheared or smeared diaper* (see Puffer and Laskowich, 2012).

The prominent light-acolored facies at the 90 meter level is a laterally extended diapir of the type described by Puffer and Laskowich (2012). Attention in this work is given to plagioclase heterogeneity in horizons 4 and 5.

Analytical Methods

Chemical analyses of mineral grains in polished, uncoated probe mounts were acquired at 5000X magnification analyzing a 5x5 micron area for 100 seconds using an EDAX energy dispersive x-ray fluorescence analyzer. The ZEISS SUPRA 55 was operated in variable pressure mode at an excitation of 15Kv and a working distance of 10 mm. The ZAF-adjusted element percents are corrected using standards provided by the Smithsonian Museum, including LAKE, ENSTATITE, San Carlos Olivine, KAK-augite, and other standards; in addition, labradorite-bearing granulites from the Brooklyn Water Tunnel analyzed using the CAMECA microprobe at Lamont Doherty Earth Observatory and at the American Museum of Natural History are used as plagioclase standards refine compositions. Linear calibrations for Fe, Mg, Ca, Na and Ti that employ a zero intercept produce an average error R^2 of 0.993 +/- .004; the correction for Si and Al average 0.963

X-ray diffractograms are obtained using a PANalytical X'Pert Pro Powder Diffraction instrument with a PIXcel^{1D} detector and diffracted beam monochromator, and sample changer. Scans used a a stepsize of 0.006 degrees two-theta and a counting interval of 40 seconds per step over a 6 to 125 degree scan interval. Rietveld Analyses were obtained for basalt using silicon wafer mounts and approximately 15 mg of dispersed powder. To remove peak overlaps, samples were also magnetically separated using several passes through a Franz Isodynamic Separator (to 1.0 amps for a channel at 40 degrees to the vertical and 20 degrees side slope). Approximately 15 mg powder were dispersed on a non-reflective PanAlytical quartz sample holder using the same counting parameters.

Mineralogical Results

Rietveld Unit cells for the OMB series sampled at 10 meter intervals yield del 241 and del 131 estimates; the unit cell parameters for magnetically-refined and mafic-poor separates of samples OM4 and OM5 (below) provide control. Data for the remaining set

$$\Gamma = 2\theta_{131} - 2\theta_{220} - 4\theta_{1\bar{3}1}$$

are shown qualitatively based on the non-magnetically-purified x-ray results. Stepwise differences in ordering parameter (Figure 3, gamma) define 4 subsets; a fifth (smeared diaper) comprises a distinct hydrothermally altered horizon, not presently characterized, and not directly correlated with potential Palisades facies. The tentative facies subset are OM1 (border facies; OM2-4 (Sodic Labradorite Facies); OM5-7 (Calcic Labradorite Facies); OM8-10 (not plotted); and OM11-12 (Upper Flow Facies). We investigate in particular the stepwise variation suggested across the sodic-to-calcic facies in OM4 & OM5.

Data from the magnetically-refined plagioclase:

	a^o	b^o	c^o	alpha	beta	gamma
OM5	8.1806	12.8805	7.1034	93.3972	116.0562	90.585
OM4	8.1851	12.8936	7.1298	92.9272	116.4055	90.7446

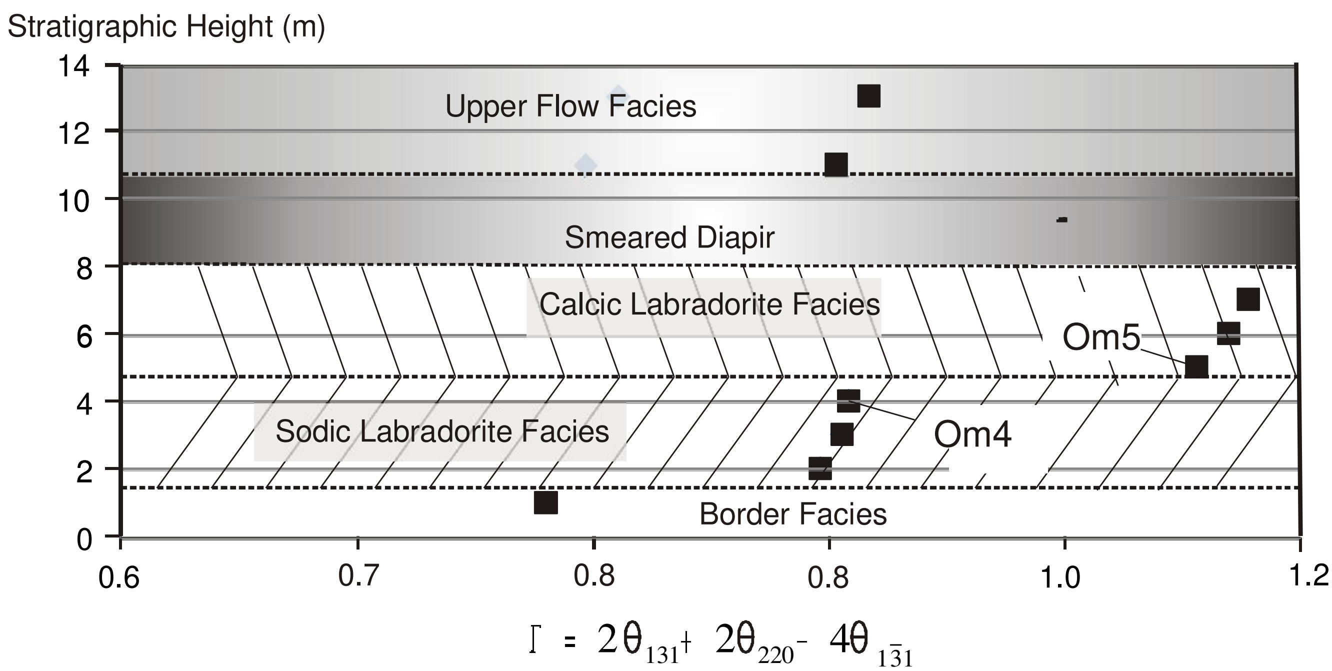


Figure 3. *Populations of Orange Mountain Basalt plagioclase at 10 meter intervals defined using the structure factor, gamma; the smeared diaper concept is an extension of the discussion of Puffer and Laskowich (2012), plagioclase data are not available for this horizon.*

In support of x-ray powder information, the core of plagioclase in the OM4 and OM5 subsets (Table 1, plotted in Figure 4) delineate a discontinuity between sodic and calcic laboradorite varieties (net An59.9 +/- 2 including outlier OM4-4 versus An69.4 +/- 0.2; the latter excludes OM5 analysis 1). The relatively extensive solid solution of Sanidine is consistent with a confining pressure of approximate 1 kbar at 1000^{o}C (OM2) and 1 kbar at 1100^{o}C (OM3) using the geothermometer of Fuhrman and Lindsley (1988).

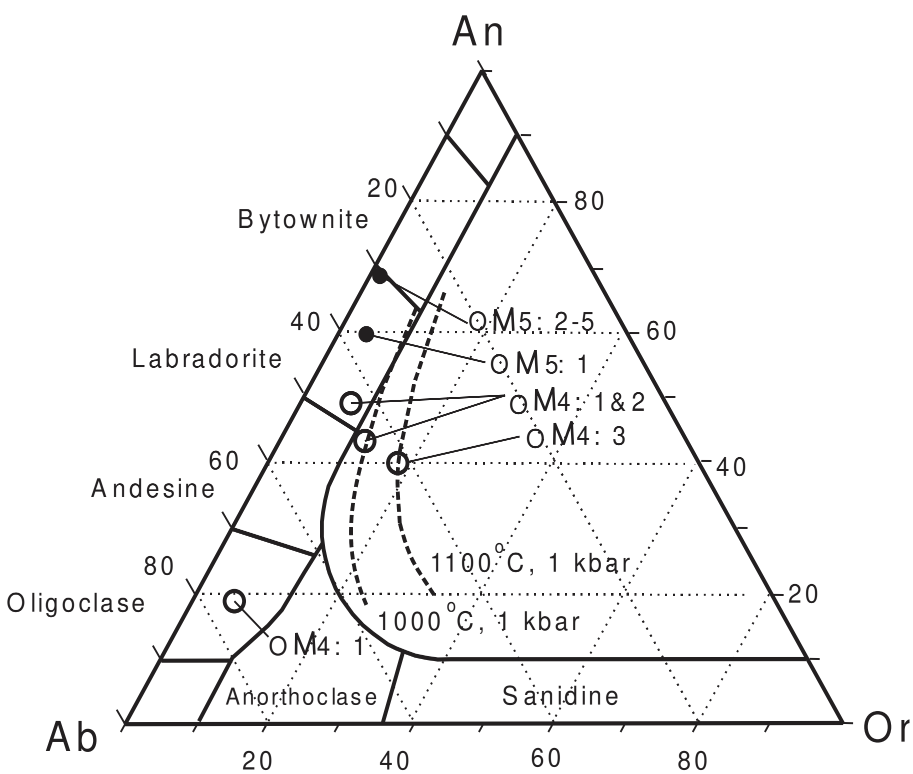


Figure 4 *Plagioclase compositions verifying the presence of discrete populations in the at a stratigraphic horizon of 45 m above the lowermost sample (OM4 vs OM5) showing an average An49.9 $\pm$2.0 excluding outlier OM4:1 for sodic labradorite average (open circles) compared to An69.4 $\pm$ 0.2 excluding outlier OM5:1; data are compared to geotherms of Fuhrman and Lindsley (1988) 1 kbar, 1000^{o}C and 1100^{o}C isotherms; outliers are attributed to low temperature hydrothermal overprinting.*

The potassic plagioclase is clearly demarked in backscatter images as distinctly darker light element enriched grains with a tendency toward euhedral morphology. This is consistent with a possible earlier pre-eruptive growth interval for plagioclase in this facies.

	Table 1. Micro-Analyses for Orange Mountain Basalt Plagioclase							
	OM 4 Samples				OM 5 Samples			
	1	2	3	4	1*	2	3	4
SiO_2	54.95	54.73	54.12	62.71	56.69	50.71	50.71	50.18
Al_2O_3	24.23	24.70	24.43	19.69	25.00	26.74	26.74	26.54
FeO	3.62	3.60	3.56	3.26	3.74	3.28	3.28	3.96
MgO	1.81	1.92	1.89	1.82	1.86	2.11	2.11	2.52
CaO	9.18	7.96	7.88	3.38	9.47	13.28	13.28	13.05
Na_2O	4.62	4.63	4.58	7.67	4.76	3.26	3.26	3.15
K_2O	1.12	1.91	3.00	1.00	1.16	0.24	0.24	0.30
TiO_2	0.46	0.54	.54	0.47	0.48	0.38	0.38	0.30
Sum	100	100	100	100	100	100	100	100
An%	48.6	42.8	39.9	18.3	59.2	68.2	68.2	68.3
Ab%	44.3	45.0	42.0	75.2	36.4	30.3	30.3	29.8
Or%	7.1	12.2	18.1	6.5	4.37	1.5	1.5	1.8
1* Plagioclase bordering a spherical quartz-rich inclusion, possibly an remnant quartzose immiscible liquid								

It is apparent that the OM4-OM5 boundary separates discrete plagioclase populations defining cryptic layering within the OMB flow. Geothermal estimates suggest that the evolution of OM4 retains evidence of a high temperature formative period.

Compositional information from the x-ray record is in close agreement with the proposed compositional heterogeneity within the OMB. An independent assessment can be obtained using a plot of the del 241 vs and del 131 structural indicators ($del\,241 = 2\theta_{\bar{2}41} - 2\theta_{\bar{2}\bar{4}1}\,;\, del\,131 = 2\theta_{131} - 2\theta_{1\bar{3}1}$ -- see review by Smith, 1974). The determination uses a linear plot of del 241 vs del 131 (Figure 5) derived from the synthetic plagioclase unit cell series of Kroll, 1971 for feldspars were synthesized at 30°C below solidus.

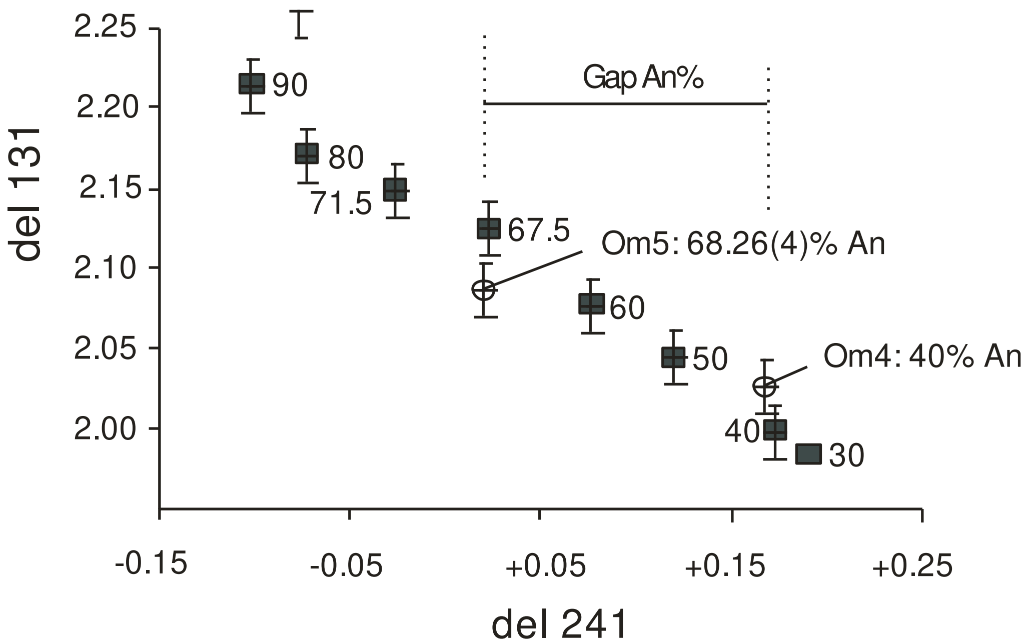


Figure 5. *Comparison of OM4, sodic labradorite, to OM5, calcic labradorite, showing distinct populations(An% Gap) in del 241 vs del 131 where* $del\,241 = 2\theta_{\bar{2}41} - 2\theta_{\bar{2}\bar{4}1}$ *and* $del\,131 = 2\theta_{131} - 2\theta_{1\bar{3}1}$ *;closed squares are synthesis experiments carried out 30°C below the solidus from Kroll (1971); open circles are tabulated from unit cells in Table 2*

The unit cells represent structural averages for powder samples and are therefore subject to distortion due to the noted ranges in composition. However, the cell parameters support the stepwise differences used to define the sodic and calcic laboradorite subsets.

Pyroxene Associations

The pyroxene in the OM series samples comprise variable associations of augite, subcalcic augite and pigeonite, with traces of enstatite; subcalcic augite and augite are the primary mafic minerals.

Discussion of the Pulse Model

The C-T-D model of Steiner and others (1992) that also forms a basis for arguments by Puffer and others (2009) maintains that subsets of the the Palisades Sill facies are comprised of cumulative remnants of earlier magmatic episodes. These remnants, including products

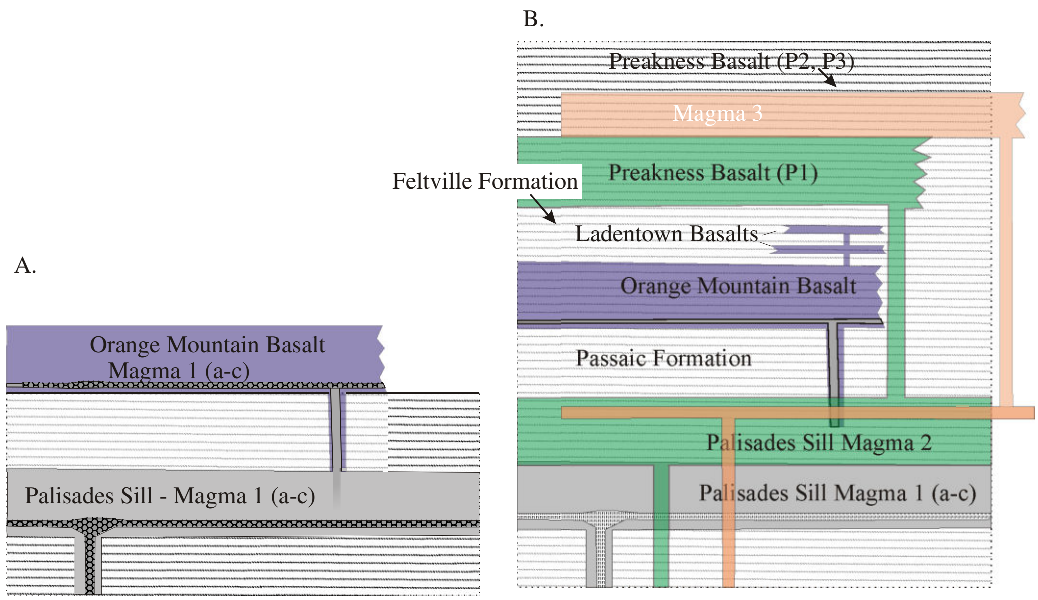


Figure 6 *Schematic linkage between the magma pulse model for the Palisades Sill and the Watchung Basalt series showing that Magma 1 pulse fed the Orange Mountain Basalt and that successive Magmas continued the building of the Preakness Basalt (NJ) and Ladentown Trap (NY)*

of flow differentiation rafted into place during prolonged and complex stages of accumulation (Figure 6 after Puffer and others, 2009). The Olivine Zone/Hyalosiderite Dolerite is used in the schematic to represent the concept that layers or facies in the

Palisades may have a direct analog in the linked OMB. This is not to argue that the Olivine Zone is the appropriate link to the OMB at the Tilcon traprock quarry, e.g. a magnesium-rich layering . The OMB is more probably related to a more differentiated member of the Pulse 1 set. The plot of stratigraphic variability in the basal Pulse 1 is at least sufficient to suggest the presence of remnant layering as highlighted in Figure 7 after Puffer and others (2009).

Packets

Facies variations in the OMB support the concept that comparable xenolithic slices were emplaced in the Palisades. Prolonged cooling of an initial mixed lava inevitably leads to coarsening of phases, the evolution of distinct mineral textures, chemical exchange across mineral associations, and structural changes in minerals including ordering and exsolution. It is proposed that these units within the Sill, packets, comprising single or multiple sets of layers that may have lost much of their original distinctive boundaries, such as internal chill contacts. (Figure 8). This includes the idea that the packets may themselves represent secondary, re-mobilized packets from deeper levels within the crust. Packet boundaries, as in the case of the OMB can in theory be recognized by careful analysis of mineral populations, textural differences, and variability in bulk composition between packets.

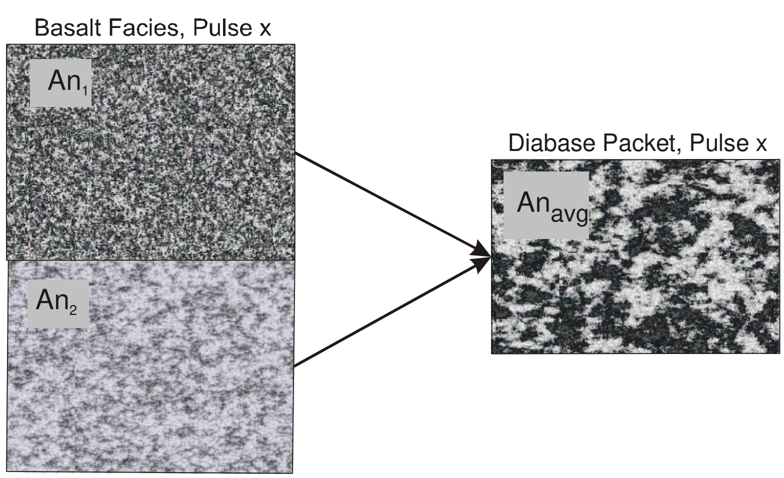


Figure 8. *Cryptic layers basalt layers, including decompression-melted aggregates produced at depth with disparate anorthite contents An_1 and An_2 intruded in a subsurface sill coarsen and homogenize over time resulting in a coarser'welded and annealed' diabase packet that comprises the net composite of xenolithic material and originally mobile crystal mush.*

Investigations of the stratigraphic layering within the Palisades have used silica, the mafic index, and trace metals among other parameters to characterize cryptic layering. The use of Europium variability (after Puffer and others, 2009) is presently used to show that the transitions for indicators are not smoothly varying but can show flows and ebbs at regular intervals (Figure 9). These, in our view, lend themselves as targets for future study of the packet concept in attempts to resolve cryptic-scale variability within the Palisades Sheet.

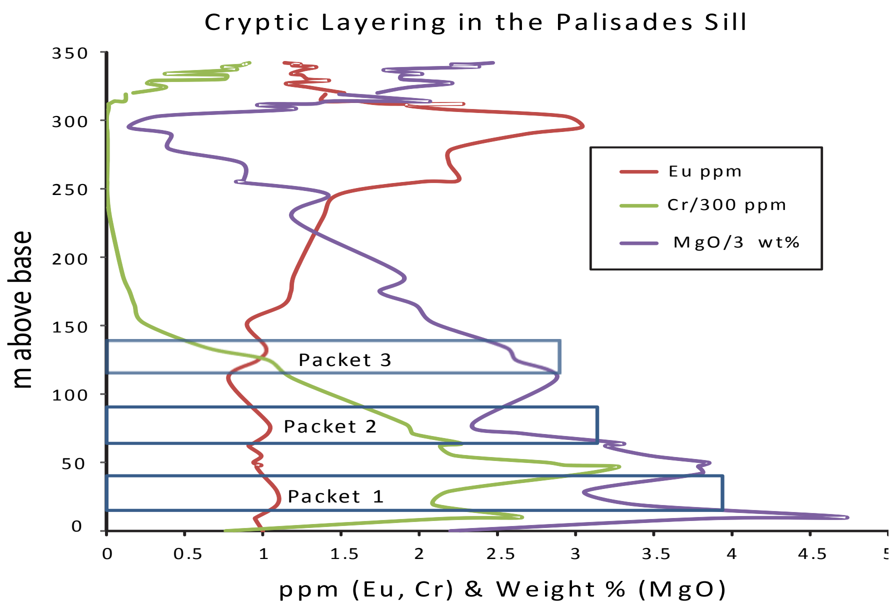


Figure 9. *Cryptic layering at the base of the sill (Magma 1) is indicated by positive Eu anomalies signifying plagioclase accumulation confirmed by decreased Cr and MgO.*

BIBLIOGRAPHY

Fuhrman, M.L., Lindsley, D.H., 1988, Ternary-feldspar modeling and thermometry, AmericanMineralogist, 73, 201-215.

Kroll, H., 1971, Feldspars in the system $K[AlSi_3O_8]$-$Na[AlSi_3O_8]$- $Ca[Al_2Si_2O_8]$: Al, Si-Verteilung und Giterparameter, Phase-Transformationen end Chemismus, Inaug-Diss. Der Westfalischen Wilhelms-Universitat in Munster.

Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesto, M., Belieni, G., and De Min, A.., 1999, Extensive 200-Million-year-old continental flood basalts of the Central Atlantic Magmatic Province, Science, 284:616-618.

Puffer, J.H., 1992. Eastern North America flood basalts in the context of the incipient breakup of angea, in: Puffer, J.H., Ragland, P.C. (Eds.), Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper, pp. 95-119.

Puffer, J. H. 2003, Geochemistryof Pangean and Rodinian Continental Flood Basalts, in The Great Rift Valleys of Pangea in Eastern North America, Tectonics, Structure and Volcanim, vol. 1, P.M. Letourneau and P. E. Olsen eds, Columbia University Press, NY, 214 pp.

Puffer, J.H., Block, K.A., Steiner, J.C., 2009. Transmission of Flood Basalts through a Shallow Crustal Sill and the Correlation of Sill Layers with Extrusive Flows: The Palisades Intrusive System and the Basalts of the Newark Basin, New Jersey, U.S.A. Journal of Geology 117, 139-155.

Puffer, J. H., Laskowich, C., 2012, Volcanic diapirs in the Orange Mountain flood basalt: New Jersey, USA, Journal of Volcanology and Geothermal Research, 237–238, 1-9 (2012) 1–9

Shervais, J.W., Vetter, S.K., Hanan, B.B., 2006. Layered mafic sill complex beneath the eastern Snake River Plain: Evidence from cyclic geochemical variations in basalt. Geology 34, 368-368.

Shirley, D.N., 1987. Differentiation and Compaction in the Palisades Sill. Journal of Petrology 28, 835-365.

Shirley, D.N., 1988. Effects of Postcumulate Fractionation in the Palisades Sheet: Further Evidence from Weehawken, New Jersey, in: Froehlich, A.J., Robinson, G.R. (Eds.), Studies of the Early Mesozoic Basins of the Eastern United States. US Geological Survey Bulletin, Denver, CO, pp. 135-140.

Smith, J. V., 1974, Feldspar Minerals in Three Voumes, Volume 1 Crystal Structure and Physical Properties, Springer-Verlag, NY, 627pp.

Steiner, J.C., Walker, R.J., Warner, R.D., Olson, T.R., 1992. A cumulate-transport-deposition model for the differentiation of the Palisades sill. Geological Society of America Special Paper 268, 193-211.

Walker, K.R., 1969. The Palisades Sill, New Jersey: a reinvestigation. Geological Society of America Special Paper 111, 178 pp.

STRUCTURE OF THE CAMP BODIES AND POSITIVE BOUGER GRAVITY ANOMALIES OF THE NEW YORK RECESS

Gregory C. Herman, John H. Dooley, and Donald H. Monteverde, NJ Geological and Water Survey, Trenton, NJ greg.herman@dep.state.nj.us

Abstract

Recent quadrangle-scale bedrock geology mapping by the NJ Geological and Water survey in the center of the Newark basin near Lambertville, NJ has resulted in the delineation of a crustal dome with an estimated 65 km diameter and 3-5 km of structural relief that is centered on the Buckingham window in Bucks, County, Pa. A structural analysis of the orientation of igneous compositional layering in dolerite plutons in northwestern New Jersey shows that layer orientation can be used to help determine magmatic sources areas. The layering analysis points to a magmatic feeder system within the footwall block of the linked Flemington - Dilt's Corner-Furlong-Chalfont fault systems where pre-Mesozoic basement is unroofed toward the basin center. This structure was previously interpreted to be an old Appalachian anticline that was simply exposed through erosion, but we illustrate how this structure is a thermal dome stemming from intrusive igneous activity of the widely recognized Central Atlantic Magmatic Province of earliest Jurassic age (CAMP). Maps and cross sections are used to show how this structure sits at a junction along the continental margin between west- and east-dipping dolerite dike swarms near the Delaware River on the New York recess part of the Eastern Appalachian Piedmont. The dike swarms are deeply penetrating, systematic tensile structures that help accommodate crustal extension and collapse in concert with large normal and transcurrent faults that are symmetrically disposed about the dome. The dikes also fed magma into the Newark basin sedimentary section in a manner that is consistent with the interpreted petrogenesis of CAMP bodies. The nature of the 'Buckingham dome' helps explain how pre-Mesozoic basement came to be elevated to its current position near the center of the basin, and why sills in the Delaware Valley step up section from the Lockatong into the Passaic Formation when moving toward the dome flanks. We also demonstrate that there is a close spatial association with exposed CAMP intrusions across the New York recess with broad-wavelength, regional, positive Bouger gravity anomalies and correlate these anomalies to well-known, regional basement Appalachian culminations and depressions. We show how these dikes and faults are arranged with respect to hypothetical, deep plutons that likely under plated the proto-Atlantic margin before being stretched and elongated during ensuing development of the passive margin. This work helps explain some of the peculiar intrusive geometry of the dolerite intrusive complexes in the Newark basin, helps tie together some long-held notions regarding Appalachian structural development, and serves as a basis for considering further how these thermal effects may vary from later epeirogenic strains.

Introduction

This year's Geological Association of New Jersey (GANJ) meeting focuses on igneous processes during the assembly and break-up of Pangea as evidenced in northern New Jersey and New York. This paper covers both local and regional igneous and tectonic processes involved in the development of the Central Atlantic Magmatic Province (CAMP) the large-igneous province LIP) that was emplaced at the onset of supercontinent breakup and the birth of the Atlantic Ocean basin (Marzoli and others, 1999). Local aspects are focused on dolerite (diabase and trap rock) dike and sill structures in the central part of the Newark basin in New Jersey (fig. 1). This work integrates stratigraphic and structural details from over a dozen geological studies involving six different

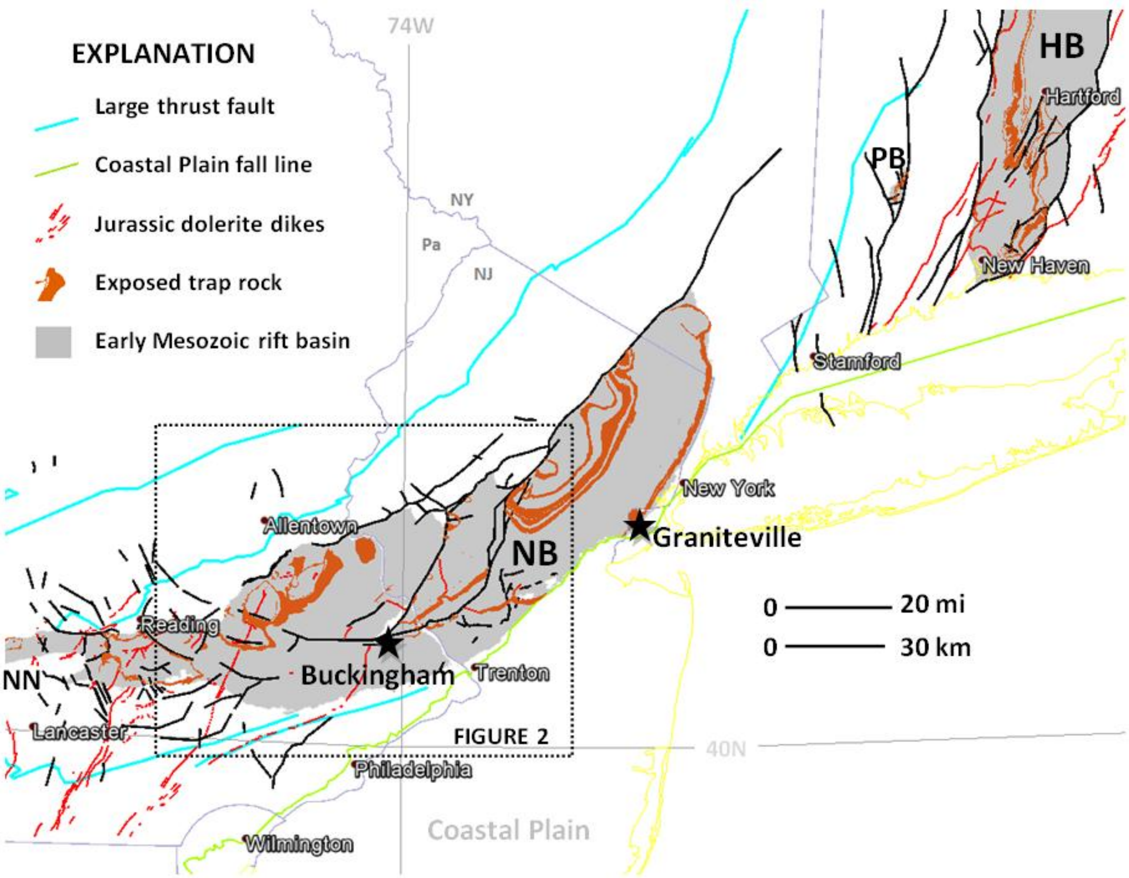


Figure 1. Map of the Atlantic coastal margin of the New York recess showing the Newark and Hartford rift basins, known or suspected faults of Mesozoic age and the location of the suspected Buckingham and Graniteville magmatic feeder areas for the central and eastern parts of the Newark basin. Abbreviations: HB – Hartford Basin, NB - Newark Basin, PB – Pomperaug basin, NN – Narrow Neck. Notice the symmetrical arrangement of large normal faults near Buckingham, Pa.

dikes and sills in the area to illustrate how these intrusions formed, both internally with respect to the orientations of igneous compositional layering, and externally with respect to their structural position in enveloping Triassic sedimentary strata. Maps and cross sections are included that delineate a crustal dome about 65 km diameter with 3-5 km structural relief that is centered on the Buckingham window, Bucks County, Pennsylvania (figs. 2 and 3). This dome structure is shown to result from structural and thermal effects of dolerite dike and sill emplacement. We illustrate how conjugate dolerite dikes striking transverse to the Appalachian grain merge in the dome to feed the complex array of nearby sills that were emplaced outward into flanking areas at varying stratigraphic levels, then subsequently sheared, tilted, and stretched within the Flemington and Hopewell intrabasinal fault blocks (fig. 2). Spurred on by recognition of the Buckingham dome (Herman and others, in review), a more regional compilation and literature review was undertaken to find similar, corroborative structures elsewhere within the Atlantic margin. This resulted in a digital compilation of exposed CAMP features along the US Atlantic margin that was compared with mapped Bouger gravity and aeromagnetic anomalies From Gettysburg, Pa to Hartford Ct. (Geological Society of America, 1987a-b). From this work we show how sub-lithosphere plutons underlie widely-recognized crustal culminations by having direct correspondence with long-amplitude, regional, positive Bouger gravity anomalies.

This paper includes two parts. First, we demonstrate:

a) that igneous compositional layering within intrusive bodies is systematic and consistent with the structural dynamics of extensional fracturing,

b) that these relationships point to a magmatic source area within the ‘Buckingham dome’, a structural culmination near the basin center in eastern Pennsylvania that probably has a thermal origin stemming from the dike and sill emplacement, and

c) how the CAMP plumbing system structurally evolved in this region relative to this dome, the enveloping Triassic sedimentary strata, and large faults.

Secondly, we use the close spatial association between CAMP intrusions with long wavelength, positive, Bouger gravity anomalies distributed throughout the New York Recess to infer how a large CAMP body could have underplated and arched continental lithosphere before accelerated phases of stretching resulted in the regional dikes swarms tapping deep-seated magma chambers that pooled beneath the lithosphere before eventual intrusion and breakthrough as volcanic flows.

Detailed aspects of this paper focus on the structural characteristics of the CAMP intrusions in the Newark basin and New Jersey in particular. Details pertaining to the geochemical nature of the intrusive system are only considered when addressing particular aspects of the timing and modes of dike emplacement and faulting within discreet phases of accelerated tectonic stretching. A significant part of this work is the use of igneous compositional layering to decipher magma injection directions that in turn, help point to magmatic source areas. Physical aspects of mineralogical layering are based on visual inspection of the respective geological sections using the naked eye and a hand lens.

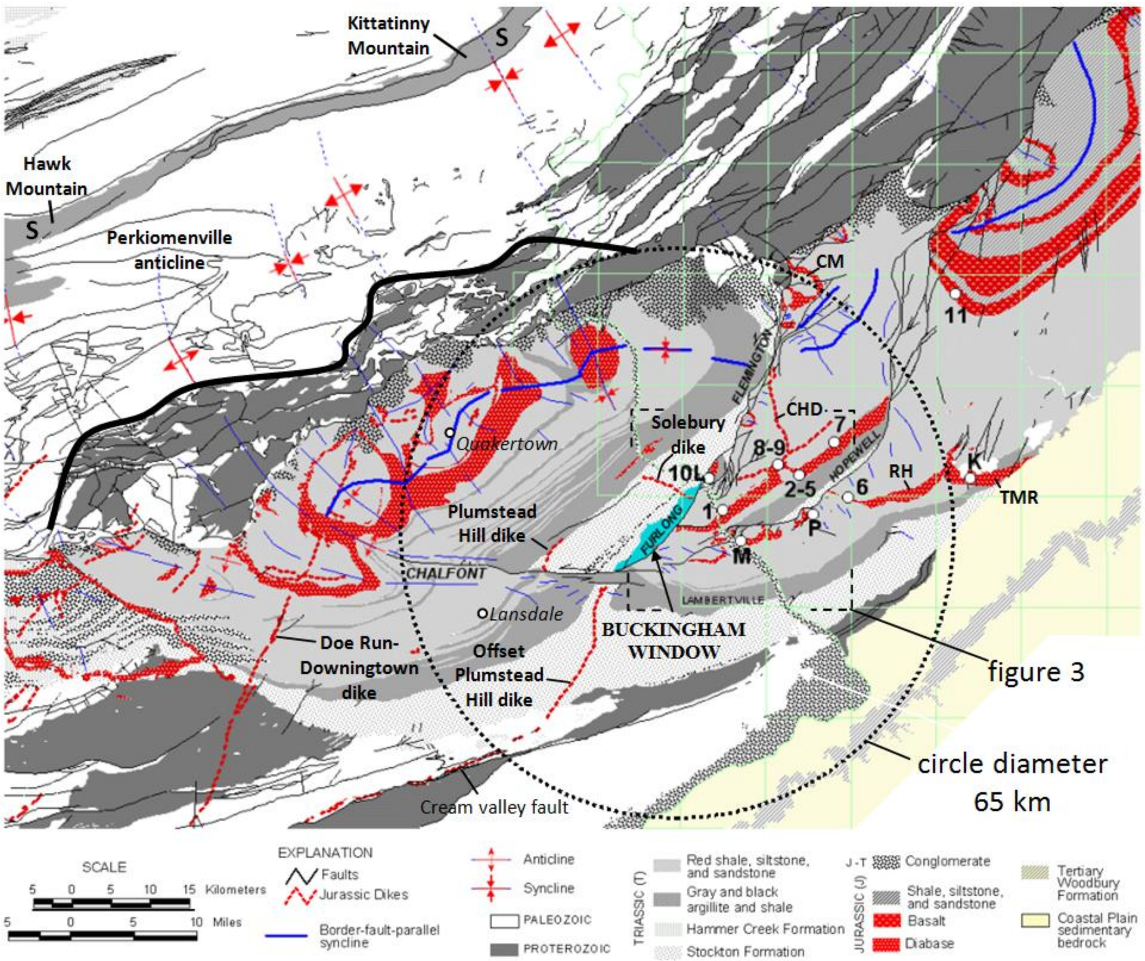


Figure 2. West-central part of the Newark basin centered on the Buckingham window in Bucks County, Pa showing locations of detailed studies in New Jersey. NJ 7-1/2' quadrangles of are outlined in light green. Note the parallel alignment of the bold, black line tracing the foreland boundary of exposed Proterozoic basement rocks in Pennsylvania and the border-fault-parallel syncline immediately to the south in the basin. CM - Cushetunk Mountain, CHD – Copper Hill dike, RH – Rocky Hill dolerite, S – Silurian quartzite and conglomerate, TMR – Ten-Mile Run dolerite

Geological Review

The Atlantic margin of the North American continent is one of the most extensively studied geological systems in the world, serving as both an archetype orogenic belt (Hatcher and others, 1989) and rift-to-drift passive margin (Vogt and Tucholke, 1986; Manspeizer, 1988). The eastern US Mesozoic basins are an integral part of that system, marking centers of crustal extension stemming from Early Mesozoic transtentional rifting and crustal thinning that preceded continental drift and on lap of the Atlantic sea. Yet the origin of the Mesozoic rift basins on the eastern continental margin of North America still remain controversial after over a century of study and debate (Manspeizer and others, 1989). A large body of work has been generated on the distribution, composition, and geometry of outcropping CAMP bodies throughout the area and region (Puffer and others, 2009). In general, the physical composition and geochemical signatures of the different bodies are well understood, but there is only a sketchy understanding of how the various dikes and sills spatially interacted with each other and their enveloping rocks during injection from a deep magma source into a sedimentary basin undergoing tectonic extension.

The New Jersey part of the Newark basin has seen a steady stream of new map and hydrogeology studies by the NJ Geological & Water survey (NJGWS) over the past three decades (http://www.njgeology.org). On-going surface mapping has been augmented by shallow subsurface research on the various fractured-rock aquifers in the basin (Herman and Serfes, 2010). This work has provided opportunities to revisit old geological problems such as the structural expression of the CAMP intrusions in the center of the basin, where complex sets of Early Jurassic dolerite sills and dikes intruded Late Triassic sedimentary rocks that were subsequently segmented into three fault blocks (fig. 3). These bodies have been shown to have shared parent magma with the York Haven suite of large, transverse dikes cutting across the Pennsylvania Piedmont to the southwest, that in places cross cut dolerite sills in the Passaic Formation in the Pennsylvania part of the basin (Smith and others, 1975). These bodies also have a geochemical and spatial connection to the Palisades sill (Husch 1984; Gottfried, 1991; Gottfried and others, 1992) and are part of the Palisades Intrusive System (Puffer and others, 2009). Drake and others (1996) describe dolerite of the Palisades system as early Jurassic, medium- to coarse-grained, sub-ophitic diabase to coarse-grained, quartz-rich to albite-rich granophyre.

The Palisades sill is the most prominent and well known dolerite body in the New York recess, cropping out for approximately 90 km along the lower reaches of the Hudson River (fig. 1). This massive sheet reaches up to 350 m thickness (averaging ~300 m, Puffer and others, 2009) and probably continues along strike to the SW beneath Coastal Plain cover where it reemerges as the Princeton-Rocky Hill diabase sheet within the hanging wall of the Hopewell fault (fig. 3; Klewsaat and Gates, 1994). The second most prominent Jurassic intrusive body in New Jersey is the Lambertville-Sourland Mountain sill complex located in the center of the basin within hanging wall of the Flemington fault system (fig. 2). In addition to the two larger sill segments (Lambertville – SW and Sourland – NE, fig. 3), this complex body also has thick dike segments leading to a higher-level, thinner sills as part of a medial-saddle structure. A solitary, thin dike (CHD – fig. 2) branches off the top of the complex and cuts across the Passaic Formation east of the Sand Brook syncline (fig. 3) and ends near the remnant basalt flow in Flemington (Darton, 1896; Herman, 2005b).

Subsurface depictions of how the different intrabasinal dikes and sills are connected and fed by sub-basin feeder systems widely vary. Bascom and others (1931) were among the first to depict the plumbing system with feeder components in a series of cross sections through the Quakertown-Doylestown district of Pa., and NJ. They depict sills reaching over 700 m thick that taper northeastward to about 200 m thick near where they spread laterally from a vertical feeder stock rising beneath an area close to the border fault system west of Quakertown, Pa (fig. 2).

Froelich and Gottfried (1984) developed schematic profiles of pre- and post-tilt stages of a typical, eastern US Mesozoic basin having large sills and lava flows. The dolerite intrusions are characterized as hypabyssal intrusions injected at high temperatures but under relatively low pressures that were fed by steeply-dipping pre-Mesozoic feeder dikes near the erosional, SE margins of the basins. The feeder dike branches upward into the Triassic section as conical ring dikes that funnel outward into conformable sills that in turn, branch upward and feed into higher sections along steep, normal fault. Beddard and others (2012) described this process as fault-mediated melt ascent and illustrated examples of how it works. The injection of magma culminates where steep feeder dikes eventually intersect the paleosurfaces to feed lava flows. It is interesting to note that their Early Jurassic section shows kilometers of doming associated with the intruded sheets, and faults that are collinear with steeply ascending dike segments.

Schlische (1992) shows steeply-dipping magmatic feeder dikes near the southwest end of the basin where a ‘narrow neck’ of Triassic rocks connects the Newark and Gettysburg basins (NN on fig. 1). His schematic profile section depicts the Palisades sill in the northeast as spanning the basin width, and systematically stepping down to the southeast in a zigzag form, presumably influenced by synchronous normal faults.

Detailed cross-sections of the NJ region by Drake and others (1996) are similar to earlier ones by Lyttle and Epstein (1986) as both interpretations depict feeder systems rising from beneath the basins northwest, faulted margin and that cut upward steeply through pre-Mesozoic basement where they branch outward into gently convex sills within the upper Lockatong and mid-Passaic sections. Portraying feeder dikes beneath the border fault area is consistent with a crustal cross-section interpretation by Ratcliffe and Contain (1985) based on a deep seismic-reflection profile crossing the northwest basin margin depicting fault-parallel magma ascent into the basin. Drake and other's (1996) interpretations depict the feeder and sills as cut and offset by later normal faults, including one that tips out near the Green Pond syncline in the New Jersey Highlands, thereby portraying Mesozoic extension reaching into the Reading Prong foreland of the Mesozoic basin. In contrast, Lyttle and Epstein (1986) depict sills that cut across and post-date earlier normal faults, and they raise the possibility of having multiple, deep dikes feeding basin intrusions as their southwestern most section shows a different feeder system beneath the basin's southeast margin. Section D-D’ of Drake and other's (1996) sections depicts the Pennington Mt sill as positioned within the lower third of Passaic Formation with a convex geometry and a northwestern limb that curves gently upward to intersect the Hopewell fault. The convex geometry is most notably seen in the larger sills like the longitudinal section of the Palisades-Rocky Hill-Lambertville mega sheet noted by Van Houten (1969) and Husch (1990) and by Hotz (1952) for similar intrusions to the

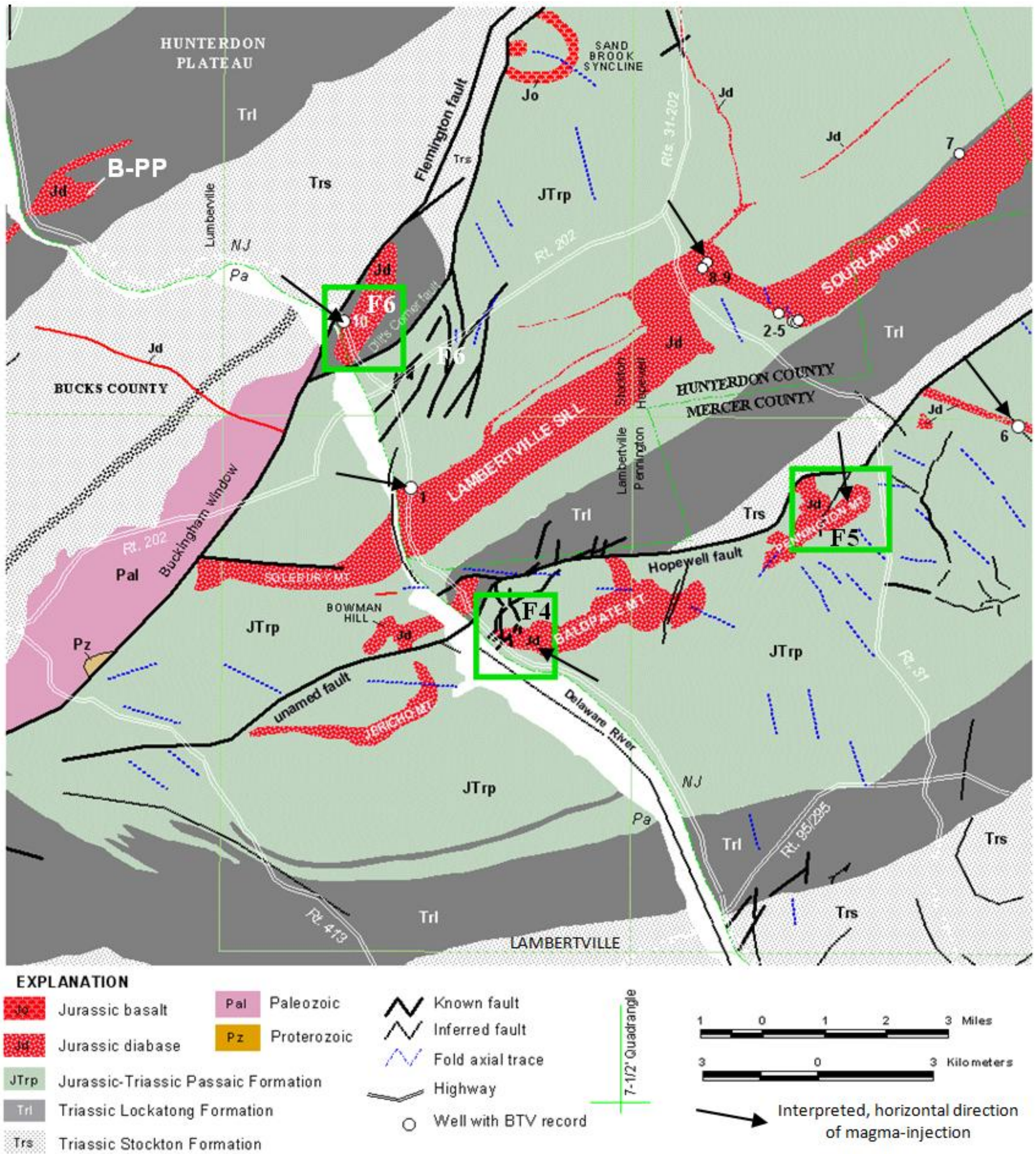


Figure 3. Central part of the Newark basin centered on the Delaware Valley near the Buckingham window in Bucks County, Pa., showing the locations of studied trap-rock quarries and water wells. Arrows show the interpreted directions of magma-injection based on the orientations of compositional layering in the dolerite at each location.

southwest in Pennsylvania. Husch and others (1988) also provided a schematic cross-strike profile interpretation of the Baldpate-Lambertville-Pennington Mt dolerite sheets as a large, continuous, northwest dipping sheet that was subsequently segmented by normal faults and eroded to give rise to their separated current forms. The restored dolerite sheet is shown to rise gently southeastward from a deep, sub-basin region near the Byram-Point Pleasant intrusion in the Lockatong section (B-PP in fig 3.), and climbs gently upward into the Passaic section. This configuration was proposed due to the more primitive, orthopyroxene-rich nature of the deep bodies in the Triassic section in contrast to the more highly fractionated and contaminated granophyres varieties occurring higher in the Passaic Formation.

Sanders and Merguerian (1997) depict a possible feeder dike for the Palisades-Lambertville-Rocky Hill sill complex in the vicinity of Graniteville, Staten Island, NY (fig. 1) on the basis of finding a fused, vertical xenolith with annular (cooling ?) joints that they suggest may stem from upward flow of magma close to a steeply inclined feeder channel. They show evidence for the emplacement of the sill away from this location towards the northeast and note that the Palisades sheet is thickest and reaches its lowest stratigraphic position near Graniteville, from where to the body progressively thins as it migrates up section both to the northeast and to the southwest.

Ratcliffe and Burton (1988) conducted a detailed structural and geochemical study of the nature of the Furlong fault near the Buckingham window from two, continuous rock cores obtained near the western end of the Solebury Mt (fig. 3) that reached a maximum 110 m below land surface. Their data indicate that the Furlong fault is a complex zone of sub parallel faults and breccia that dip moderately southeast and bounds the core of the 'Buckingham anticline' where Lower Paleozoic and a smidge of Middle Proterozoic basement crop out to form an eye-shaped window near the center of the basin (figs. 2 and 3) . Both cores encountered Triassic red mudstone above 2 feet of highly altered fault breccias, overlying fine-to-coarse grained dolerite about 60 meters thick separated from underlying Middle Paleozoic dolostone and white quartzite by a thin (<3 cm) hematitic breccia. The faults were parallel, dip moderately southeast and were hydro-thermally altered along with associated country rocks by low-temperature secondary minerals (<300^{o} C). From geological and structural considerations, they concluded that the dolerite intruded and chilled against faulted rocks, and that this fault sliver probably represents a partially down-dropped fragment from the upper part of the nearby Solebury-Lambertville sill. They also raised the possibility that the dolerite may have intruded the fault before fault movement ceased. As part of this same work, they map and describe granophyre intrusions occurring midway along the Flemington fault at the Sand Brook syncline (fig. 3) and near the fault’s northern tip where it connects with border faults near Cushetunk Mt (fig. 2; Herman and others, 1992). Kummel (1898) also thought that trap ascended along the Flemington fault even though back then it was “not conclusively proven”. It is clear from this work that fault segments comprising the Flemington fault system locally facilitated the ascent of dolerite melt. It is also clear the Ratcliff and Burton (1988) recognized the arching of basement into the Buckingham window as an anticline, but didn't postulate how it formed. Bascom and others (1931) thought that the anticline represents a breeched

Paleozoic fold. Ratcliff and Burton (1988) concluded that "Faulting and late-stage igneous activity may have overlapped in the Furlong fault, but the bulk of the data appears to favor considerable faulting after intrusion of the diabase".

Structural Analyses of Compositional Layering in Dolerite Bodies in the Delaware Valley, NJ

The phrase 'igneous compositional layering' is used here to identify primary igneous mineral layering as opposed to mineral layering in metamorphic and metaigneous rocks elsewhere in the region. Steiner and others (1992) point out that various differentiation and flow processes have been identified to account for mineral layering in intrusive sills, including the Palisades sill. They show layered, chemostratigraphic horizons of varying mineral compositions that form within thick intrusions from magma mixing, crystal settling, in-situ crystallization and convection. Crystal settling and in-situ crystallization are cited as the most frequently applied and generally recognized explanations for mineralogical layering and crystal fractionation. Our focus here is not on the processes responsible for the layering, but simply how layers are oriented relative to the dominant fracture systems and the bounding limits of the intrusive body, in other words with respect to the tops, bottoms, and sides of an intrusion.

A systematic study of the orientation of igneous compositional layering in a few dolerite bodies is summarized below from integrating the results of different geological studies conducted in the New Jersey part of the Newark basin over the past decade (fig. 3). Most of this work was done in and near trap-rock quarries cut into land surface, and in water wells drilled into shallow bedrock in the 15 - 200 meter depth range (Herman, 2010). The trap-rock quarries are owned and operated by Trap Rock Industries, Inc. (TRI) of Kingston, NJ. The NJGWS was given supervised access to map in and around their Pennington, Moore's Station, and Lambertville facilities (figs. 3 to 6) as part of our regional bedrock geologic mapping work and to provide TRI with geology data that can be used to help implement best-management practices for minimizing environmental impacts from mining operations. Structural data from the surface quarries are combined with structural data stemming from fractured-bedrock aquifer studies to show how igneous compositional layering and systematic secondary fracture planes reflect the direction of magma injection, and hence the direction of their magmatic source area(s). First we'll look at structural relationships for the trap-rock quarries and then we'll cover structural data obtained in the subsurface using an optical borehole imaging (OBI) televiewer tool. The trap rock quarries are reviewed in a top-down sense with respect to looking at intrusions higher in the Triassic section, then lower. Uncertainty increases the deeper we go.

Trap-Rock Quarries

The surface quarries are cut into three separate dolerite bodies that are among the dozen such bodies distributed throughout the Delaware River valley including small remnants of the Orange Mt. basalt (fig. 3). Mapping of these quarries followed an introductory excursion into

TRI's Kingston facility (point K in fig. 2) having the largest footprint of the facilities visited and requiring more study for reasons to be discussed below. The orientation of compositional layering in three other trap-rock quarries (P, M, and L in fig. 2) is summarized in figures 4 to 8. Compositional layering was taken where mineral layering was seen with the naked eye and sometimes examined with a hand lens. All of the quarries are located near the traces of large extensional faults having complex slip motions from fault blocks having been dropped down and incrementally stretched southeast to east (Herman, 2009). Consequently, igneous compositional layering is locally obliterated or obscured by secondary clusters of cross-cutting, densely-spaced factures and shear planes (Laney and Gates, 1996; Herman, and others, 2010). But compositional layering is locally seen where tectonic strains are minimal and mineral layering occurs in sub parallel alignment with pervasive sheet joints that curve gently, or 'horse tail' and abruptly terminate against the planar bases of adjacent layers (fig. 5B) or the enveloping Triassic sedimentary layers (fig. 4B). This fracture geometry is the same at that reported for dolerite dikes of Mesozoic age in coastal Maine (Swanson, 1992) where extension fractures systematically flare outward and upward from the center of the intrusion toward enveloping surfaces. This is also the same geometric pattern as plumose markings on the faces of ordinary rock joints in the Newark basin (Herman, 2005a; 2009). Extension fractures characteristically develop outward and upward radiating, plumose ridges or hackle marks on parted and exposed fracture surfaces that indicate their tensile origin (Hodgson, 1961; Pollard and Aydin, 1988). The medial axes for these plumose structures generally lay sub parallel to the long axes of the enveloping surface and parallel to the direction of fracture propagation, and resemble the shafts of feathers.

Figure 9 illustrates this plumose geometry using a longitudinal cross-section cartoon of a sill having mineral layering and sub-parallel sheet joints systematically flaring outward from a central medial conduit. The relative structural position of Moore's Station and Pennington quarries are included to illustrate how the mapped structures vary in a quarry with respect to their position in a sill. The layers and sub parallel sheet joints have either convex (upward) or concave (downward) geometries relative to the body's enveloping surface. Sheet joints commonly show plumose structure on exposed surfaces (fig. 6) that likely arise from volume-loss changes occurring normal to layering from the pluton cooling (Balk, 1925). Sills, dikes, and joints are all different types of extension fractures that occur in transitional-tensile structural arrays and thereby impart brittle shear strains in crustal rocks as part of normal tectonic subsidence (Herman, 2009). Other secondary fractures locally occur in orthogonal arrangement to the primary layers that form polygonal cooling joints of similar form as those seen in the Watching basalts (Faust, 1978). In other places, thick compositional layers contain shear fractures with sigmoid shapes that indicate synchronous cooling and shearing (fig. 6B and Herman and others, 2010).

The Pennington Mountain and Baldpate Mountain dolerite bodies sit within the hanging wall of the Hopewell fault close to its surface trace (fig. 3). Both bodies have dike segments branching from their northwest boundaries that funnel toward and terminate against the Hopewell fault at high angles. These dikes segments probably represent feeder systems from up-dip parts of the Solebury-Lambertville-Sourland dolerite complex where the migrating magma

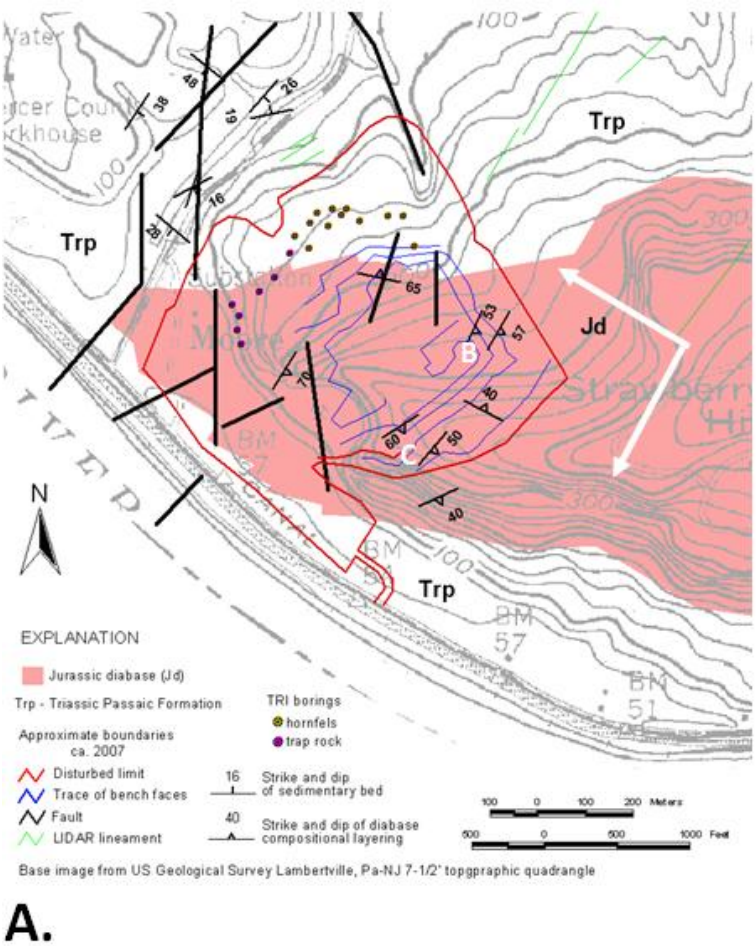
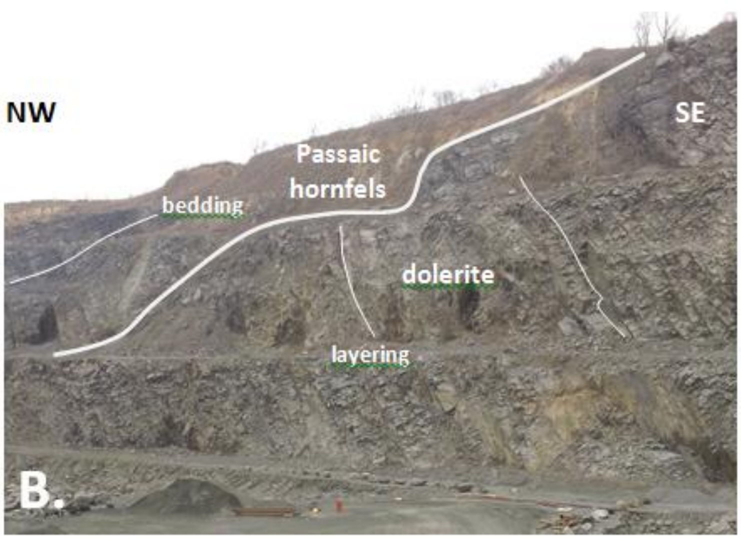


Figure 4. Geological map and photographs from the Moore's Station quarry. **A**.White arrows on map show inferred magma-injection directions based on layer orientations. Note the local, near-orthogonal variability of layering strikes. Locations for photos B. and C. are shown on the northeast and southeast bench cuts. **B.** Northeast view of the nonconformity between bedded Passaic Formation hornfels and underlying dolerite with sheet joints spaced ~0.5 to 2.0 m. **C.** Northeast view showing igneous compositional layering in the southeast bench cut with the face cut shown in B. visible in the distance.



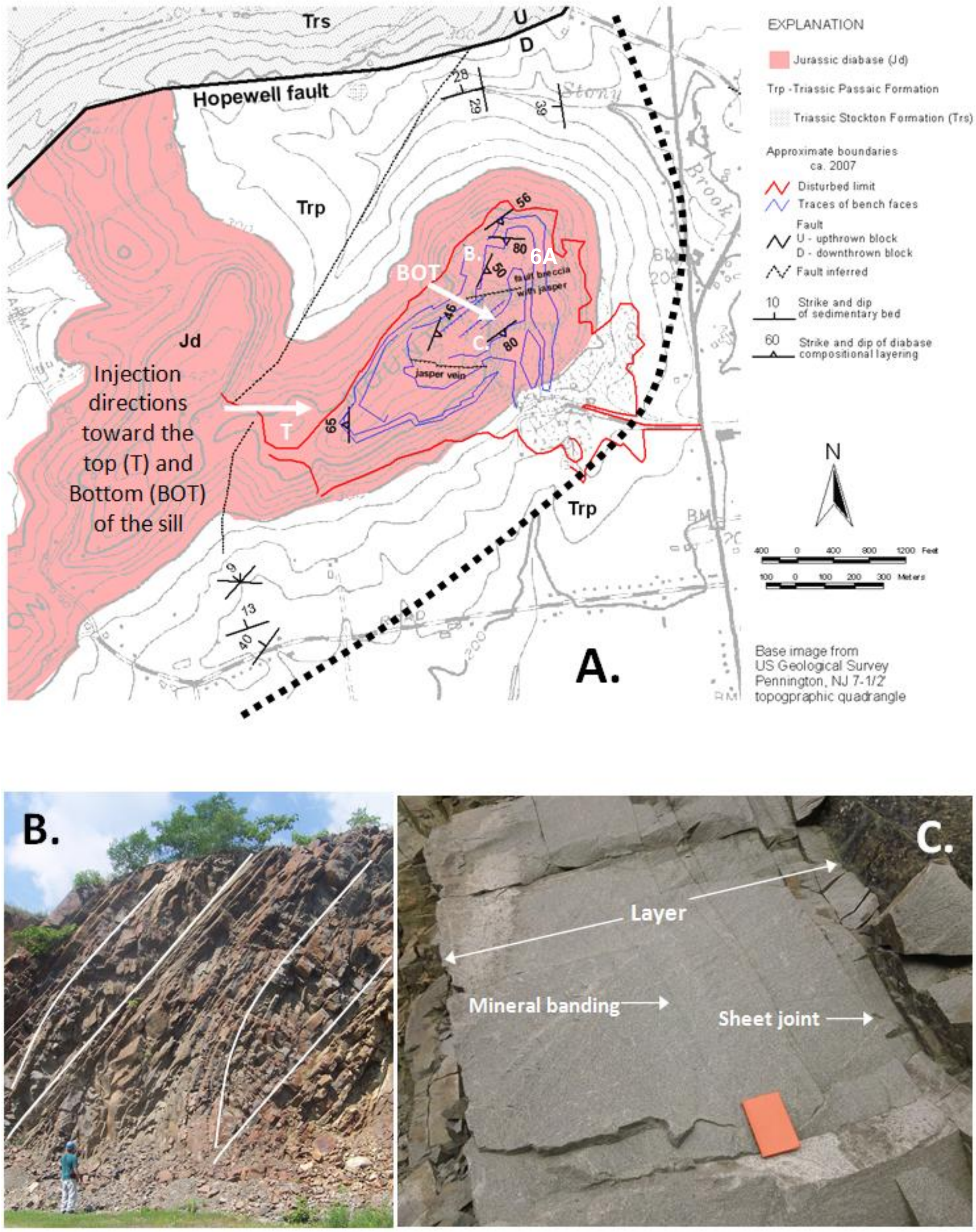


Figure 5. Geological map (**A**.) and photographs (**B.** and **C.**) from the Pennington trap-rock quarry. White arrows on map show inferred injection directions based on layer orientation. **B.** West view of SE-dipping layering showing concave horse tailing of sheet joints against adjacent layers that are about 4-5 m thick. **C.** Detailed view of steeply dipping compositional layer showing mineral banding seen on a joint surface sheet joints oriented sub parallel to layering. Layer is about 1.5 m thick.

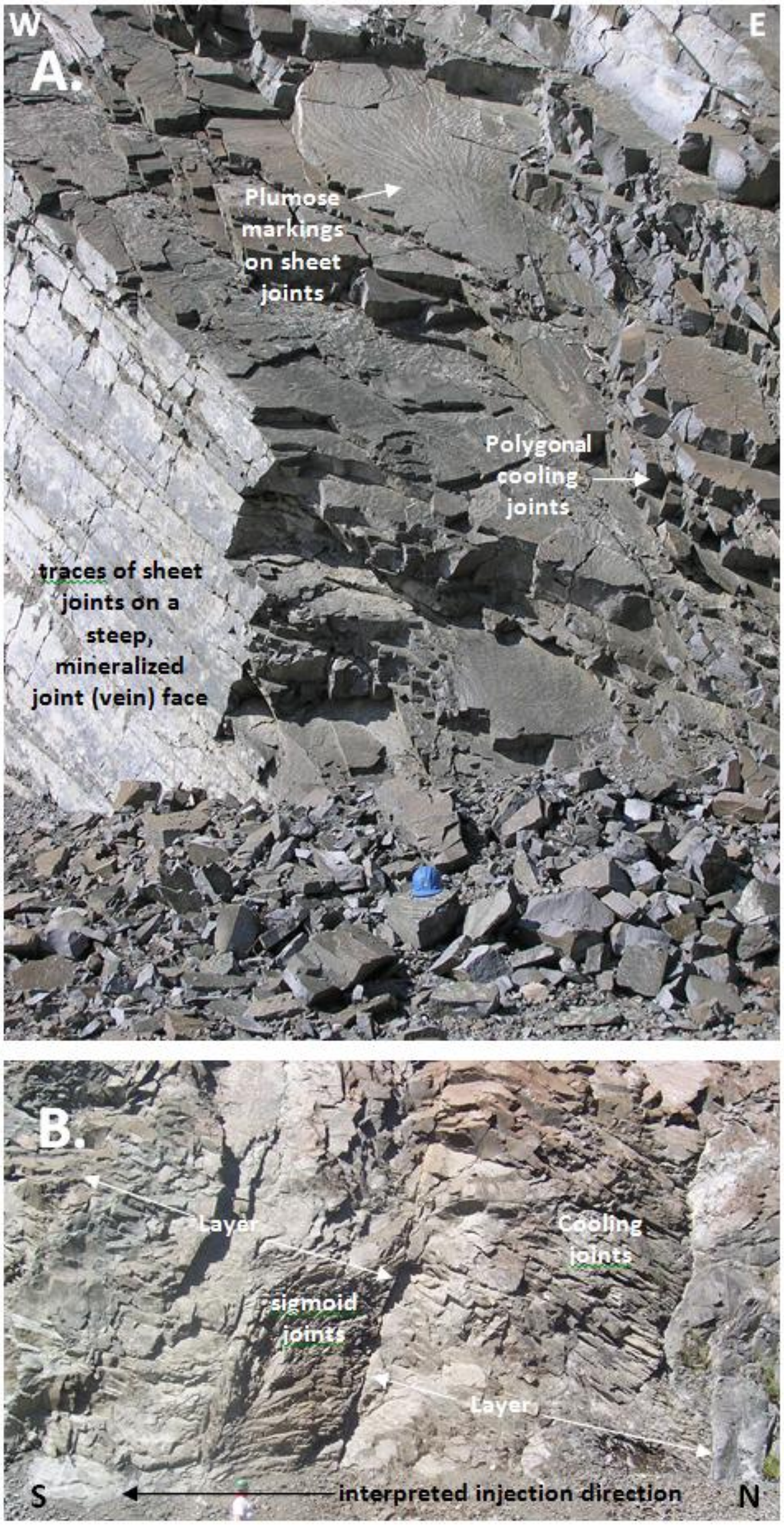
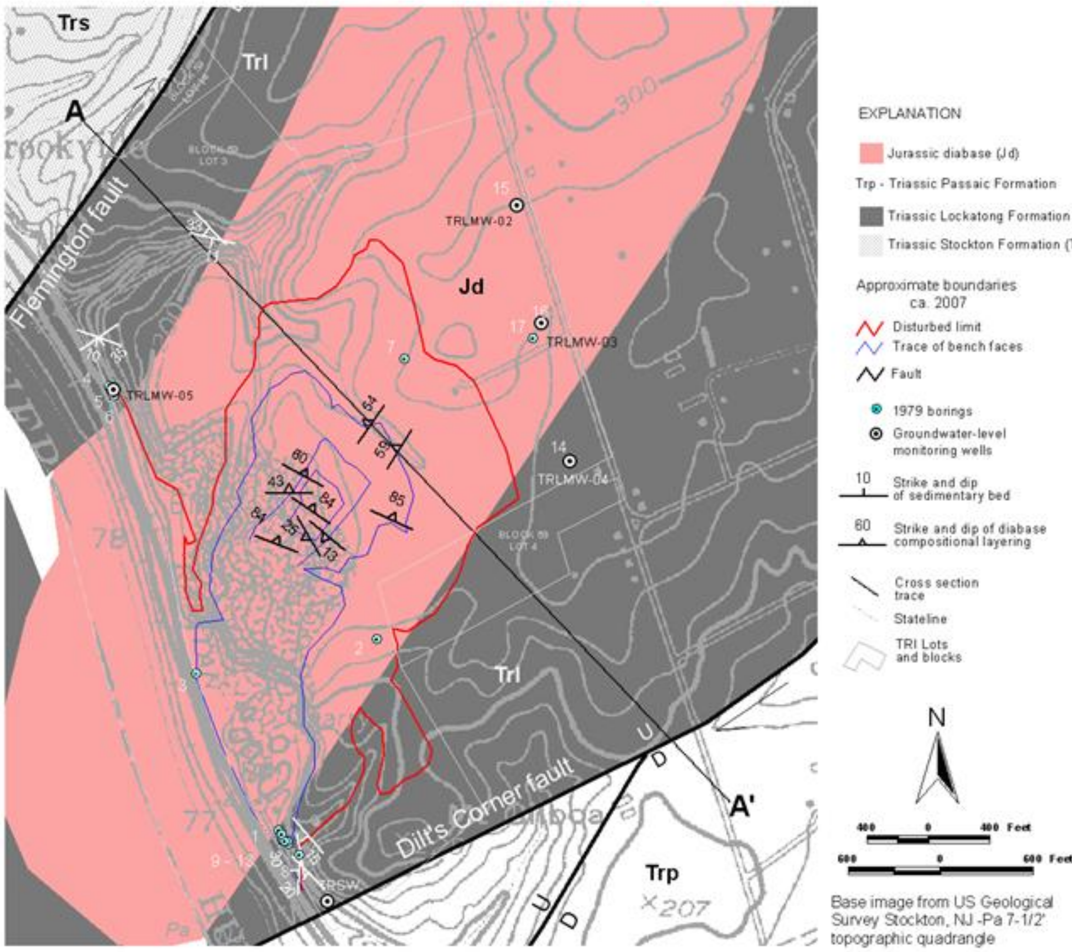


Figure 6. Photographs showing compositional layering and jointing in the Pennington quarry (photos locations noted on figure 5A). **A.** Northwest view showing sheet joints and cooling joints. Sheet joints spaced about 0.5 m parallel to layering. Note the plumose markings on sheet-joint faces. Polygonal cooling joints are normal to layering. **B.** West showing massive layers (about 8-10 m thick) with cooling joints oriented at high angle to layering, and slickensided sigmoid fractures that may indicate synchronous cooling and shearing. The cooling joints are interpreted as occurring on the base of layers indicating injection and sill growth from the inside out.



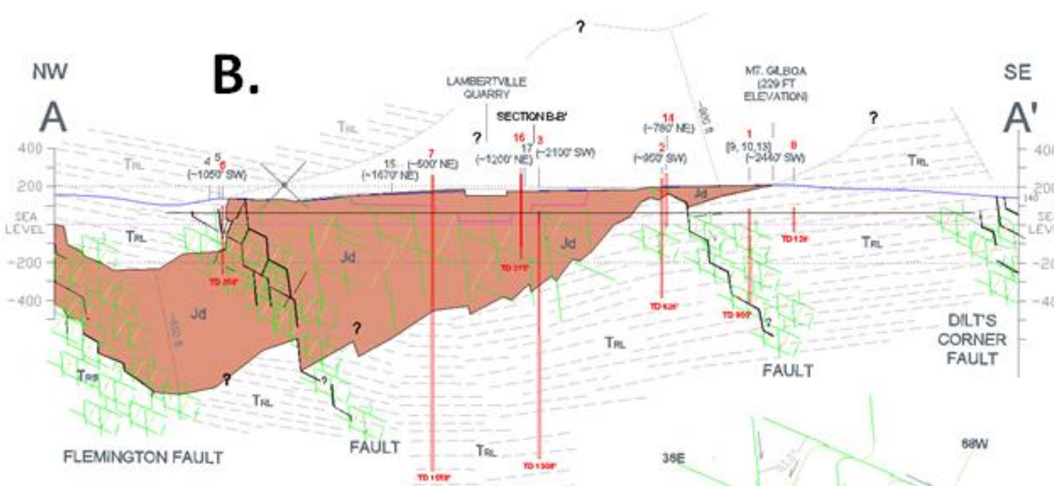


Figure 7. Geological map (**A.**) and cross section (**B.**) of the Lambertville quarry. **C.** Structural diagram showing the geometry of four sets of small-faults mapped in the quarry.

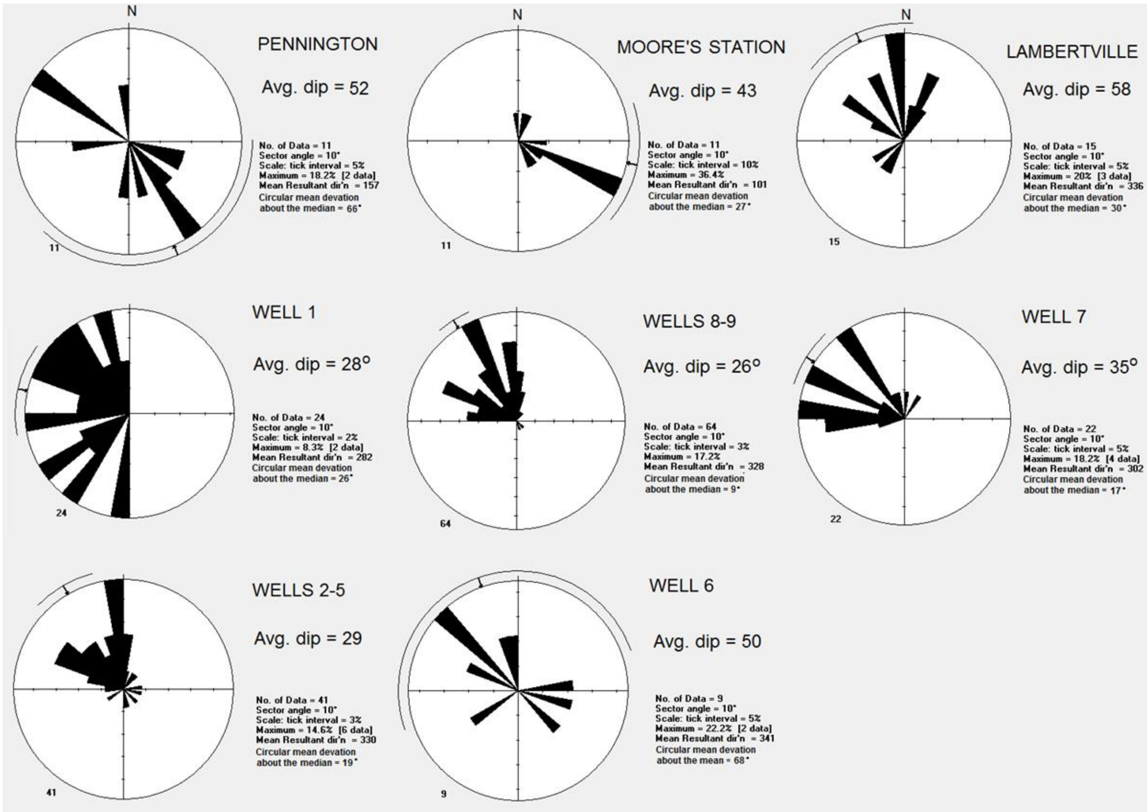


Figure 8. Circular histogram plots showing frequency of layering dip directions azimuths) at each location (figs. 2 and 3). The mean resultant direction is plotted as a vector beside an arc for the circular mean deviation. Layering generally shows unimodal clustering about the mean direction, with circular dispersion about the mean being generally less than 30^{o}. Exceptions are the Pennington quarry and Well 6 with bimodal distributions discussed in the text.

front intersected, climbed, and crossed the Hopewell fault as it was wedging forward to the southeast within the basin (fig. 10 The magma likely ascended as linear conduits along intersections of normal fault planes that are arranged in acute alignment to form rhombohedral fault blocks, with a resultant, main fault trace having a zigzag form upon detail inspection (fig. 7C, Herman and others, 2013). The dike segments stemming southeast from the trace of the Hopewell fault probably feed Baldpate and Pennington Mountains into upper stratigraphic sections in the hanging wall fault block (fig. 10). hese dikes probably rose along release bends in transtentional fault systems where younger faults striking parallel to the Flemington fault (S2 strikes of Herman, 2009) intersect and overlap older, en echelon faults that parallel the border fault (S1 strikes). Such intersections and associated synclinal sags have been mapped along the basin border faults (Bascom and others, 1931; Schlische and Olsen, 1988). Another dike emanates from the Hopewell fault immediately to the East that feeds the Rocky Hill sill (figs. 2 and 3).

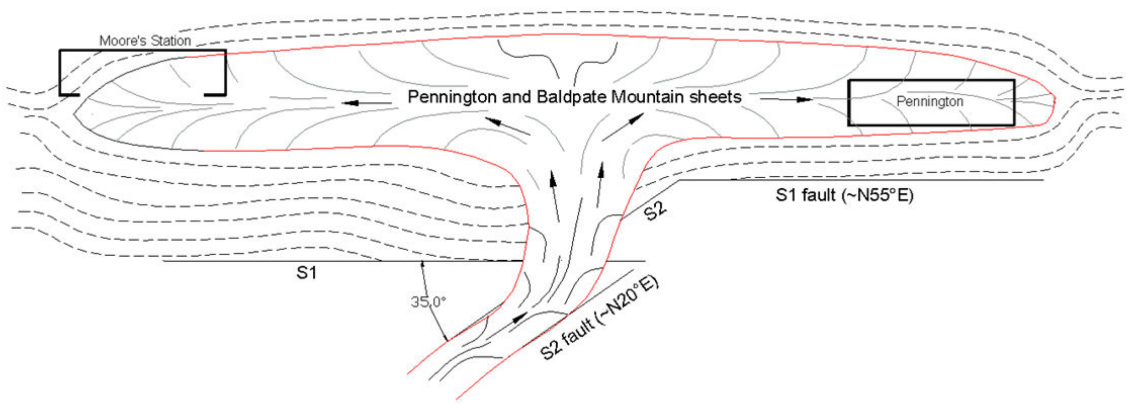


Figure 9. Schematic profile of a sill fed by a moderately to steeply dipping dike ascending along linked fault segments having acute differences in strike. Igneous compositional layering and sub parallel sheet joints curve upward and outward from a medial plane lying midway between the top and bottom of the sill along which magma is fed away from the source toward the propagating tips. The propagation direction is opposite to the layering dip toward the top of the sill and with it towards its base. The locations and relative positions of the Moore's Station and Pennington quarries are boxed and labeled.

The Lambertville quarry (fig. 7) is cut into the Stockton dolerite (diabase; Husch and others, 1988). This body intrudes the Lockatong Formation (Drake and others, 1996) but the geometric form of the intrusion is uncertain due to pervasive shear strains and associated rotations of primary structures as seen in the quarry. This body exhibits the highest tectonic strains of any of the bodies studied and is sandwiched between two large faults having normal and oblique slips (Ratcliffe and Burton; 1988, Houghton and others, 1992; Herman, 2005a). The contact between the dolerite and Lockatong Formation strikes about N40^{o}E but the strike of enveloping beds is almost orthogonal to the contact (fig. 7). This indicates that this body locally cuts Triassic strata at a high angle, which is confirmed by drilling data near the western contact where diabase lies directly beneath the Lockatong Formation in the subsurface (fig. 7B), and yet is only a stone's throw away from shear faces of dolerite in outcrop. It's possible that the Stockton dolerite locally thickens along some of the fault zones as it gradually ascends from a lower stratigraphic section into higher ones to the southeast in a manner similar to that depicted by Husch and others (1988).

Recent bedrock geology mapping in the Lambertville quadrangle, Pa-NJ (fig. 2, and Herman and others, 2013) resolved some structural discrepancies between bedrock maps on either side of the Delaware River in Pennsylvania (Berg and others,1980) and New Jersey (Owens and others, 1998). The Belle Mountain (NJ)– Bowman Hill (Pa) dolerite body is mapped as a stock that rises up through the hinge zone of a footwall anticline in the Lockatong Formation, with its upper contact plunging gently westward beneath the lower section of the Passaic Formation across the river in Pennsylvania (fig. 3). This is consistent with Ratcliff and Burton's (1988) report of the Bowman Hill-Belle Mt. body being a stock-like feeder to Jericho Mountain (fig. 3).

The Stockton dolerite appears to have similar geometry to the Belle Mt. - Bowman Hill stock and may be the same body that is now segmented and translated southeastward from post-intrusion faulting. It is interesting to note that the Bowman Hill body includes a dike segment that veers toward the Hopewell fault with the same strike as the segment of Jericho Mt. immediately across the fault to the southeast (fig. 3). This relationship suggests that melt ascended along the Hopewell fault system to feed the Belle Mt.-Bowman Hill-Jericho Mt. complex as a single body as in the manner depicted in figures 9 and 10, but with up to three separate dike sources. A fourth dike segment occurs along the Hopewell fault east of Pennington Mountain that feeds the Rocky Hill sheet (figs. 2 and 3). This dike is aligned with the dike segment of Sourland Mountain across the Hopewell fault to the northwest, and has been studied in the subsurface with a BTV record (Well 6, fig. 3; Herman and Curran, 2010). This is a natural segway into the orientation analyses of mineral compositional layering gained from subsurface OBI work.

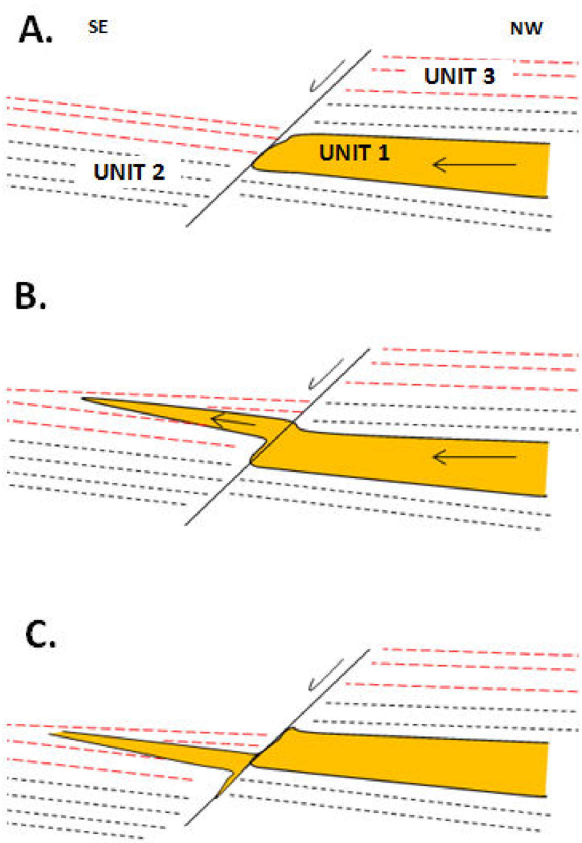


Figure 10. A sequence of cartoon profiles illustrating how magma may interact with a fault during and after sill emplacement. **A.** Dolerite sill (UNIT 1) is injected into UNIT 2 from the NW toward the SE and approaches a pre-existing normal fault. **B.** Upon contact with the fault, the melt ascends along the fault and crosses into a higher stratigraphic level (UNIT 3). **C.** Melt injection stopped and ensuing fault slip offsets all three units.

Optical BTV Studies of Water-Well Boreholes

The orientations of igneous compositional layers in the subsurface are measured using an OBI system thtat photographs structures exposed in the boreholes of water wells with sections open to bedrock (Herman, 2010; Herman and Curran, 2010). Explanation of the methods of data acquisition and processing of OBI digital records is beyond the scope of this work, and the reader is referred to Herman (2010) for further explanation on the acquisition and interpretation of such BTV data. Figure 11 includes a section of Well 9 and a schematic diagram that illustrates how planar features are photographed and unrolled in order to measure their strike and dip. The stratigraphic and structural analysis of an optical BTV

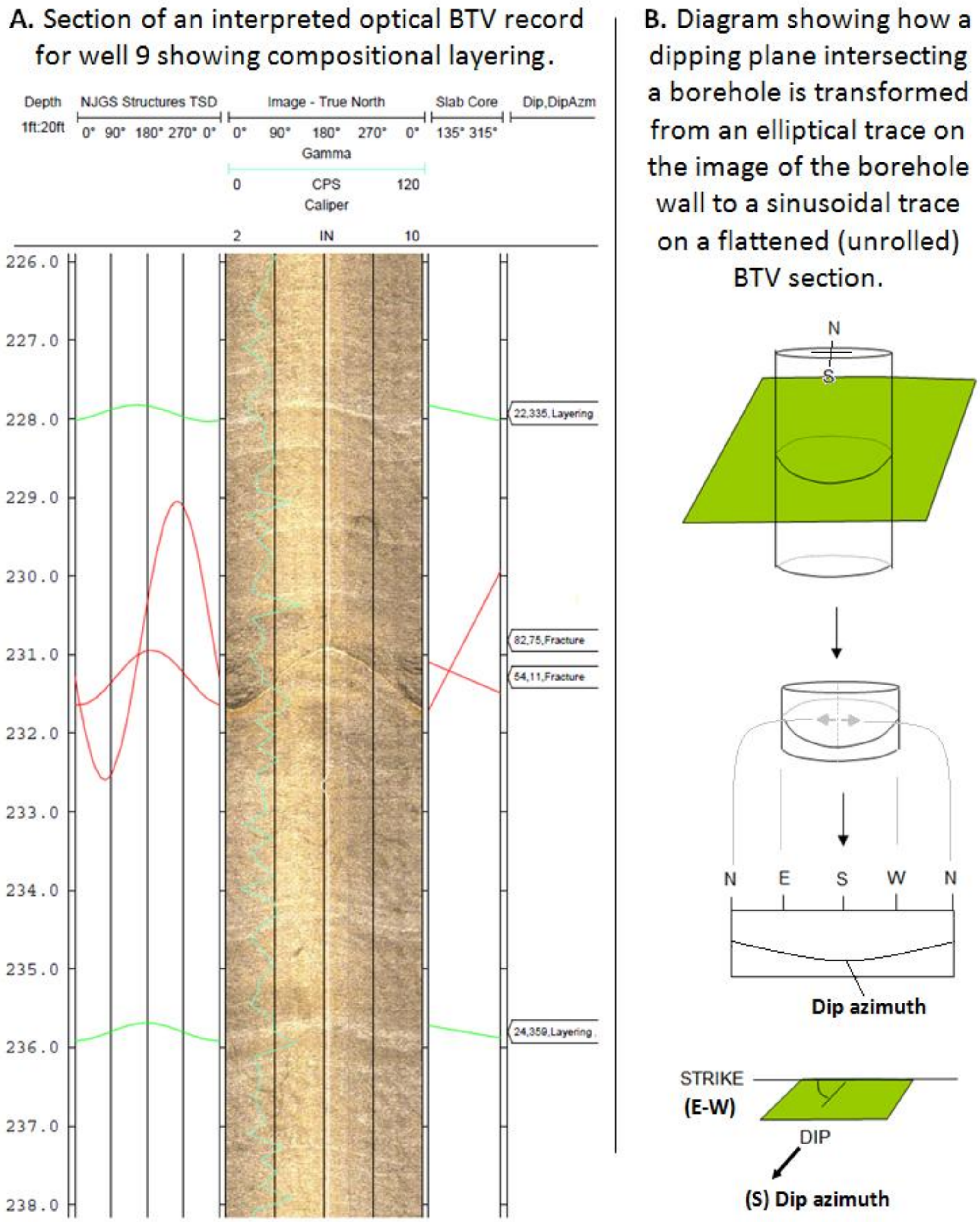


Figure 11. **A.** Part of an optical BTV record of Well 9 (location shown on figs. 2 and 3). Layering dips 22 to 24^{o} toward azimuths 335 to 359^{o}. in this section. **B.** A series of schematic diagrams illustrate how a dipping, planar structure that is penetrated by a borehole makes an elliptical trace on the borehole wall that is photographed, unrolled, and flattened for measurement. In this latter case, the plane dips south.

record includes the identification, grouping, and measurement of primary and secondary structural planes. Compositional layering in igneous rocks is the only primary planar structure recorded in igneous rocks and is identified in OBI records where parallel planes of contrasting mineralogical composition produce alternating light- and dark-colored bands from the variable intensities of light from a diode source that is reflected off the borehole wall and captured by a digital camera (fig. 11A). Secondary structures that overprint compositional layering include tension fractures and shear planes that locally offset layering and other fractures (Herman and Curran, 2010). Tension fractures and shear planes sometimes have visible accumulations of secondary minerals that are interpreted as mineral veins if no associated strain slip is seen.

Herman and Curran (2010) include hydrogeological sections for wells 1 to 6 with stratigraphic sections having variable colors, textures, and fracture densities. Darker-colored sections have more mafic components (pyroxene, hornblende, and magnetite) than lighter ones with proportionately more feldspar and quartz. Dolerite layers alternate from light-gray to dark-gray with varying degrees of fracturing but shade is seemingly unrelated to fracture density. Their shaded layers range in thickness from less than a meter to more than 30 meters whereas densely fractured sections range in thickness from about a meter to about 10 meters. Layering commonly shows unimodal distributions of orientation that resemble cross bedding in sedimentary rocks (fig. 8). These records have circular mean deviations about the median direction of layering that are generally less than 30^o. Exceptions to this trend are seen for the Pennington quarry and well 6 that show bimodal distributions with circular deviations of over 60^o (fig. 8). The bimodal nature of layering in the dike may result from the well having penetrated parts of both sides of the dike and therefore crossed layers and sheet joints of opposite orientations as depicted in figure 9; a well that penetrated only the upper or lower section where layering is consistently oriented in one direction would show a unimodal distribution, whereas a well fully penetrating the unit, or straddling the median conduit, would show a bimodal distribution. The latter scenario also probably applies to the Pennington quarry (fig. 8) and is the basis for positioning the extent of quarry workings in figure 9 as straddling both lower and upper sill sections.

Figure 12 summarizes the layer orientations that were obtained using the BTV records on a longitudinal, schematic profile through the Lambertville-Sourland Mt. dolerite complex. The orientations of compositional layers and sub parallel sheet fractures indicate southeast-directed injection at most points observed (fig. 3). One clear exception to this case is the Moore's Station quarry on the west end of Baldpate Mt. where injection from the east is consistent with having this body fed from the aforementioned dike segment located to the east along the Hopewell fault (figs. 2, and 3). A northwestern magmatic source is consistent with Husch and others (1988) observations that the comparatively mafic dolerite of the Byram-Point Pleasant body is close to a hypothetical feeder dike, and that this body probably was connected to the more felsic ones situated in higher stratigraphic sections to the southeast. This then leads us to the obvious question: where are the feeder dikes for this intrusive system?

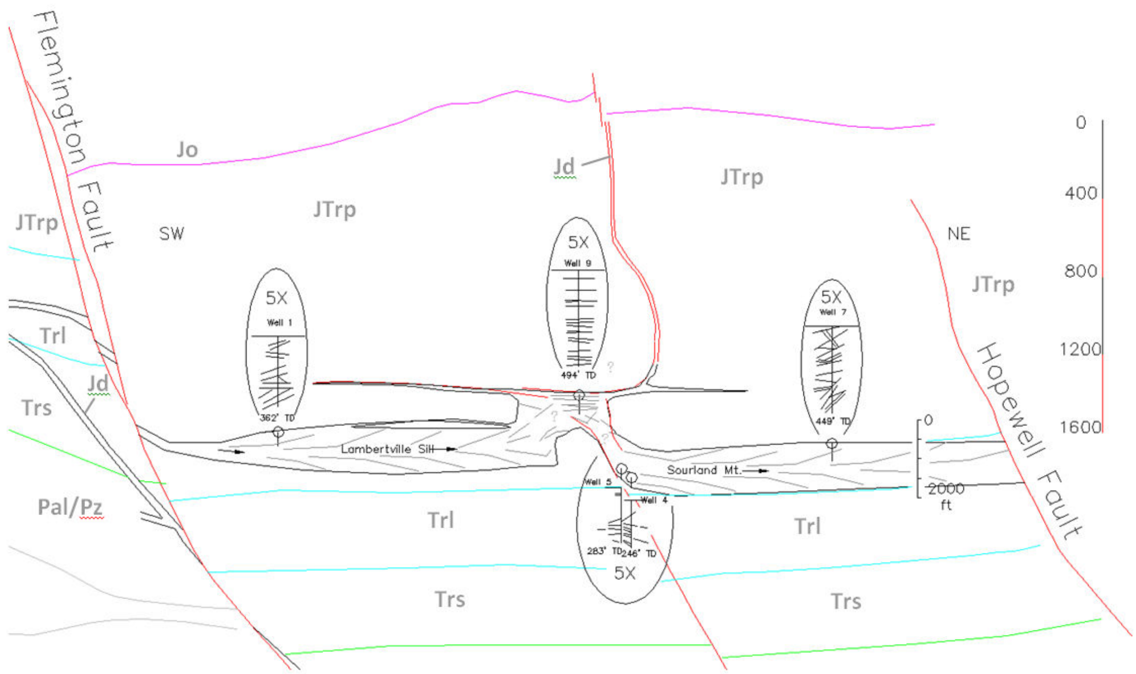


Figure 12. Schematic, longitudinal cross section showing apparent layering orientations within the Lambertville-Sourland dolerite complex. Jo - Orange Mt. basalt, JTrp - Passaic Formation, Pal/Pz - Paleozoic and Proterozoic rocks undivided, Trl - Lockatong Formation, Trs - Stockton Formation.

The Buckingham Dome

Large Early Jurassic dikes cut the Eastern US continental margin along its length from Georgia to Maine (King, 1961; 1971, Wiegand and Ragland, 1970, and McHone and others, 1987). In the vicinity of the New York recess, they commonly strike about N20^{o} E to N30^{o} E, lie mostly transverse with respect to older Appalachian structures in the region from Lancaster, Pa to Buckingham, Pa (fig. 1), and are portrayed as dipping steeply about the vertical (Berg and others, 1980). In the Hartford basin they are shown as steeply dipping to the west-northwest by Phillpotts and Martello (1986). The map traces of these dikes are commonly tens of kilometers in length, sometimes exceeding 100 km, but they are usually not wider than a few tens of meters (Smith and others, 1975). The only place where large, transverse dikes cut across the area of concern is where the Plumstead Hill dikes (Bascom and others, 1931) and the Solebury dike (Ratcliffe and Burton, 1988) strike toward convergence just west of the Buckingham window (figs. 1 and 2). As currently mapped by Berg and others (1980) these dikes terminate in the lower section of the Lockatong Formation after discordantly crossing pre-Mesozoic basement and the Stockton Formation from the south (fig. 2). But earlier geological maps show that these structures are more extensive than currently portrayed and may directly connect to the Byram-Point Pleasant body (fig. 13).

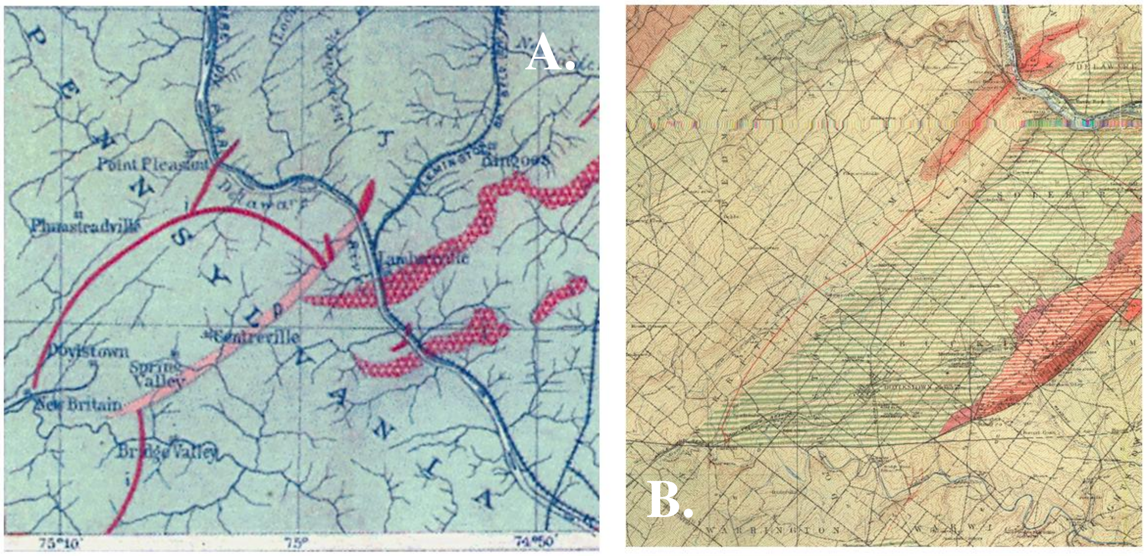


Figure 13. **A.** Part of Plate 1 from Darton (1896) showing the Plumstead Hill and Solebury dikes connecting with the Byram-Point Pleasant dolerite body. **B**. Part of Bascom and others (1931) map details showing an extended range for the Plumstead Hill and Solebury dikes in comparison to that of Berg and others (1980).

These dikes also have some unique structural aspects. For example, the Plumstead Hill dike is offset by the Chalfont fault with about 10 km of apparent left lateral displacement (fig. 10). To the south of the Chalfont fault, the offset parts of the dike (fig. 2) occupies a strange antiformal crease in the Stockton Formation before continuing southwestward where it cuts across pre-Mesozoic basement rocks of the Pennsylvania Piedmont and veers southwestward along the trace of the Cream Valley fault for almost 40 km before horse tailing out near the trace of the Doe Run-Downingtown dike (figs. 1 and 2; Bascom and others, 1909). The Solebury dike is cut off by the Furlong fault, but strikes parallel to western dike segments of the Lambertville Sill, Sourland Mountain, and the Rocky Hill sheet (figs. 1 to 3). When considering the apparent offset of the Plumstead Hill dikes, it is likely that together, the Solebury dike and the aforementioned dike segments of the dolerite sheets in New Jersey either represent the same feature that is cut, offset, and repeated in several fault blocks, or a parallel set of structures that dip steeply to moderately eastward to the east of Buckingham, Pa. (figs. 1 and 14). Having pre-Mesozoic basement cropping out in the Buckingham window near the center of the basin requires at least 5 kilometers of structural relief as nicely illustrated by Olsen (1980) with a palinspastic, longitudinal cross section through the central part of the basin (figs. 14 and 15). We adapted his section and inserted an intermediate stage of crustal deformation that illustrates a hypothetical crustal dome that we propose formed in association with the emplacement of the convergent, conjugate Plumstead Hill and Solebury dikes and associated plutons before being cut, segmented, and offset by later faulting. It is likely that this ‘Buckingham dome’ represent a thermal welt in the crust where the geometry of the Early Jurassic dolerite dikes changes polarity along the Appalachian margin near the Delaware

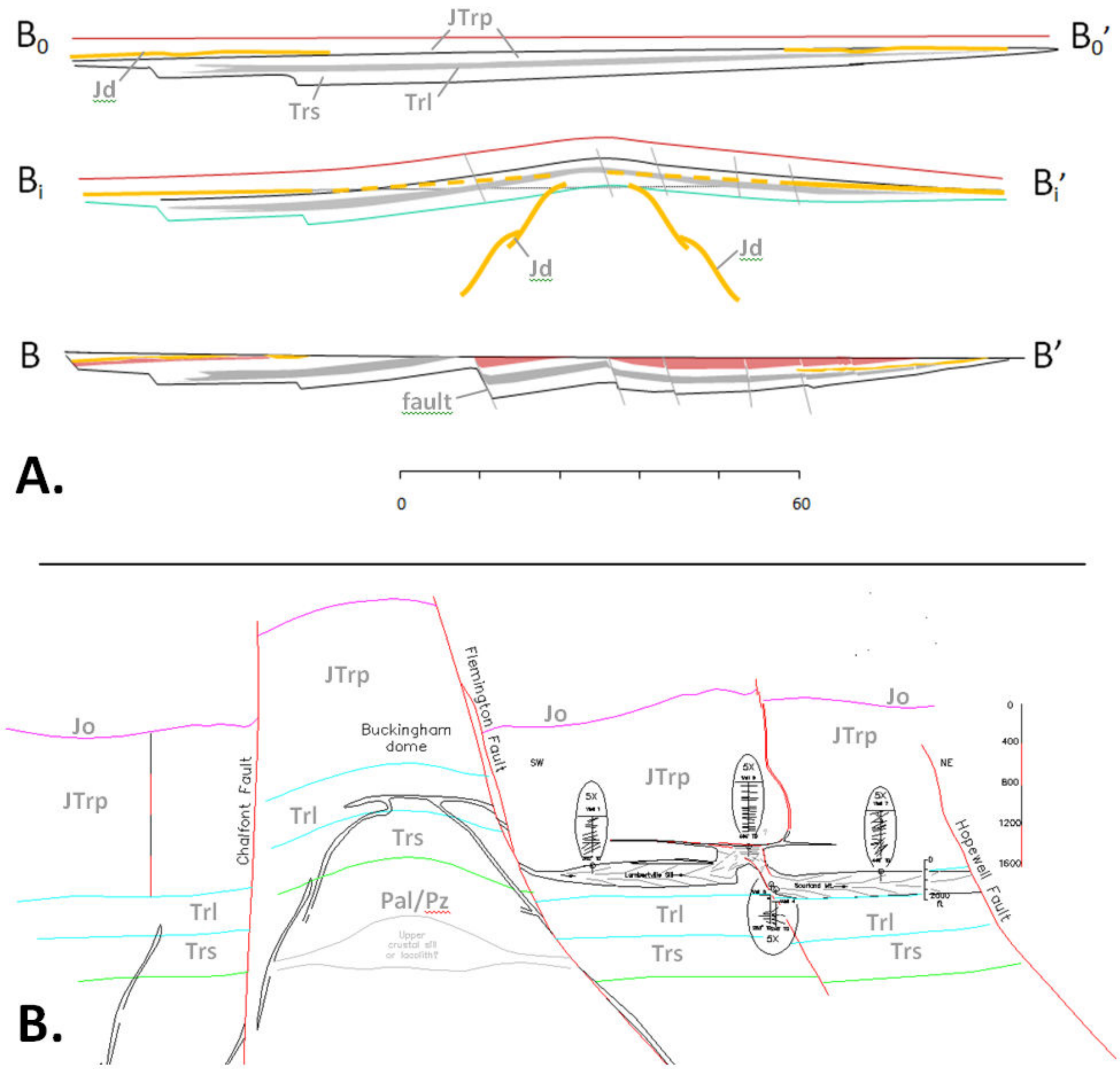


Figure 14. Longitudinal cross sections illustrating dolerite dikes and plutons relative to the Buckingham dome. **A.** The dome in B_i-B_i' is an intermediate-phase of crustal strain that's inserted between an adapted version of Olsen's (1980) current (B-B') and restored (B_0-B_0') sections (map trace shown on fig. 15). **B.** An expanded range for the cross section in figure 12 showing the Lambertville-Sourland dolerite complex relative to the feeder dikes in the Buckingham dome. Abbreviations are the same as for figure 12.

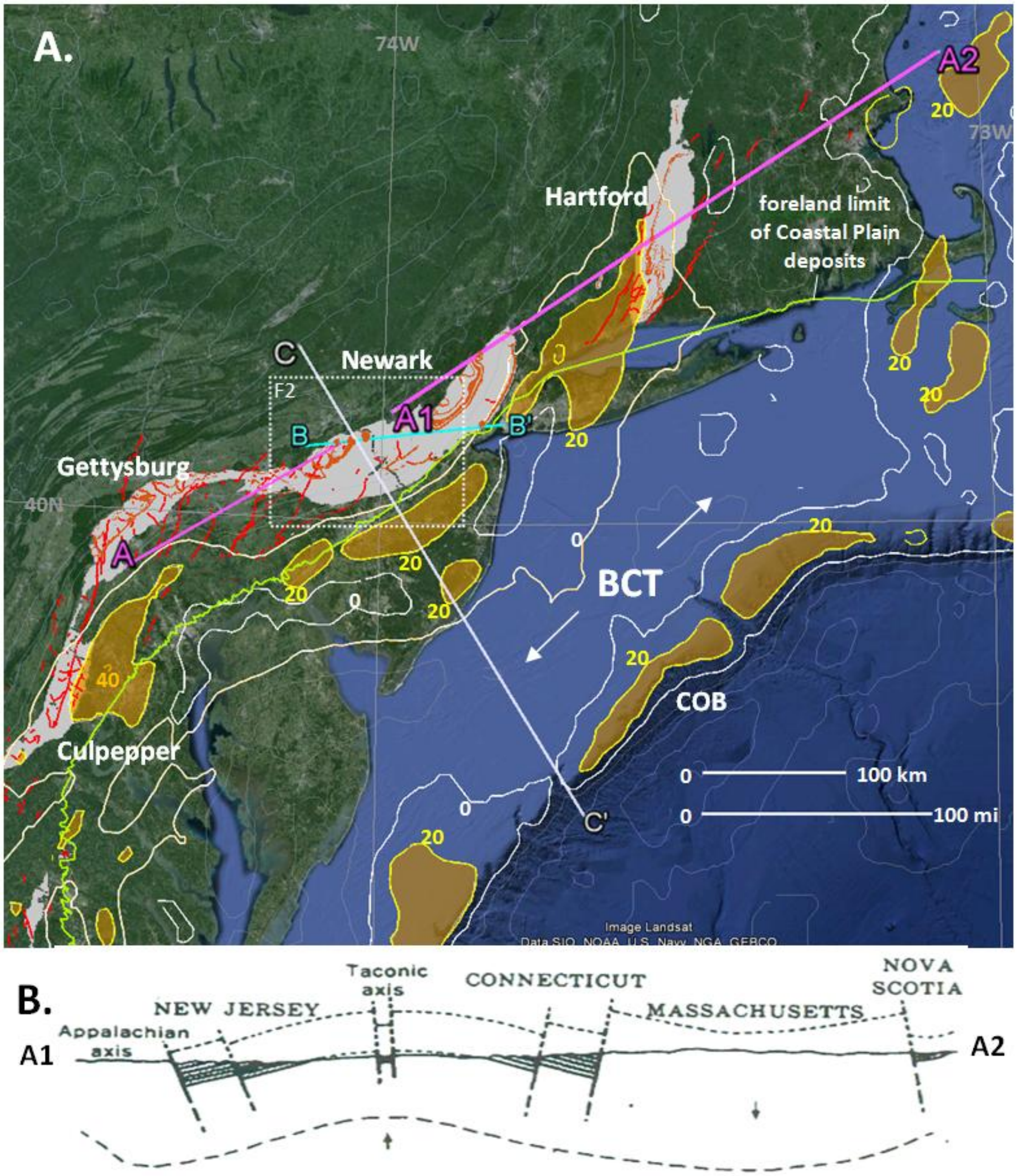


Figure 15. **A.** Map of the New York Recess showing exposed Early Mesozoic rift basins (gray polygons), and CAMP dikes (red lines) and exposed dolerite bodies (small, solid orange polygons in rift basins) in relationship to positive Bouger gravity anomalies. Positive anomalies are highlighted using white (0 mGal) and yellow (20 mGal) polylines. The broad-wavelength, >20 mGal anomalies are emphasized using semi-transparent orange polygons that probably indicate the locations of thick remnants of deep CAMP plutons. **B.** Longitudinal cross-section A1-A2 from Woodworth (1932) showing arching of the Taconic axis relative to rift basins and a Massachusetts trough. BCT - Baltimore Canyon Trough.

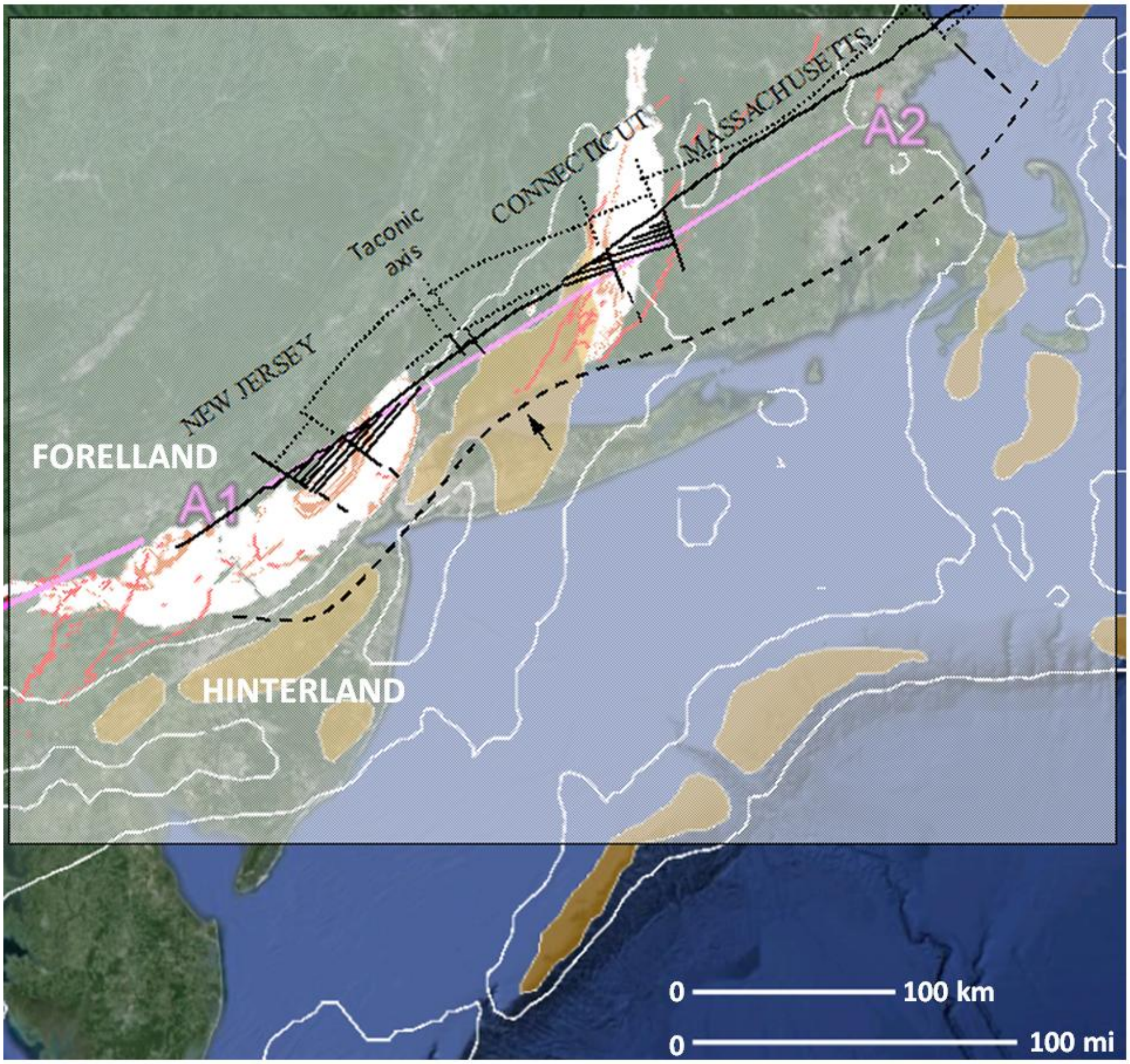


Figure 16. Woodworth's (1932) cross section image that is rotated, rendered semi-transparent, and placed on top of a non-annotated version of the GE compilation shown in figure 15. This shows the crustal arch overlying a 20mGal Bouger anomaly located between the Newark and Hartford basins.

River, with predominately steep, northeast striking and west dipping dikes in Pennsylvania giving way to northwest striking and steep- to moderately east-dipping dikes in New Jersey (figs. 14 and 17). Intrabasinal doming is therefore proposed to have occurred in the basin during the Triassicperiod prior to Early Jurassic volcanism. This helps explain how primitive melts associated with the more mafic sills were emplaced within lower parts of the Triassic sedimentary section and climb up section into higher stratigraphic positions nearby. Therefore, rather than having a single, northwest-dipping dolerite sheet that later gets segmented and repeated by faulting (Husch and others, 1988), the convergent dikes in the Buckingham dome fed sill-like dolerite bodies laterally outward into increasingly higher stratigraphic levels into marginal sub basins that flanked the dome. This scenario is different from prior tectonic interpretations of the basin insofar that thermal doming accompanying taphrogenesis in the Newark basin that has not been previously identified or incorporated into tectonic interpretations. The implications for this are far reaching, so we conducted a literature search and a map compilation of CAMP features in the region in order to gain corroborating or refuting evidence for testing the hypothesis. One strong line of evidence supporting the concept stems from comparing the CAMP bodies with regional Bouger gravity anomalies (Geological Society of America Committee for the Gravity Anomaly Map of North America, 1987).

Camp Bodies with Respect to Regional Bouger Gravity Anomalies

Earlier gravimetric studies of the eastern North American rift basins in the 1960s and 70s established the direct correlation of gravity anomalies with exposed diabase bodies (Sumner, 1977) because dolerite is mafic with a higher density than enveloping sedimentary rocks. Average density values of 3.0 and 2.6 gm/cm^3 were used by Daniels (1985) for characterizing residual gravity anomalies in the Narrow Neck region of Pennsylvania. In a similar manner, geophysical studies of the continental margin assume comparative density values of 3100 and 2875 kg.m^3 for mafic and felsic crustal blocks, respectively (Behn and Lin, 2000). Bouger-gravity-anomaly maps depict lateral variations in crustal densities after accounting for other gravitational effects stemming from shape irregularities of the Earth's geoid, lateral elevation changes, surface irregularities, Earth tides, and isostatic corrections (Telford and others, 1976). For this study, we compared the locations and forms of positive Bouger gravity anomalies occurring along the Atlantic margin of the New York recess to exposed CAMP bodies including bodies in and outside of the basins.

A digital version of the gravity anomaly map of North America (Geological Society of America, 1987) was downloaded from the World-Wide-Web and combined with a digital compilation of CAMP bodies using Google Earth $_{TM}$ (GE). The comparison was facilitated by parsing and combining CAMP elements for the various States from digital geological map themes that were compiled and made available by the US Geological Survey (http://mrdata.usgs.gov/geology/state/). Figure 15A shows parts of this GE compilation for the area of the New York recess. This map shows a close spatial association of dolerite dike swarms with positive Bouger anomalies stretching from the Culpepper basin in the southwest to the Hartford basin in the northeast. The large, transverse suite of dikes near the Hartford basin is rooted above the center of >20 mGal anomaly that spatially coincides with a regional crustal arch depicted by Woodworth (1932) as separating west-dipping strata in Newark basin from the east-dipping strata in the Hartford basin (fig. 15B and 16). Moreover, the foreland edge of the positive Bouger anomaly (along the zero mGal isopleth) coincides with the southern terminus of the pervasive dike swarm distributed about the narrow neck of Early Mesozoic strata that connects the Gettysburg and Newark basins (figs 1 and 15A). These relationships are the basis for proposing a direct correlation of regional, long-wavelength, positive Bouger anomalies with deep, subsurface CAMP plutons that under plate the passive margin in their current, stretched and segmented form. The high-magnitude, long-wavelength Bouger anomalies probably correlate to thicker CAMP remnants, with one underlying New Jersey's inner Coastal Plain in addition to other areas of the recess where similar Bouger anomalies overlap marginal area of the Culpepper and Hartford basins (figs. 15A and 16) . The 20 mGal anomaly underlying the NJ Coastal Plain is different from the others because it does not directly underlie parts of a rift basin (fig. 15). However, the southwest continuation of the Plumstead Hill dike parallel's the Cream-Valley fault for about 40 km length, and therefore provided a path for magma to have ascended from sub-lithosphere levels on the southeast margin of the basin towards the basin and into the foreland. This is another example of fault-mediated magmatic ascent of CAMP bodies along synthetic (SE-dipping) major, orogen-bounding faults as depicted by Harry and Sawyer (1992), for this area, along the Brevard zone in the Southern Appalachian orogenic belt (King, 1971), and elsewhere (Magee and others, 2013). It is important to remember that this entire margin has been elongated from regional rifting, and today's physical separation of the anomaly from the dike swarm in the NJ region was likely much less than it is today. In that respect two regional cross-sections were developed along longitudinal (fig. 17) and transverse (fig. 18) lines with respect to the Appalachian grain in the New York Recess in order to estimate how much the margin was extended. The longitudinal section incorporates earlier sections of Woodworth (1932) and Olsen (1980), and the transverse section (fig. 18) used a profile framework from a deep, nearby seismic study of the continental margin (LASE study group, 1986). Both sections depict current crustal conditions relative to hypothetical, deep, sub-lithosphere dolerite bodies in various forms. The transverse section includes a restored (palinspastic, fig. 18B) interpretation that depicts the crustal structure at an earlier rift stage, before major extension and relaxation of the continental margin but after emplacement of a sub-lithosphere magma chambers that probably uplifted the overlying orogenic wedge comprising the lithosphere (fig. 18). This stage probably preceded an accelerated stage (S2 ? of Herman, 2009) of rifting when the large, transverse fractures cut the lithosphere and tapped these chambers to provide avenues for the magma to rise through the lithosphere as dikes that fed dolerite, hypabyssal rocks. The respective lengths of the these two sections are compared in figure 18 to derive an estimate of the horizontal component of the finite stretch along the line of section (fig. 15A).

Discussion

These interpretations incorporate aspects of earlier ones in the region to portray how the CAMP dolerite dikes locally blistered the crust and operated in concert with large normal faults in the New York Recess and as it was being stretched, thinned, and intruded with magma. The associated strain effects are shown as reaching well into foreland regions beyond the rift basins. The geological implications of these hypotheses are provocative with respect to some popular notions surrounding continental tectonic rifting and evolution of this passive margin. Many of these considerations reach beyond the scope of this paper. For example, there has been much debate over the mantle plume versus non-plume origin of CAMP (McHone, 2000; Wilson, 1997, among others). One reason for this arguments is the prior lack of evidence for crustal arching and doming in this region that characteristically accompany taphrogenic LIPs elsewhere (for example, Neugebauer, 1978; Bott, 1981; Bell and others, 1988). But we have just shown where these characteristic structures occur in the New York recess, and that they likely stem from CAMP activity. Nevertheless, we on focus the remaining discussion on some recognizable complications and limitations of the methods that we used and aspects of the model that need more work.

Using igneous layering and correlative sheet-joint orientations to infer injection directions hinges on the premise that the internal structure of the large, transverse dolerite dikes is governed by the same structural principles as small tension fractures. Most of the observations appear to substantiate this, but complications arise when observation points are positioned with respect to a complex body having structural segments that can be viewed either as a dike or sill for structural analysis. For example, well clusters 2-5 and 8-9 are both congruent to the northwest-striking dike segment that attaches the southwest termination of Sourland Mountain to the upper sill in the aforementioned structural saddle (fig. 3). Well 6 is clearly drilled into a dike segment and shows a bimodal population of layering dipping in opposite directions but layering strikes nearly normal to the trend of the igneous contact (fig. 3, and Herman and Curran, 2012, fig. 1C1). Most of the igneous layering was measured in small sections near the top and bottom of thick sills where they display a unimodal strike and dip direction but with generally steeper dips than their enveloping beds (figs. 4 and 5). Using these criteria, the Stockton dolerite appears to be more of a dike or plug than a sill. Another complication may arise from having cumulate layers formed near sill bases rather than solely from magmatic injection. For example, Herman and Curran (2012, fig. 1B7) show a ~3m section deep in well 5 at about 75 m depth where magnetic distortion obscures the OBI record from a probable magnetite cumulate layer. Having cumulate layering settling parallel to the lower igneous contact of a sill would therefore be one exception to the model. The layering for wells 2-5 are grouped in figure 8 and show a small deviation from the mean, but Herman and Curran (2012) show a syncline axis plunging gently north through the well field based on layering orientations at each well site. This serves as a reminder that layering in these bodies are subjected to later tectonic strains that can complicate the use of a simple plumose geometric model for inferring magma injection trends.

One striking map pattern associated with the Buckingham dome is the symmetric arrangement of the Flemington-Chalfont fault system around the core of the dome on its southeast side (fig. 1). This arrangement suggests that the Chalfont-Flemington fault system simply allowed the hinterland and marginal flanks of the dome core, now partly preserved as the Buckingham widow, to spall off and sag relative to the footwall block (figs. 2 and 14B); it appears that the hinterland half of the dome was simply broken off and slumped downward to the south and east. The compilation of Mesozoic faults about the dome includes faults of similar strike to transverse folds that have been previously mapped in the southwest part of the basin by Bascom and others, (1931) and Schlische (1992) among others. These transverse fault segments and broad, open, and gentle transverse folds in the basin continue into the Paleozoic foreland as late-stage, cross-cutting faults and transverse warps (fig. 2). This viewpoint expands the Mesozoic rift strains into a broader region of Appalachian terrain than has been previously portrayed and involves parts of the Appalachian foreland orogenic belts in the transtentional collapse of the eastern continental margin of the North American plate. Figure 2 also shows how the foreland trace of exposed Proterozoic rocks in the Reading Prong mimics the crenulated trend of major longitudinal synclines in the basin as additional proof of the strain continuum. In order for this hypothesis to be true, Mesozoic extension strains should be manifest in outcrops of these pre-Mesozoic basement rocks, but this remains untested.

The longitudinal section A-A2 (fig. 17) depicts hypothetical CAMP bodies underplating the lithosphere where the section crosses the >0 mGal Bouger anomaly between the Newark and Hartford basins (fig. 15A). A queried, thin deep plutonic remnant is included at MOHO depths beneath the Buckingham dome (BD) in order to raise the prospect of a deep body directly contributing to the growth of the dome, but thermal doming effects may stem solely from the crust being blistered by invasion and coalescence of the different dike swarms at this junction of the Appalachians. For example, the up warping of the Stockton Formation along the trace of the offset Plumstead Hill dike(s) east of Lansdale, Pa (fig. 2) is a unique structure in the basin and qualifies to be conserd as a thermal structure. Section A-A2 also emphasizes the symmetrical arrangement of the regional dike swarms with respect to centers of down warping involving major lithospheric blocks. These same structural relationships are seen within basin strata at the outcrop-scale where systematic extension fractures dip in the opposite direction of structural sags in bedding (Herman, 2009). It is more likely that the conjugate, transverse dikes that fed into the dome tapped melt chambers located toward the hinterland and marginal areas where deep-seated synthetic (southeast-dipping), terrain-bounding faults tapped deep magma chambers now represented by deep plutons that were stretched and dislocated to the southeast. The regional transverse cross section C-C’ (fig. 18) provides one explanation of how within the constraints of a known geophysical framework (LASE, 1982).

Based on the distribution of the positive Bouger gravity anomalies and the places where the large, transverse dolerite dikes cut the continental margin it seems likely that there are many CAMP feeder systems occurring in the New York recess. For example, the Doe Run-Downingtown dike (fig. 2) is a good candidate as a feeder for dolerite bodies in the

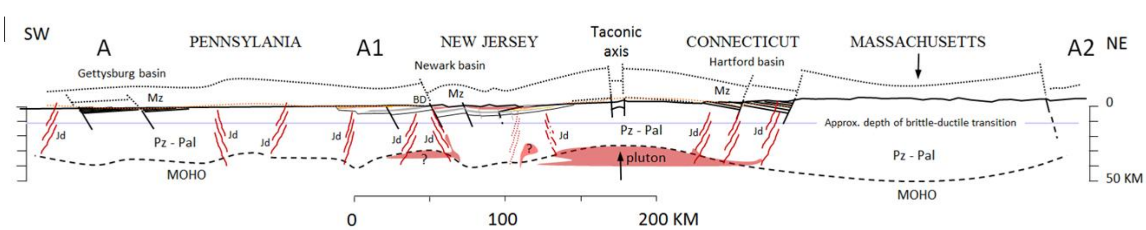


Figure 17. Regional, longitudinal profile across the New York Recess incorporating Olsen's (1980) and Woodworth's (1932) cross sections and depicting Early Mesozoic (Mz) basins relative to deep dolerite plutons beneath the continental lithosphere and overlying, deeply-penetrating dolerite dike swarms. Pz-Pal – undivided Proterozoic and Paleozoic basement, BD – Buckingham dome. MOHO - Mohorovičić discontinuity

Quakertown area as it rises from the same terrain-bounding suture as for the Plumstead Hill dike and has a direct, cross-cutting connection to the dolerite sill-dike complexes. The southwest tips of Connecticut valley dike swarms represent other feeders into Connecticut and Massachusetts based on the aforementioned spatial relationship with the gravity anomaly, but the location of a deep feeder for the Palisades Sill isn't as apparent.

The common, saucer-shape geometry of sill-like plutons in the Newark basin is a well-known structural form of hypabyssal sills emplaced in the 0-6 km depth range at many places throughout the world (Malthe-Sorenssen and others, 2003). The upturned saucer form of Palisades Sill has a median point lying near Graniteville, NY (fig. 1) where Sanders and Merguerian (1997) found some evidence to support a nearby, centralized magmatic feeder that fed the sill outward in opposing directions, like that portrayed in figure 9. We demonstrate that most of the dolerite bodies cropping out in the hanging walls of the intrabasinal faults were probably fed systematically away from the Buckingham dome (figs. 2 and 3). This includes the saucer-shaped Rocky Hill dolerite (fig. 2) that joins to meet the southwest end of the Palisades sill (Ten-Mile Run dolerite, fig. 2) just west of the Kingston quarry where an unusual, upward-flaring dike may occur as a result of sill reflect sill coalescence. The aforementioned >20mGal Bouger anomaly sitting between the Newark and Hartford basin has a small finger-like protrusion that reaches southwest close to the Graniteville location, the suspected feeder location for the Palisades. We simply may not have the tilted, eroded perspective that would reveal a deep-seated dike or dike system at this location. Although it is comfortable to place a suspected feeder source at a halfway mark along the strike of the Palisades Sill, that would have efficiently served magma to both lateral margins, the source remains hidden and speculative for this well-known body at this time.

Kohn and others (1993) characterized the Mesozoic thermal regime for the Central Appalachian piedmont using evidence from Sphene and Zircon fission-track dating methods. Their findings indicate that pre-Mesozoic basement in the Piedmont of the New York recess experienced an anomalous thermal event with crustal temperature exceeding ~220^{o} C beginning about 217-218 Mya. This Norian age corresponds with lower- to middle sections of the Passaic Formation in the Newark basin (Olsen and others, 1996). Their work also led them to postulate that the elevated, regional geotherm was probably associated with rift-related lithospheric thinning and associated mantle upwelling. Despite the fact that these dates are based on surface samples, and therefore deep-crustal temperatures exceeded those cited values, this information helps constrain the lower age limit of Late Triassic, positive structures, including thermal arches and domes stemming from the CAMP genesis and evolution. An upper age limit is provided by the radiometric-age dating of volcanism at 201-202 Mya (Sutter, 1988; Dunning and Hodyich, 1990). The volcanic stage reportedly lasted only about 600 Ka (Olsen and others, 2003). The lower and upper age limits provide a 20 Ma time interval from the CAMP genesis in this region to eventual culmination with continental volcanism. However, a narrower bracket of time on the order of about 3-10 my, has been reported for similar processes operating in analogous tectonic settings (He and others, 2003) and from the results of laboratory models (Griffiths and Campbell, 2012). We therefore need to closely inspect the Triassic sedimentary section for telltale stratigraphic variations that should be present as these regional arches and localized domes were developing during the Late Triassic. A currently held viewpoint is that structural inversion of this region post dates the CAMP volcanism and therefore occurred at late tectonic stages of basin development in the Jurassic (Bédard, 1985; Schlische and others, 2002). We need to be careful to separate positive inversion structures stemming from the CAMP thermal effects (Brodie and WHite, 1994) from other, later crustal inversions related to the compressive crustal states that we experience today (Goldberg and others, 2003).

A paired set of elongated, positive Bouger-gravity anomalies run parallel to the western Atlantic margin on either side of the Baltimore Canyon Trough (BCT - fig. 15A). One is the aforementioned set located on the margins of the rift basins with pockets locally exceeding 20 mGal. Another, more hinterland set of anomalies coincide with the continental shelf break before the continental-oceanic boundary (COB, fig. 15A.) These anomalies have been spatially associated and linked to other CAMP bodies characterized as seaward dipping (seismic) reflectors (SDRs) that may represent wedges of embryonic ocean crust (McHone and others, 2002; Benson, 2003). The positive Bouger anomalies along this margin are slightly segmented where regional section C-C' crosses (fig. 15A). The discontinuous, elongate map pattern of these anomalies therefore suggests that the SDRs have variable thickness in the same manner as their more foreland CAMP counterparts. In the case of section C-C', this wedge either has a minimum thickness or is absent. One can't also help but notice the jig-saw nature of the trailing edge of the foreland set of positive anomalies with the leading edge of the hinterland set (Fig. 15A). The similar, paired nature of the 0 mGal isopleths makes reconnecting them a simple finite strain analysis. Although some attempts have been made along these lines, the scope of this work is limited to the field-based results and some regional considerations stemming from the more local breakthroughs (no pun intended).

One estimate of crustal stretching of the US Atlantic margin along regional section C-C' in the New York region is 30% as illustrated in figure 18. This is a based on a simple two-dimensional model employing brittle, plane strains including rigid-block rotation and translation of a series of nested fault blocks that were under plated by a thick CAMP pluton (fig. 18). This interpretation was constrained by crustal structures outlined in the foreland (Herman, 1992) and hinterland parts of the section (LASE, 1982), but it lacks three-dimensionality and the accounting of deep, ductile strains that undoubtedly occurred. This section is therefore used only for deriving an minimum stretching estimate for the passive margin.

A casual survey of the variation of horizontal separation between the matched 0 mGal isolines measured normal to their traces along the eastern US margin shows ranges in distance of 30 to 230 km, with the greatest separations seen in the south. In the New York Recess, apparent horizontal separations are on the order of 30 to 160 km, with the minimum located within the Baltimore canyon trough off New Jersey, and the most in Massachusetts (Fig. 15A). These paired anomalies exhibit the same potential magnitude and complimentary geometric form, and are therefore assumed to correspond to segments of a larger, once-continuous CAMP system of bodies that may had both plutonic and volcanic, perhaps from the same elongate, complex chamber system underlying the orogenic axis. Perhaps, many of the gneiss domes and piedmont roots of the

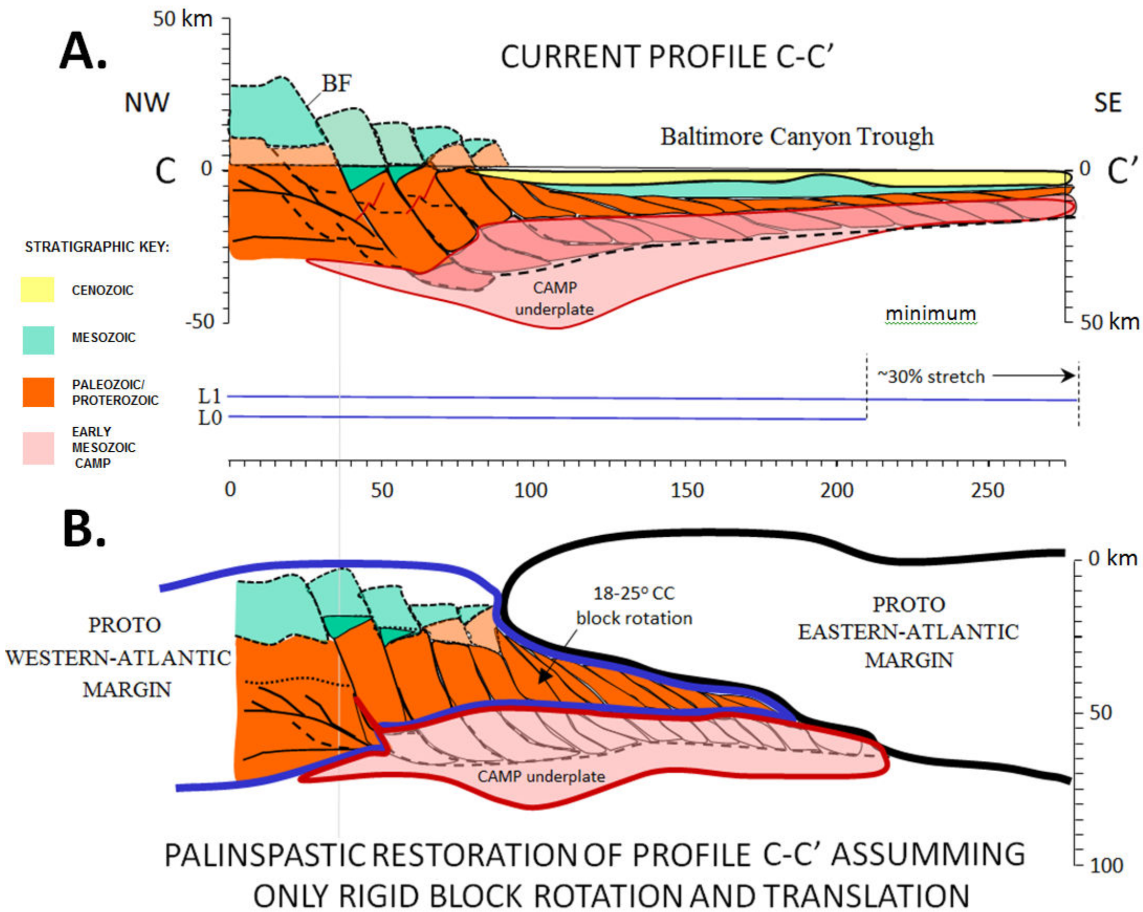


Figure 18. Transverse cross-section B-B' across of the hinterland parts of the New York Recess depicting current lithosphere structures (**A**.) and a restored (palinspastic) version (**B**.) representing a prior stage when the CAMP melt had accumulated beneath the lithosphere before ensuing, accelerated extension and release to hypabyssal levels. The framework of the current section is constrained by LASE (1986).

US Appalachian mountains are arched upward and exposed as a result of the CAMP. The finite stretching and segmentation of the Atlantic passive margin appears to have left a taffy-like gravity fingerprint of how the margin evolved, with the maximum amount of stretching and thinning occurring beneath the Baltimore Canyon Trough in this region (Harry and Sawyer, 2010;).

It's been over a decade since Withjack and others (1998) and Schlische (2003) provided critical summaries on the tectonic evolution of the Eastern North American rift system based on over a centuries worth of preceding geological studies. To summarize here, they outlined four tectonic phases:

1) Proto-Atlantic-margin crustal extension beginning in the Middle- to Late Triassic with half-graben basin formation.

2. Latest Triassic halt of basin subsidence in the southern United States.

3. Earliest Jurassic NW-SE contraction in the southern US and coeval NW-SE extension in the northern US based on the systematic arrangement of Early Jurassic dike swarms along the margin (King, 1961; 1971).

4. General Middle Jurassic NW-SE contraction that persists today.

Forty years earlier Sanders (1963) outlined 4 tectonic stages of Mesozoic age that affected Late Triassic rocks of the mid-Atlantic states of Pennsylvania, New Jersey, New York and Connecticut:

1. Initial graben formation and infilling with more than 30,000 feet (~9 km) of non-marine sediment followed by intrusive and extrusive igneous activity.

2. Longitudinal crustal arching in the center of the graben, uplift, inversion of topography, erosion and drainage reversals, graben floor attains positive structural relief of more than 30,000 feet; no igneous activity or transverse folding

3. Second-generation graben subsidence, development of transverse folds northeast of Hunterdon Plateau, NJ with maximum structural relief exceeding 30,000 ft.; no igneous activity.

4. Offsetting of transverse folds by faults, some with strike-slip-displacement of up to 12 miles (~19 km) ; development of longitudinal Valley-and-Ridge type folds southwest of Hunterdon Plateau during strike-slip faulting; injection of porphyritic dolerite dikes into faults; formation of mineral deposits along faults.

Our findings support most of Sanders (1963) ideas, which incorporated long-held observations that the US Atlantic margin contains transverse arches and troughs of Mesozoic age as illustrated by Woodworth (1932). King (1961) provided an eloquent summary statement about this region after analyzing how the dike swarms along the US continental margin change orientation along the Appalachian grain from the southwest to the northeast:

> "A different pattern is shown by the normal faults and sedimentary basins of the Newark group. These follow closely the strike of the older rocks amidst which they lie, and may have been conditioned by fracture and displacement along existing lines of weakness. Pairing of the major basins and associated faults on opposite sides of the central axis of the Appalachians suggests that this axis was again raised into a broad arch during Triassic time."

Recent work by Herman (2012) shows that the eastern half of the Newark basin was repeatedly extended during three stages of overlapping extension strains that vary in a systematic, counterclockwise manner to reflect : 1) early SE stretching, 2) intermediate and accelerated stretching directed toward the ESE, and 3) a final stretch directed ENE prior to inversion of the crustal stress field at some later time from primary tension to primary compression that persists today (Goldberg and others, 2003). The exact causes and timing of the stress-field inversion from active to passive margin remain unproven with only abstract notions at this time (Herman, 2006). In conclusion, the structural nature of the passive, western Atlantic margin of the North American tectonic plate has been the focus of studies for over a century. But the nature and timing of positive, epeirogenic uplifts affecting this margin are still being refined and debated. We demonstrate that the structure of the CAMP bodies involved thermal uplifts during active rifting, both on a regional and more localized scale, and thereby lay the groundwork for differentiating between Early Mesozoic tectonic thermal uplifts from later epeirogenic ones. Our work offers a slightly different scenario on how this part of the US Atlantic margin and helps explain many geological conundrums arising from the geological map expression of the CAMP plumbing system. These views are in line with tectonic interpretations in analogous tectonic terrain but the conclusions should be tested further through continued field and laboratory work. To that end, this representation of the proto-Atlantic margin should be considered as a base model that incorporates some fundamental structural concepts and kinematic constraints that warrant consideration when advancing or refuting these ideas.

References

Balk, R., 1925, Primary structure of granite massives: Geological Society of America Bulletin, vol. 36, p. 679-696.

Bascom, F., Wherry, E. T., Stose, G. W., and Jonas, A. I., 1931, Geology and mineral resources of the Quakertown-Doylestown district, Pennsylvania and New Jersey: U.S. Geological Survey Bulletin 828, 69 p. Plate 1.

Bascom, F., Clark, W. B., Darton, N. H., Knapp, G. N., Kuemmel, H. B., Miller, B. L., and Salisbury, R.D, 1909, Philadelphia folio, Norristown, Germantown, Chester, and Philadelphia, Pennsylvania-New Jersey-Delaware: U.S. Geological Survey Folios of the Geologic Atlas: 162 p.

Bédard, J. H., 1985, The opening of the Atlantic, the Mesozoic New England igneous province, and mechanisms of continental breakup: Tectonophsysics, vol. 113, no. 3-4, p. 209-232.

Bédard, J. H. Naslund, H. R., P. Nabelek, P., Winpenny A., Hryciuk, M., Macdonald, W., Hayes, B., Steigerwaldt, K., Hadlari, T., Rainbird, R., Dewing, K., and Girard, É, 2012, Fault-mediated melt ascent in a Neoproterozoic continental flood basalt province, the Franklin sills, Victoria Island, Canada: Geological Society of America Bulletin vol. 124, no. 5/6, p. 723-736.

Behn, M.D. & Lin, J., 2000, Segmentation in gravity and magnetic anomalies along the US East Coast passive margin: implications for incipient structure of the oceanic lithosphere, Journal of

Geophysical Research, v. 105, no. 25, p. 769–790.

Benson, R. N. , 2013, Age Estimates of the Seaward-Dipping Volcanic Wedge, Earliest Oceanic Crust, and Earliest Drift-Stage Sediments Along the North American Atlantic Continental Margin, *in* The Central Atlantic Magmatic Province: Insights from Fragments of Pangea, eds, W. Hames, J.G. Mchone, P. Renne and C. Ruppel), American Geophysical Union, Washington, D. C.. doi: 10.1029/136GM04

Berg, T. M., Edmunds, W. E., Geyer, A. R., and others, compilers, 1980, Geologic map of Pennsylvania: Pennsylvania Geological Survey, 4th ser., Map 1, 2nd ed., 3 sheets, scale 1:250,000.

Bott, M. H. P., 1981, Crtustal doming and the mechanism of continental rifting: Tectonophysics, vol. 73, iss. 1-2, p 1-8.

Brodie, L., and White, 1994, Sedimentary basin inversion caused by igneous underplating: Northwest European continental shelf: Geology v. 22, p. 147-150.

Daniels, D. L., 1985, Gravimetric character and anomalies in the Gettysburg basin, Pennsylvania – A preliminary appraisal, in Robinson, G. R., Jr., and Froelich, A. J., eds.,: U.S. Geological Survey Circular 946, p. 128 – 132.

Darton, N. H., 1896, The relations of the Traps of the Newark System in the New Jersey Region, U.S. Geological Survey Bulletin No. 67., 97 p., 1 plate, 1:538360 scale.

Drake, A. A., Jr., Volkert, R. A., Monteverde, D. H., Herman, G. C., Houghton, H. F., Parker, R. A., and Dalton, R. F., 1996, Bedrock geological map of northern New Jersey: U.S. Geological Survey Miscellaneous Investigation Series Map I-2540-A, scale 1:100,000, 2 sheets.

Dunning, G. R., and Hodych, J. D., 1990, U-Pb zircon and baddeleyite age for the Palisade and Gettysburg sills of northeast United States: Implications for the age of the Triassic-Jurassic boundary: Geology, v. 18, p. 795-798.

Faust, G. T., 1978, Joint systems in the Watchung Basalt flows, New Jersey USGS Professional Paper 864-B, 45 p.

Froelich, A. J., and Gottfried, D., 1984, Early Jurassic diabase sheets of the Eastern United States -- A preliminary overview, in Nonprofit sample and core repositories open to the public in the United States, by Schmoker, J. W., Michalski, T. C., and Worl, P. B., U.S Geological Survey Circular 942. Chapter 15, p 79-86.

Geological Society of America Committee for the Magnetic Anomaly Map of North America, 1987a, Magnetic anomaly map of North America: Geological Society of America, continent-scale map-003, scale 1:5,000,000, 4 sheets.

Geological Society of America Committee for the Gravity Anomaly Map of North America, 1987b, Gravity Anomaly Map of North America(1:5,000,000), Boulder, Colorado, Geological Society of America, Continent-Scale Map-002 (5 sheets). URL: www.ngdc.noaa.gov/geomag/fliers/se-2004.shtml

Goldberg, D., Lupo, T., Caputi, M., Barton, C., and Seeber L., 2003, Stress Regimes in the Newark Basin Rift: Evidence from Core and Downhole Data, i*n*: LeTourneau, P. M. and Olsen, P. E., eds.,The Great Rift Valleys of Pangea in Eastern North America, v.1, Tectonics, Structure, and Volcanism, Columbia University Press, New York, Chapter 7, p.

Gottfried, D., 1991, Geochemical data Jurassic diabase associated with early Mesozoic basins in the eastern United States: western Newark Basin, Pennsylvania and New Jersey, U.S., Geological Survey Open File Report 91-322-D, 26 p

Gottfried, D., Froelich, A. J., and Grossman, J. N., 1991a, Geochemical data Jurassic diabase associated with early Mesozoic basins in the eastern United States: eastern Newark Basin, New York, New Jersey, U.S., Geological Survey Open File Report 91-322-C, 6 p.

Harry, D. L., and Sawyer, D. S., 2010, A dynamic model of extension in the Baltimore Canyon Trough region: Tectonics, vol. 11, no. 2, p. 420-436.

Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W., 1989, eds., The Geological Society of America, Volume F2, The Appalachian-Ouachita Orogoen in the United States: The Geology of North America, Boulder Co., 767 p.

He, Bin, Yi-Gang Xu, Sun-Ling Chung, Xiao-Long Huang, and Ya-Mei Wang, 2003, Sedimentary evidence for a rapid kilometer-scale crustal doming prior to the eruption of the Emeishan flood basalts: Earth and Planetray Science Letters,vol.213, p.391-405.

Herman, G. C., 1992, Deep crustal structure and seismic expression of the central Appalachian orogenic belt: Geology, Vol. 20, No. 3, p. 275-278.

Herman, G. C., 2005a, Joints and veins in the Newark basin, New Jersey, in regional tectonic perspective: *in* Gates, A. E., editor, Newark Basin – View from the 21st Century, 22nd Annual Meeting of the Geological Association of New Jersey, College of New Jersey, Ewing, New Jersey, p. 75-116.

Herman, G. C., 2005b, Stratigraphy and structure of the Passaic Formation and Orange Mountain Basalt at Mine Brook Park, Flemington, New Jersey, *in* Gates, A. E., editor, Newark Basin - View from the 21st Century, 22nd Annual Meeting of the Geological Association of New Jersey, College of New Jersey, Ewing, New Jersey, p. 134-144.

Herman, G. C, 2006, Neotectonic setting of the North American Plate in relation to the Chicxulub impact: Geological Society America Abstracts with Programs, Vol. 38, No. 7, p. 415

Herman, G.C. 2009, Steeply-dipping extension fractures in the Newark basin (5 MB PDF), Journal of Structural Geology, V. 31, p. 996-1011.

Herman, G.C. 2010, Hydrogeology and borehole geophysics of fractured-bedrock aquifers (5 MB PDF), *in* Herman, G.C., and Serfes, M.E., eds., Contributions to the geology and hydrogeology of the Newark basin: N.J. Geological Survey Bulletin 77, Chapter F., p. F1-F45.

Herman, G.C. and Curran, J., 2010, Borehole geophysics and hydrogeology studies in the Newark basin, New Jersey (38 MB PDF), *in* Herman, G.C., and Serfes, M.E., eds., Contributions to the geology and hydrogeology of the Newark basin: N.J. Geological Survey Bulletin 77, Appendixes 1-4, 245 p.

Herman, G.C., Dooley, J.H., and Mueller, L.F., 2010, Geology of the Pennington Trap Rock (Diabase) Quarry, Mercer County (6 MB PDF), *in* LaCombe, Pierre, ed., Geology of Trenton and its impact on the Capitol City: 27th Annual Meeting of the Geological Association of New Jersey, Trenton, NJ, p. 92-119.

Herman, G. C., Houghton, H. F., Monteverde, D. H., and Volkert, R. A., 1992, Bedrock geologic map of the Flemington and Pittstown 7-1/2' quadrangles, Hunterdon County, New Jersey: N.J. Geological Survey Open-file Map 10, 1:24,000 scale.

Herman, G.C., and Serfes, M.E., 2010, eds., Contributions to the geology and hydrogeology of the Newark basin: N.J. Geological Survey Bulletin 77, 6 chapters, 4 appendixes, 554 p.

Herman, G. C., Witte, R. W., Monteverde, D. H., and Stanford, S. D., in review, Geological map of the Lambertville quadrangle, Hunterdon and Mercer Counties, New Jersey: NJ Geological and Water Survey Open-File Map. scale 1:24,000.

Hodgson, R. A., 1961, Regional study of jointing in Comb ridge-Navajo Mountain Area, Arizona and Utah, American Association of Petroleum Geologists Bulletin, v. 45, p. 1-38

Hotz, P.E., 1952, The form of diabase sheets in southeastern Pennsylvania: American Journal of Science, v. 250, p. 375-388.

Houghton, H. F., Herman, G. C., and Volkert, R. A., 1992, Igneous rocks of the Flemington Fault zone: Geochemistry, structure, and stratigraphy, *in* Puffer J. H. and Ragland, P. C., eds., Eastern North American Mesozoic Magmatism, Geological Society of America Special Paper 268, p. 219-232

Husch, J., 1984, Mesozoic basaltic rocks from west-central New Jersey and Pennsylvania: Major and trace element geochemistry of whole-rock samples, *in* Puffer, J., ed., Igneous Rocks of the Newark Basin: Petrology, Mineralogy, Ore Deposits, and Guide to Field Trip: Field Guide and Proceedings of the First Annual Meeting of the Geological Association of New Jersey, Newark, NJ, p. 81-95

Husch, J. M, 1990, The Palisades sill: Origin of the olivine zone by separate magmatic injection rather than gravity settling. Geology, v. 18, p. 699-702.

Husch, J. M., Bambrick,T. C., Eliason, W. M., Roth, E. A., Schwimmer, R. A., Sturgis, D. S., and Trione, C. W., 1988, A review of the petrology and geochemistry of Mesozoic diabase from the central Newark basin: New petrogenetic insights, *in* Husch, J. M. and Hozik, M. J., eds., Geology of the Central Newark Basin: Field Guide and Proceedings of the Fifth Annual Meeting of the Geological Association of New Jersey, Lawrenceville, NJ, p. 149-194

King, P. B., 1961, Systematic pattern of Triassic dikes in the Appalachian region: U.S. Geological Survey Professional Paper 424-B, p. B93-B95.

King, P. B., 1971, Systematic pattern of Triassic dikes in the Appalachian region - second report: US Geological Survey Professional Paper 750-D, p. 48-44.

Klewsaat, D. R, and Gates, A. E., 1994: Northeastern Geology, vol. 16, no. 3&4, p. 237-250.

Kohn, B. P., Wagner, M. E., Lutz, T. M., and Organist, G., 1993, Anomalous Mesozoic Thermal Regime, Central Appalachian Piedmont: Evidence from Sphene and Zircon Fission-Track Dating: Journal of Geology, vol. 101, no. 6, p. 779-794.

Kummel, H. B., 1898, The Newark system or red sandstone belt, New Jersey Geological Survey, Annual report of the State Geologist 1897, p.23-164.

Laney, S.E., and Gates, A.E., 1996, Three-dimensional shuffling of horses in a strike-slip duplex: An example from the Lambertville sill, New Jersey: Tectonophysics, v. 258, p. 53-70.

LASE Study Group, 1986, Deep structure of the U.S. East Coast passive margin from large aperture seismic experiments (LASE), Marine Petroleum Geology, vol. 3., p. 234-242.

Magee, C., Jackson, C. A., and Schofield, N., 2013, The influence of normal fault geometry on igneous emplacement and morphology: Geology, vol. 41, no. 3., p. 407-410.

Manspeizer, W., 1988, ed., Triassic-Jurassic rifting: Continental breakup and the origin of the Atlantic Ocean and passive margins: Elsevier, New York, NY., 998p.

Manspeizer, W., DeBoer, J., Costain, J. K., Froelich, A. J., Couruh, C., Olsen, P. E., McHone, G. J., Puffer, J. H., and Prowell, D. C., 1989, Post-Paelzoic activity, *in* Hatcher, R.D., Jr., Thomas, W. A., and Viele, G. W., eds., The Appalachian-Ouchita Orogen in the United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. F-2, p. 319-374.

Marzoli, A., Renne, P., Piccirillo, E., Ernesto, M., Bellieni, G., and De Min, A, 1999. Extensive 200-million-yearold continental flood basalts of the Central Atlantic Magmatic Province: Science v. 284, p. 616–618.

Malthe-Sorenssen, A.; Planke, S.; Svensen, H.; Jamtveit, B., 2003, Tectonic effects of sill emplacement: EGS - AGU - EUG Joint Assembly, Abstracts from the meeting held in Nice, France, April 6 - 11, atract #8645, http://adsabs.harvard.edu/abs/2003EAEJA.....8645MTectonic effects of sill emplacement

McHone, J. G., 2000, Non-plume magmatism and rifting during the opening of the central Atlantic Ocean: Tectonophysics, vol. 316, p. 287-296.

McHone, J.G., Ross, M.E., and Greenough, J.D., 1987, Mesozoic dyke swarms of eastern North America, *in* Halls, H.C. and Fahrig, W.H., eds., Mafic dyke swarms: Geological Association of Canada Special Paper 34, p. 102-111.

McHone, J. G., Talwani, M., Hames, W., Marzoli, A., Ragland, P., Turrin, B., Coffin, M., Barr, S., White, C., and Morris, D., 2002, Large igneous provinces, seaward dipping reflectors, and the Central Atlantic Magmatic province, *in* Olsen , P. E. and Kent, D. V. ,eds.,Climatic, Biotic, and Tectonic Pole-to-Pole Coring Transect of Triassic-Jurassic Pangea: International Continental Drilling Program.

Neugebauer, H. J., 1978, Crustal doming and the mechanism of rifting Part 1: Rift formation: Tectonophysics, vol. 45, issues 2-3, p. 159-186.

Lyttle, P. T., and Epstein, J. B., 1986, Geologic map of the Newark 1° x 2° quadrangle, New Jersey, Pennsylvania, and New York: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-1715, scale 1:250 000, 2 sheets.

Olsen, P. E., 1980, Triassic and Jurassic formations of the Newark basin, *in* Manspeizer, W., ed., Field studies of New Jersey Geology and guide to field trips: 52nd annual meeting of the New York State Geologial association: Newark, New Jersey, Rutgers University, p. 278-311.

Olsen, P. E., Kent, D., Cornet, B., Witte, W. K., and Schlische, R. W., 1996, High-resolution stratigraphy of the Newark rift basin (early Mesozoic, eastern North America), Geological Society of America Bulletin, v. 108, p. 40-77.

Olsen, P. E., Kent, D. V., Et-Touhami, M., & Puffer, J., 2003, Cyclo-, magneto-, and bio-stratigraphic constraints on the duration of the CAMP event and its relationship to the Triassic-Jurassic boundary. Geophysical Monograph Series 136, p. 7-32.

Owens, J. P., Sugarman, P. J., Sohl, N. F., Parker, R. A., Houghton, H. F., Volkert, R. A., Drake, A. A., Jr., and Orndorff, R.C., 1998, Bedrock Geologic Map of Central and Southern New Jersey, U. S. Geological Survey Miscellaneous Investigation Series Map I-2540-B, scale 1:100,000, 4 sheets.

Pollard, D. D., and Aydin, A. A., 1988, Progress in understanding jointing over the past century: Geological Society of America Bulletin, v. 100, p. 1181-1204, p. 1181-1204.

Philpotts, A. R. and Martello, A., 1986, Diabase feeder dikes for the Mesozoic basalts in southern

New England, Amercian Journal of Science, v. 286, p. 105-126

Puffer J. H., Block, K. A., and Steiner, J. C., 2009, Transmission of flood basalts through a shallow crustal sill and the correlation of sill layers with extrusive flows: the Palisades Intrusive

Ratcliffe, N. M. and Burton, W. C., 1988, Structural analyses of the Furlong fault and the relation of mineralization to faulting and diabase intrusion, Newark basin, Pennsylvania in, Froelich, A. J. and Robinson, G. R. Jr., eds., U.S. Geological Survey Bulletin 1776, p. 176-193.

Ratcliffe, N. M., and Costain, J. K., 1985, Northeastern seismicity and tectonics, *in* Jacobson, M. L., and Rodriguez, T. R., compilers, National earthquake hazards reduction program, summaries of technical reports, Volume 20: U.S. Geological Survey Open-File Report 85-464, p. 54–58.

Sanders, J. E., 1963, Late Triassic tectonic history of northeastern United States: American Journal of. Science, v. 261, p. 501-524.

Sanders, J. E.; and Merguerian, C., 1997, Geology of the Palisades and Newark basin of New Jersey 14 September 1997: New York, NY, On the Rocks Field Trips sponsored by 92nd Street YMCA, 164 p.

Schlische, R. W., 1992, Structural and stratigraphic development of the Newark extensional basin, eastern North America: Evidence for growth of the basin and its bounding structures: Geological Society of America bulletin, vol. 104, p. 1246-1263.

Schlische, R. W., 2003. Progress in understanding the structural geology, basin evolution, and tectonic history of the eastern North American rift system, *in* LeTourneau, P. M., Olsen, P. E. , eds.: The Great Rift Valleys of Pangea in Eastern North America 1, Tectonics, Structure, and Volcanism. Columbia University Press, New York, pp. 21–64.

Schlische, R. W., Withjack, M. O., and Olsen, P. E., 2002, Relative timing of CAMP, rifting, continental breakup, and inversion: tectonic significance, *in* Hames, W.E., McHone, G. C., Renne, P. R., and Ruppel, C. R., eds., The Central Atlantic Magmatic Province: Insights from Fragments of Pangea: American Geophysical Union Monograph 136, p. 33-59.

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

Steiner, J. C., Walker, R. J., Warner, R. D., and Olson, T. R., 1992, A cumulus-transport-deposition model for the differentiation of the Palisades sill, Geological Society of America Special Paper 268, p.193-217

Sumner, J. R., 1977, Geophysical investigation of the structural framework of the Newark-Gettysburg Triassic basin, Pennsylvania: Geological Society of America Bulletin, vol., 88, p. 935-942.

Sutter, J. F., 1988, Innovative approaches to the dating of igneous events in the early Mesozoic basins of the eastern United States, *in* Froelich, A. J., and Robinson, G. R., Jr., eds., Studies of the early Mesozoic basins of the eastern United States: U.S. Geological Survey Bulletin 1776, p. 194-200.

Swanson, M. T., 1992, Structural sequence and tectonic significance of Mesozoic dikes in southern coastal Maine, *in* Puffer, J. H., and Ragland, P. C., eds., Eastern North American Mesozoic magmatism: Geological Society of America, Special Paper 268, p. 37-62.

Telford, W. M., Geldhart, L. P., Sheriff, R. E., and Keys, D. A., 1976, Applied Geophysics: Cambridge University Press, Cambridge, 860 p.

Van Houten, F. B., 1969, Late (sic) Triassic Newark Group, north-central New Jersey and adjacent Pennsylvania and New York, *in* Subitzky, Seymour, ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions: Geological Society of America, Annual Meeting, Atlantic City 1969: New Brunswick, NJ, Rutgers University Press, p. 314-347.

Vogt, P. R., and Tucholke, B. E., 1986, eds., The Geology of North America, Volume M, The western north Atlantic region: Geological Society of America, Boulder, Co., 696 p.

Wiegand, P. W., and Ragland, P. C., 1970, Geochemistry of Mesozoic dolerite dikes from eastern North America: Contributions to Mineralogy and Petrology 4. XII, vol. 29. no. 3, p. 195-214. 12

Wilson, M., 1997, Thermal evolution of the Central Atlantic passive margins: continental break-up above a Mesozoic super-plume: Journal of the Geological Society, vol. 154, no. 3, p. 491-495.

Woodworth, J. B., 1932, Contributions to the study of mountain building: American Journal of Science, series 5, vol. 23, no. 134, p. 155-171.

GENERATION AND EVOLUTION OF GRANOPHYRE IN THE PALISADES SILL

Karin A. Block

Department of Earth and Atmospheric Sciences, The City College of New York, New York, NY 10031

Abstract

Evolved liquids from mafic magmatism are crystallized as ferrogabbros and granophyre in a thick portion of the Palisades sill. They comprise a suite of cogenetic rocks that possess similar composition but distinct mineralogical and textural attributes. Other distinct features in the Palisades sill, such as the olivine zone and geochemical reversals have been attributed to multiple pulse influx. Examination of the mineralogy and texture of the cumulative end product of tholeiitic magma reveals variations along strike indicative of episodic deformation and mobilization of trapped residuum during tapping of the magma chamber which may account for the inordinate accumulation of iron enriched rocks in the northern portion of the sill. This is consistent with the observations pertaining to deformation of residuum in mid-ocean ridge gabbros to conduct magma to the surface during continued growth of the oceanic crust. In this context, the deformation structures in the Palisades may serve a similar purpose in providing a conduit for the extrusion of the Watchung flood basalt flows per the model advanced by Puffer et al. (2009).

Introduction

Late stage differentiates in continental basaltic intrusions tend to comprise small fractions of the total magma volume and are generally the products of a tholeiitic line of descent. The Palisades contains a layer of iron-enriched, relatively felsic material that increases in thickness toward the north end of the Palisades sill, more than can easily be accounted for by fractionation of underlying diabase. In conjunction multiple pulses as a mechanism for the origin of shallow mafic intrusives in New Jersey, the hypothesis is put forward by Husch (1992) as a way for evolved liquids to migrate discordantly updip and accumulate northward. Thus repeated reinflation and injection of magma in the a Palisades-Lambertville-Rocky Hill megasheet would produce a large accumulation of granophyres (Husch, 1992) and would provide a way for the prolonged magmatism (> 300ka; Olsen and Fedosh, 1988) required to connect the extrusion of flood basalts with the first two Watchung flows.

Review of petrogenetic models

Multiple injections has been the working model for the petrogenesis of geochemical and mineralogical features in the sill. The first viable multiple injection model was developed by (K. R. Walker, 1969). Walker's model was based on samples and analysis of the Palisades from Kings Bluff to Haverstraw revealing a limited extent to the famous olivine zone. Shirley (1987) followed up this work through comprehensive analysis of a continuous section in Fort Lee, NJ, where he attributed spikes and reversals in Mg# (100*Mg/Fe+Mg) and trace elements (Ni, Co) at 10, 35, 95 m to the input of three or four magma pulses followed by compaction and filter pressing to expel residual liquid upwards where it was pinned by the crystallization front. These residual liquids crystallized into granophyres containing a maximum in incompatible elements.

Husch (1990) proposed that multiple magma types from a heterogeneous mantle could account for the internal layering and mineralogical differences in various parts of the sill. Specifically, he noted the discrepancy in fractionation trends where the majority of the intrusion is pyroxene-dominated fractionation as would be expected in a quartz tholeiite, while the olivine zone would require a fractionation trend typically associated with olivine tholeiites. Instead of regarding the olivine layer as a Mg-rich secondary pulse, he proposed that the olivine layer was the entrained residue of a deep magma chamber, emplaced as a smeared lens over previously injected material. Subsequent studies of the Palisades by Steiner et al. (1992) and Gorring and Naslund (1995), have proposed a variety of models that elaborate on Husch's ideas. Steiner et al. (1992) proposed a cumulus-transport-deposition (C-T-D) model based on a dataset built on Shirley and Walker's study sections extending sampling through Englewood Cliffs, NJ north to Upper Nyack, NY and the Haverstraw quarry. C-T-D argues for multi-phase fractionation induced by convective overturn and development of cumulates by flow differentiation. Gorring and Naslund (1995) filled a gap in the Palisades picture by examining the lower section of the sill at Alpine, NJ and found evidence that magma chamber recharge could account for heterogeneity in the layering of the Palisades. Geochemical reversals in Mg#, Cr, and Ni trends were interpreted as markers of magma input horizons. Most recently, Puffer et al. (2009) connected multiple injections with open system crystallization by geochemically correlating pulse boundaries in the Palisades with the first two Watchung flows. The Palisades may have therefore served as a conduit or feeder for prolonged extrusion during rifting of Pangea.

Figure 1: Palisades diabase at Upper Nyack, NY.

Late stage differentiates along strike

The Palisades Sill is a shallow tabular mafic intrusion ranging in thickness between 250 and 340 m, thinning northward along the western bank of the Hudson River. The sill is mostly concordant and dipping 10-15° W through Upper Nyack, NY (Figure 1). In Rockland County, NY the sill becomes discordant, adopts a much steeper dip and curves into a ring dike as it trends toward the surface. In fact, several workers have concluded on the basis of geochemical (Husch, 1988) and magnetic data (Maes, 2003) that the Palisades magma originated in the south near Staten Island and propagated northward with each pulse.

Table 1: Modal composition of late stage differentiates per the nomenclature of Walker (1969). All quantities are in volume %.

	Quartz	Hornblende	Brown Ferroaugite	Green Ferroaugite	Biotite
ferrophypersthene dolerite	10	3	10	21	0.2
fayalite granophyre					0.3
granophyric dolerite	24.5	12.5			1.5
ferrodolerite	23	6.5	18	5	

The volume and mineralogy of rocks crystallized during the later stages varies greatly along strike. Walker (1969) described numerous late stage members as ferrohypersthene dolerite, fayalite granophyre, granophyre dolerite, and ferrodolerite containing varying amounts of quartz, hornblende, and biotite (Table 1). A stratigraphic profile of the Palisades upper and lower border series and differentiated products based on published petrography and geochemistry reveal that the Upper Nyack evolved liquids occupy a larger fraction of the sill thickness (Figure 2).

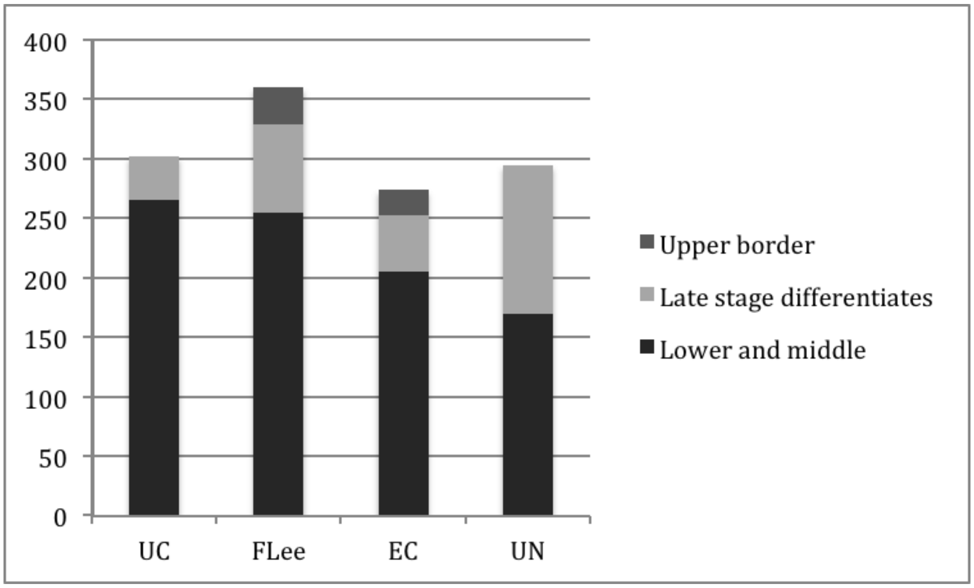


Figure 2: Relative thickness (in m) of Palisades late stage differentiates along the strike based on petrography and total iron oxide. UC is Union City, NJ, FLee is Fort Lee, NJ, EC is Englewood Cliffs, NJ and UN is Upper Nyack, NY. No samples reported for the upper border series at UC and UN. Data is from Walker (1969); Shirley (1987); and Block (unpublished).

A plot of FeO_T vs. SiO2 of published Palisades and Watchung Basalt data shows that the Upper Nyack section correlates mainly with the Preakness Basalt, with some of its silica-poor and iron-rich members coinciding with more differentiated members of the Preakness Basalt and near the field occupied by the Hook Mountain Basalt (Figure 3). The considerably iron-enriched rocks (FeO_T > 14 wt%) at Upper Nyack occupy 40-60 % of the total thickness of the sill. Given that Upper Nyack Palisades is at a higher stratigraphic level than sections this corresponds to pooling of late stage differentiates updip in agreement with the Husch (1992) model.

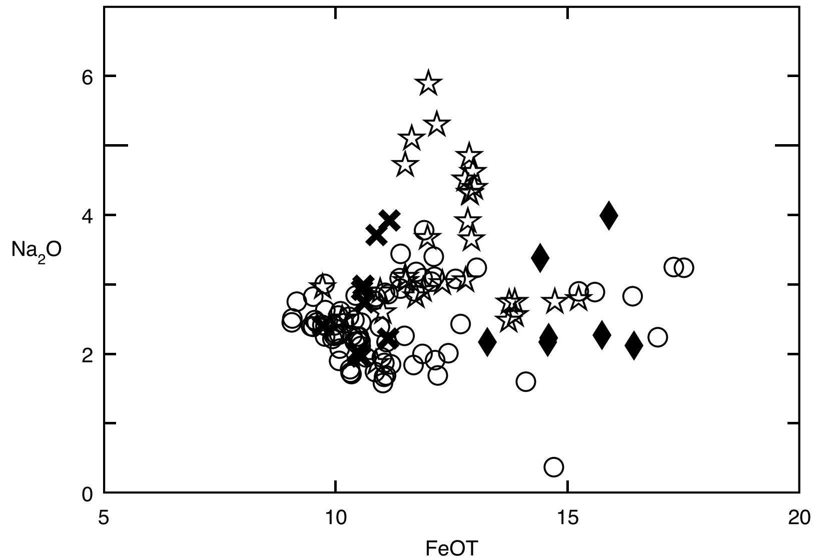


Figure 3: FeOT vs. Na2O variation in the Palisades at Upper Nyack (open circles) and in the Orange Mountain Basalt (filled crosses), Preakness Basalt (open stars), and Hook Mountain (filled diamonds).

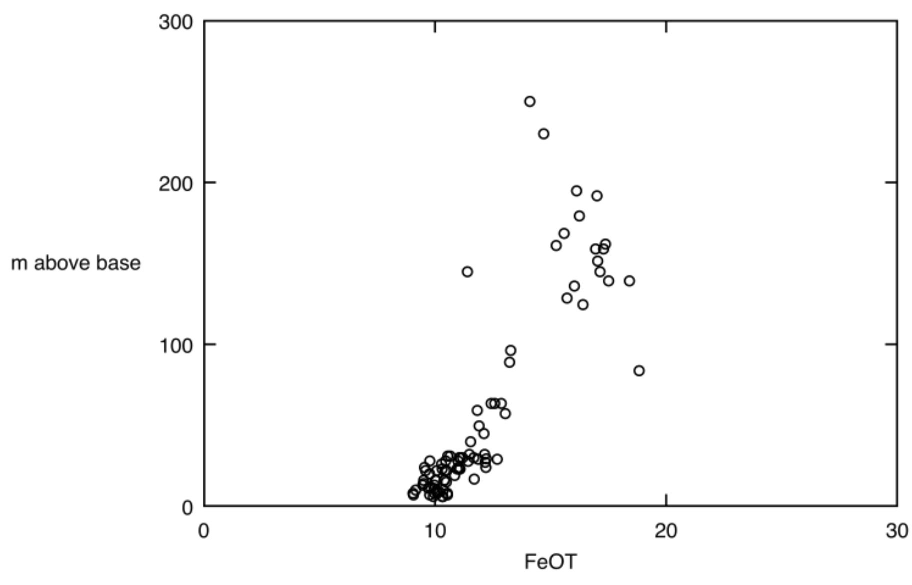


Figure 4: Total iron oxide variation with stratigraphic height at Upper Nyack, NY. Note elevated iron values at approximately 84 m (sample R-14) and above 100 m.

In areas of extreme iron enrichment, such as in sample R-14 in Upper Nyack (Figures 5A and 5B), the ferrogabbros exhibit significant alteration likely as a result of deuteric processes.

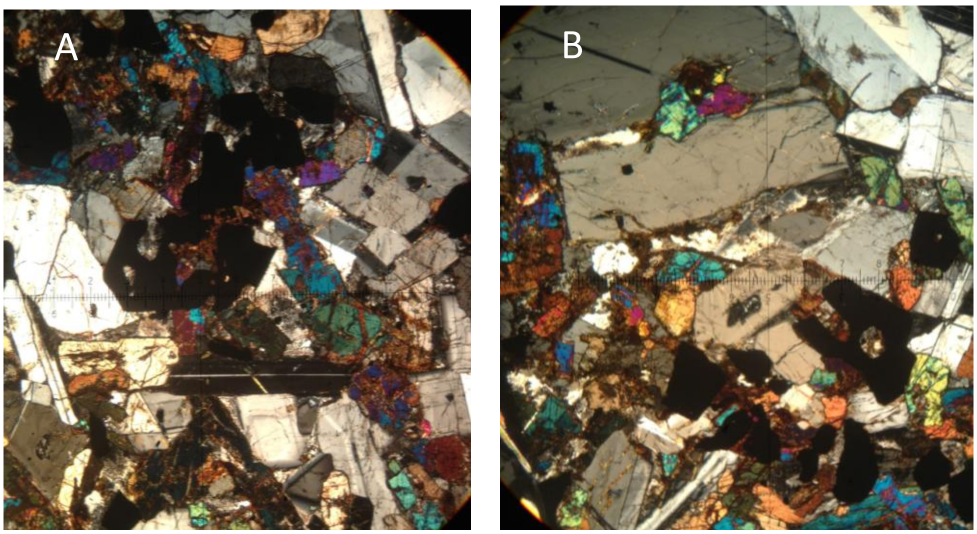


Figure 5: Thin section micrographs A and B (crossed polars) of sample R-14 ferrogabbro (Upper Nyack, 84 m above basal contact). Large euhedral plagioclase and abundant dendritic and skeletal opaques (ilmenite-magnetite) are present alongside interstitial pyroxene altering to amphibole.

Comparison of granophyres: Fort Lee and Upper Nyack

Compositionally, Upper Nyack granophyres are virtually identical to those at Fort Lee (Table 2). These rocks represent the latest stages of crystallization. However, the mineralogy and texture is different. Granophyres at Fort Lee exhibit signs of extensive pneumatolytic alteration. Although there are primary hornblendes present, secondary amphibole replaces pyroxene and appears to have sheared during crystallization to produce foliation more consistent with metamorphic texture (Figure 6A). At Upper Nyack, the granophyres do not possess mylonitic characteristics, however, hornblende is accompanied by pervasive sericitization of plagioclase and abundant myrmekite surrounding secondary sodic plagioclase. Chlorite is absent and biotite is present, further supporting the presence of magmatic fluids post-crystallization (Figure 6B).

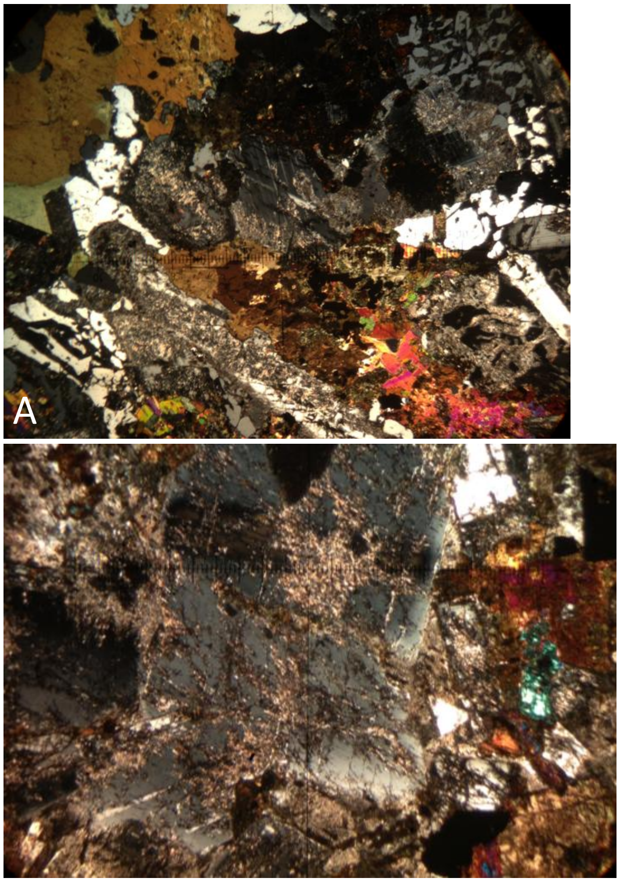


Figure 6: Thin section micrographs (crossed polars) of granophyres at Fort Lee (A) and Upper Nyack (B).

Table 2: Major oxide composition and CIPW norm of some Palisades granophyres. F-2 and F-4 are from Fort Lee, NJ, RL-2 and RL-7 are from Upper Nyack, NY (unpublished data from K. Block).

	F-2	F-4	RL-2	RL-7
SiO_2	56.72	60.91	59.57	62.58
TiO_2	2.05	1.77	2.01	1.55
Al_2O_3	11.41	11.71	11.68	11.69
FeO_T	15.61	14.07	14.70	14.10
MgO	1.94	1.49	1.73	1.25
CaO	4.75	3.07	5.64	3.30
Na_2O	1.20	1.42	0.37	1.60
K_2O	2.39	2.64	1.97	3.09
P_2O_5	2.78	1.97	3.00	1.98
Total	98.85	99.05	100.67	101.14
Quartz (Q)	23.85	28.87	32.89	27.47
Corundum(C)	4.86	5.65	5.86	4.45
Orthoclase(Or)	14.12	15.60	11.64	18.26
Albite(Ab)	10.15	12.02	3.13	13.54
Anorthite(An)	5.42	2.37	8.40	3.45
Hypersthene(Hy)	30.10	26.62	27.99	26.45
Ilmenite(Il)	3.89	3.36	3.82	2.94
Apatite(Ap)	6.44	4.57	6.95	4.59

Tectonism and deformation

In considering the along-strike variation in mineralogy and texture in the Palisades, the ongoing extensional environment. Mylonitic fabric in the granophyres of Fort Lee is indicative of shearing and deformation in near-solidus conditions. Field evidence suggests that silica-rich fluids continued to migrate upwards in the magmatic column, penetrating the upper border series rocks (Figure 7). It is likely that reheating and deformation as a result of pulse influx in conjunction with rifting helped mobilize fluids and interstitial residuum from the crystal mush under near-solidus conditions to produce the thick granophyre horizon in the Palisades and possibly the greater Palisades-Lambertville-Rocky Hill megasheet.

Figure 7: Felsic veins penetrating upper border series diabase in Fort Lee, NJ.

Accumulated Residuum

The diversity of texture and mineralogy of late-stage differentiates along strike support the lateral migration hypothesis of Husch (1992) and furthermore indicate that magmatic fluids helped mobilize residual material. While it has been established that the lower and middle layers of the Palisades Sill correlate with the extrusive Orange Mountain and Preakness Basalts no connection has been made between the intrusives and the last of the Watchung flows, The Hook Mountain Basalt. In the Palisades, the iron-rich horizon at Upper Nyack correlates with the Hook Mountain Basalt, but resides between Palisades Pulses reminiscent of the Preakness, which erupted approximately 300ka earlier. Furthermore, the iron enriched melt is of a relatively high density compared to lower cumulates. The nearly solidified Preakness pulses would impede the movement of bottom layer residue toward the upper reaches of the intrusion. Nonetheless, late differentiates appear to have moved to the top of the pile with each incremental magmatic pulse. Reheating and tectonics may facilitate the movement of interstitial residue upwards in the rock column. Subsequent pulse influx could push the remaining melt up-dip, shearing the residuum before it completely solidified, enriching the pulse in felsic content, and resulting in accumulation of granophyre with each increment of magma.

Not only would the accumulated residue reside as a mushy layer that is easily penetrated by later pulses, the prolonged extensional tectonism occurring in relation to the early break-up of Pangaea may have helped channelize the interstitial melt to create the thick accumulations seen in the PRHL megasheet. This same extensional decompression triggered partial-melting of the sub-continental lithospheric mantle source and was accompanied by faulting that allowed penetration of late pulses through largely solidified but still pliable diabase, resulting in resorption of phases still near their melting point.

References

Gorring, M.L., Naslund, H.R., 1995. Geochemical reversals within the lower 100 m of the Palisades sill, New Jersey. Contributions to Mineralogy and Petrology 119, 263-276.

Husch, J.M., 1988. Significance of major- and trace-element variation trends in Mesozoic diabase, west-central New Jersey and eastern Pennsylvania.

Husch, J.M., 1990. Palisades sill: Origin of the olivine zone by separate magmatic injection rather than gravity settling. Geology 18, 699-702.

Husch, J.M., 1992 Geochemistry and petrogenesis of the Early Jurassic diabase from the central Newark basin of New Jersey and Pennsylvania. Geological Society of America Special Papers 268, 169-192.

Olsen, P. E. and Fedosh, M. S., 1988, Duration of the early Mesozoic extrusive igneous episode in eastern North America determined by use of Milankovitch-type lake level cycles. Geological Society of America, Abstracts with Programs., v. 20, no. 1, v. 59.

Puffer, J.H., Block, K.A., Steiner, J.C., 2009. Transmission of Flood Basalts through a Shallow Crustal Sill and the Correlation of Sill Layers with Extrusive Flows: The Palisades Intrusive System and the Basalts of the Newark Basin, New Jersey, U.S.A. Journal of Geology 117, 139-155.

Shirley, D.N., 1987. Differentiation and Compaction in the Palisades Sill. Journal of Petrology 28, 835-365.

Steiner, J.C., Walker, R.J., Warner, R.D., Olson, T.R., 1992. A cumulus-transport-deposition model for the differentiation of the Palisades sill. Geological Society of America Special Paper 268, 193-217.

Walker, K.R., 1969. The Palisades Sill, New Jersey: a reinvestigation. Geological Society of America Special Paper 111, 178 pp.

NEW YORK CITY GEOLOGY AND ITS INFLUENCE ON GEOTHERMAL HEAT PUMP SYSTEMS: A CASE STUDY AT SNUG HARBOR, STATEN ISLAND

Alex Posner\ Project Director, NYC DDC
Brett Miller \Design Engineer, NYC DDC
Dennis Askins \Project Manager, NYCDDC

ABSTRACT

The New York City Department of Design and Construction has always strived to pioneer sustainable solutions for the City, paving the way for other agencies and the public in promoting geothermal and other high performance building related technologies through their Sustainable Design program. The new edition of the Geothermal Heat Pump Manual provides design and construction professionals with the necessary tools for understanding the complex nature of the geology in the five boroughs and how that information can be utilized to integrate a geothermal system into a building project to maximize resources.

This edition reflects the latest industry research available and incorporates the various 'lessons learned' in overcoming many of the unforeseen obstacles and challenges encountered in properly selecting and designing these systems, and the many refinements that were made and incorporated along the way.

New York City's geology is quite complex and varies throughout the five boroughs, presenting challenges for implementing Geothermal Heat Pump systems. Understanding how these systems interact with the earth is essential to proper design and requires a brief overview of geology and ground water resources. Geologic formations identified in the City range from Precambrian bedrock, 1.2 billion years old to modern, unconsolidated Pleistocene deposits composed of sand, silt, and clay, less than 12,000 years in age. The presence of ground water aquifers and their geochemical characteristics fluctuate considerably, even between adjacent properties. Therefore, a site's distinct hydrogeologic profile is a major factor in determining which systems are suitable and guide the ultimate ground coupling selection.

Geology and ground water resources influences the selection of a Geothermal Heat Pump System for a site based on one or more of the following criteria:

- Depth to Bedrock
- Rock Strength
- Thermal Gradients
- Ground Water Yield
- Hydraulic Conductivity

- Ground Water Quality and Temperature
- Aquifer Thickness

A DDC case study will be explored, identifying the design and approach for Geothermal Heat Pump System at Snug Harbor Cultural Center on Staten Island. A Standing Column well was initially proposed, but subsequently redesigned for a Close Loop system because of geologic constraints.

At this site, the glacial overburden material was 155 ft. thick, followed by a saprolite, containing weathered serpentinite from 155 ft. to 174 ft. Competent bedrock starts at 174 ft., composed of serpentinite down to 353 ft. Gneiss and Schist compose the remainder of the rock core down to 869 ft.

Analysis of a deep pilot borehole for determining the feasibility of a geothermal system revealed new insights into Tectonic processes that took place during the emplacement of the serpentinite bedrock on Staten Island. Obduction of the oceanic crust into the upwelling wedge, produced serpentinite slices or slivers into the high pressure and temperature metamorphic wedge. Evidence is found at the base of the ophiolite sliver that is in contact with the serpentinite and gneiss/schist which appears to be a shear fault zone with highly fractured bedrock. There is a color change in the serpentinite rock cores from blue/green to a red/orange, and appears to be caused by high pressures and temperature during obduction.

FIELD TRIP ROAD LOG

John H. Puffer[1], Alan Benimoff[2], and Chris Laskowich[3]
1. Rutgers Univ., Newark NJ.
2. College of Staten Island/CCNY.
3. 14 Old Rifle Camp Rd., West Paterson NJ.

Stop 1. Staten Island Serpentinite Exposure at Abandoned Exit Ramp off I-278.

This stop will be described by Alan Benimoff.

The rock is a serpentinite emplaced during the Taconic orogeny, during the assembly of Pangea. The serpentinite was emplaced as an ophiolite along a plate suture between an island arc (Hartland terrane) and sediments accumulating along the Laurentian continental margin (Manhattan Schist). The Serpentinite is composed of lizardite, chrysotile, antigorite olivine, chromite, magnetite, anthophylite, magnesite and several trace accessories. You should be sure to keep samples sealed in plastic bags to prevent exposure to asbestos fibers.

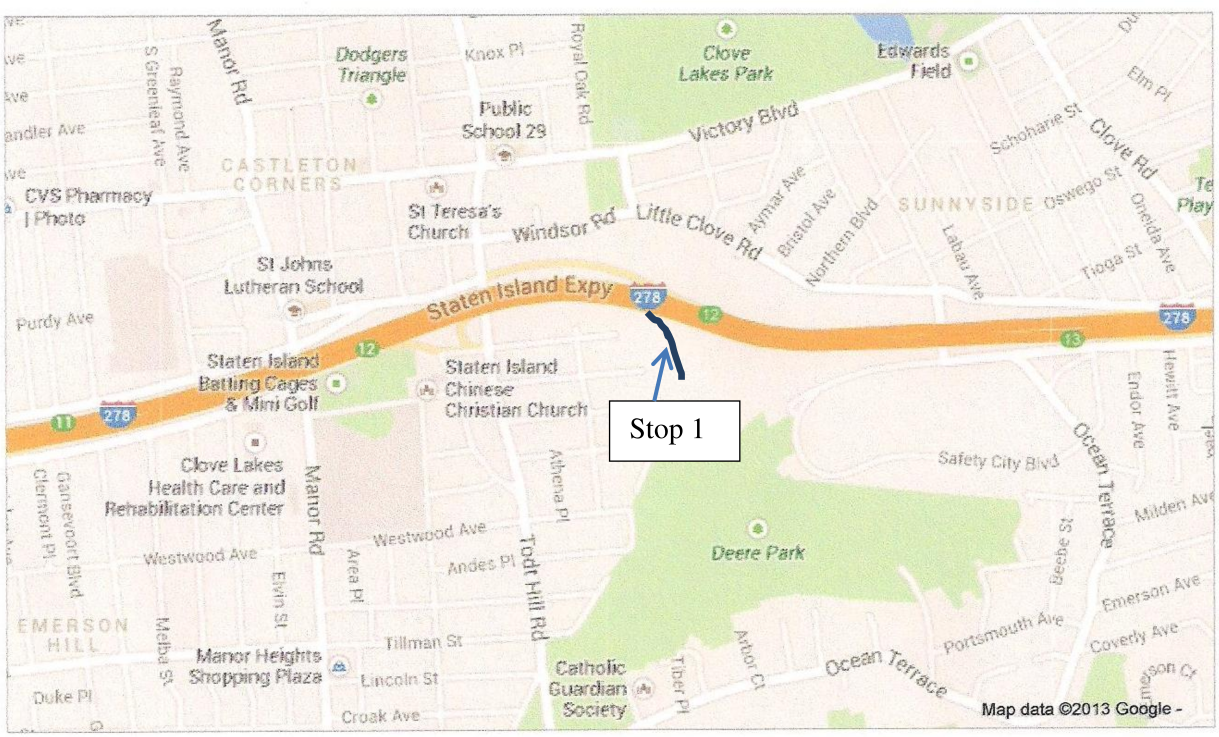


Figure 1. Location map of serpentinite exposure along abandoned eastbound exit ramp off I-278.

Stop 2. Palisades Diabase and Lockatong Hornfels Exposure at Ross Dock along Henry Hudson Drive.

This stop will be described by Alan Benimoff, Karin Block, Jeffery Steiner, and John Puffer.

The contact between the Palisades Sill and the Lockatong Formation is exposed along the west side of Henry Hudson Drive. The Palisades Sill is part of the CAMP large igneous province and was intruded during the early break-up of Pangea. Palisades diabase is composed of plagioclase, augite, and minor magnetite, ilmenite, orthopyrxene, olivine, and amphibole. The Lockatong Formation is lake sediment that was metamorphosed into a hornfels composed largely of plagioclase, biotite, pyroxene, and garnet. Some of the Lockatong has been locally fused into either syenite, trondhjemite, or granite depending largely on variations in the composition of the protolith.

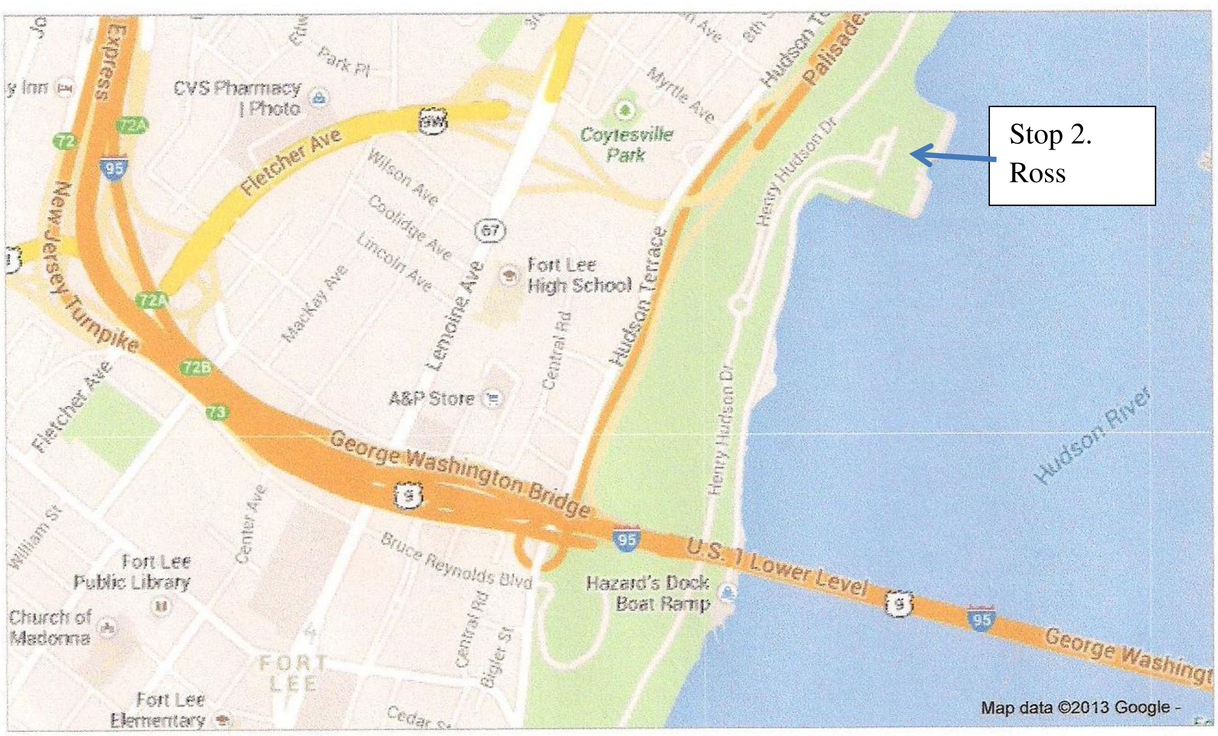


Figure 2. Location map of Ross Dock. The lower contact of the Palisades Sill is exposed along the northwestern edge of Henry Hudson Drive.

Stop 3. Preakness Basalt Exposure at base of second flow, Claremont Ave

This stop will be described by John Puffer

The Preakness Basalt was extruded during the break-up of Pangea and is co-magmatic with most of the upper half of the Palisades Sill on the basis of near identical ages and chemical composition. The exposure (Figure 3) is located at the lower contact of the second of about 5 thick continental flood basalt flows that together make up the Preakness. The flow beneath the contact is about 150 m thick and is one of the thickest flows on earth. Several pegmatoids are exposed on the central cliff face. Preakness basalt is composed of labradorite, clinopyroxene, devitrofied glass, magnetite, ilmenite, and minor potassic feldspar, apatite, and other trace minerals.

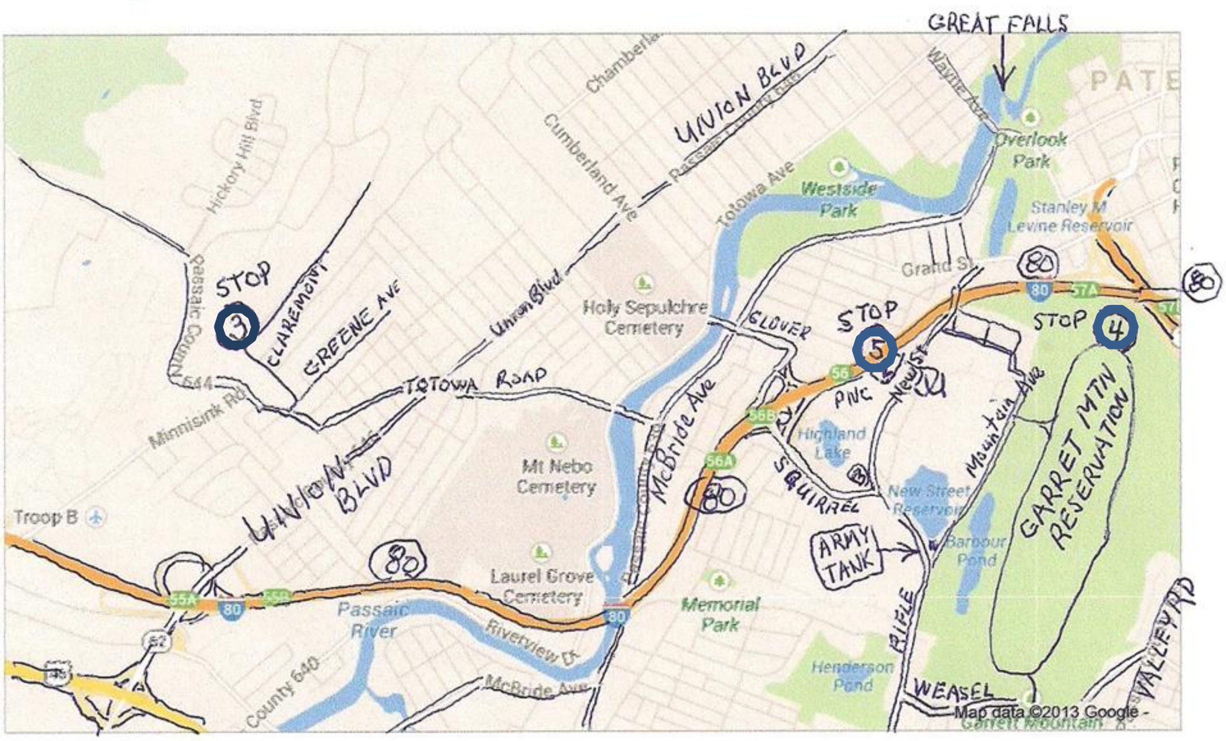


Figure 3. Map locations for field trip stops 3, 4, and 5, West Paterson, NJ.

Stop 4. Orange Mountain Basalt Exposure at Garret Mountain Reservation

This stop will be described by Chris Laskowich and will be our lunch stop.

The overlook at on Orange Mountain basalt exposure (Figure 3) displays a northeastern western vista across the eastern Newark Basin. The city of Paterson built on the Passaic Formation can be seen in the foreground together with the Palisades Sill in the background. Preakness Mountain can be seen to the north.

Stop 5. Volcanic Pillow and Pahoehoe structures in Orange Mt basalt at Lower and Upper New Street Quarries,

This stop will be described by Chris Laskowich and John Puffer; responsible mineral collecting is encouraged.

The Upper and Lower New Street Quarries are located within the second of three Orange Mountain Basalt flows. Most of the second flow (OMB2) is either pillowed during extrusion into brackish water or is characterized by subaerial pahoehoe flow structures. The pillowed portion is mineralized with zeolites including stilbite, heulandite, pectolite, and chabazite. Some amathist is also exposed between pillows. The subaerial pahoehoe portion is mineralized with prehnite and calcite. The Lower New Street Quarry exposes pillows at the base and a wide variety of pahoehoe structures on the upper quarry wall including