The Timing, Layering, Comagmatic Basalt Flows, Granophyres, Trondhjemites, and Magma Source of the Palisades Intrusive System

by

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Abstract

Our understanding of the Palisades is currently undergoing considerable revision. New radiometric data is being accumulated showing that the duration of Palisades intrusive activity is much greater than previously estimated. Active research issues include: In-situ fractionation vs. multiple intrusion of pre-fractionated magma pulses; correlation of Palisades layers with Watchung basalt flows; the origin of the olivine layer; and the role of contamination vs. fractionation in the development of the Sandwich Horizon, granophyres, trondhjemites, and syenite bodies within the sill. We will examine evidence pertaining to each of these issues at field trip stops between Staten Island and Nyack Beach State Park.

Preliminary unpublished evidence gathered at these sites and elsewhere indicates that the Palisades was intruded over a prolonged time span by multiple pulses of magma that were variously pre-fractionated at depth. Each pulse underwent limited additional fractionation after emplacement. According to recently published work and unpublished mineralogical evidence, the lower Palisades consists of several layers that correlate with individual Orange Mountain basalt flows while each of several upper Palisades layers correlate with Preakness basalt flows. Recently published geochemical evidence also indicates that trondhjemite dikes and syenite veins near the base of the sill are products of country-rock fusion. In contrast, preliminary unpublished evidence suggests that the siliceous Sandwich Horizon and granophyres layers at central and upper sill positions are the product of complex processes including fractionation. Finally, most geologic evidence supports a Palisades magma source related to decompression -melting triggered by Pangean crustal thinning and rifting along previous plate sutures located over subduction enriched mantle.

Introduction

The Palisades sill has been the subject of considerable geologic literature. Up until the last few years it has generally been thought of as a composite intrusion consisting of an initial thin intrusion followed by a much thicker intrusion of similar composition that underwent considerable in-situ fractionation. Recent and ongoing research has modified this simplistic fractionation model for the Palisades that is presented in many petrology text-books and is making progress toward several additional new or unresolved issues including:

1) Geochronology - the unresolved timing of the intrusion and extrusion of Palisades magma based on the latest geocronological techniques;

2) In-situ fractionation vs. multiple intrusion of pre-fractionated magma pulses - development of a new concept that the Palisades was intruded as multiple pulses of magma (at least eight) that transmitted huge quantities of basalt to the surface from deep sources where fractionation and contamination occurred

before injection into the Palisades. This concept replaces the idea that most chemical variation within the Palisades is due to in-situ fractionation;

3) Correlation of Palisades layers with Watchung basalt flows - the unresolved correlation of individual layers of Palisades rock with overlying basalt flows based on a) geochemical evidence and b) mineralogical evidence;

4) The Olivine Zone - the unresolved origin of the olivine layer. Is it an olivine cumulate (F. Walker (1940), a facies produced as a contact effect during the intrusion of the second magma (Walker, 1969), an intrusion of a separate OLN magma batch (Husch 1989), or the emplacement of olivine and CPX enriched crystal mush from an unspecified source (Steiner et al. 1992).

5) The Sandwich Horizon and Granophyres – what was the role of contamination vs. fractionation in their development?

6) Trondhjemites and syenite – what was the source of trondhjemite melt that has been injected into the Palisades as several thin cross-cutting veins and syenite bearing migmatite found at the base of the sill?

7) The source of the Palisades (CAMP) magma – probably the most controversial aspect of Palisades research.

Each of these issues will be discussed in this guidebook. The field-trip stops that we have selected will display evidence bearing on these issues and will hopefully stimulate lively discussions. But first a brief review of the Geologic setting of the Palisades intrusive system and its position within the ENA and CAMP (Central-Atlantic-Magmatic-Province) classification system.

What's so special about the Palisades?

As a reminder to experienced geologists and as a reason for new students to pay attention is a short list of reasons why the Palisades is quite special. 1) The Palisades is part of one of the largest (if not the largest) magmatic events since the Precambrian. It is part of a LIP (large igneous province) that covered large parts of Europe, Africa, North America, and South America with a thick layer of volcanic rock. 2) The Palisades intruded into a rift system associated with the early stages of the opening of the Atlantic Ocean. The separation of Africa from North and South America began with Palisades magmatism and continues to this day at the mid-Atlantic-ridge. 3) The igneous rock that flowed through the Palisades and related intrusions (at or near the Triassic-Jurassic boundary) is responsible for one of the most important mass extinctions on earth; rivaled only by the effects of the meteor impact at the Cretaceous – Tertiary boundary and Siberian volcanism at the Triassic – Permian boundary (and possibly some early Paleozoic extinctions). About 23% of all families and 48% of all genera went extinct. Most large land animals were eliminated, leaving dinosaurs with little serious competition.

Geologic Setting

The Palisades Intrusive System consists of a composite sill together with a network of thinner co-magmatic sills and dikes exposed within the Newark Basin of New Jersey and New York. The Palisades sill portion of the system (Fig. 1) is mapped by Drake et al. (1996) as medium- to coarse-grained subophitic diabase to coarse-grained quartz-rich to albite-rich granophyre. The diabase is composed mainly of plagioclase (An50-70), clinopyroxene (mostly augite), orthopyroxene, magnetite, and ilmenite with accessory apatite, quartz, alkali feldspar, hornblende, titanite, zircon, and olivine. The Palisades sill is as much as 360 to 400 m thick (Drake et al. 1996) but is typically just over 300 m thick.

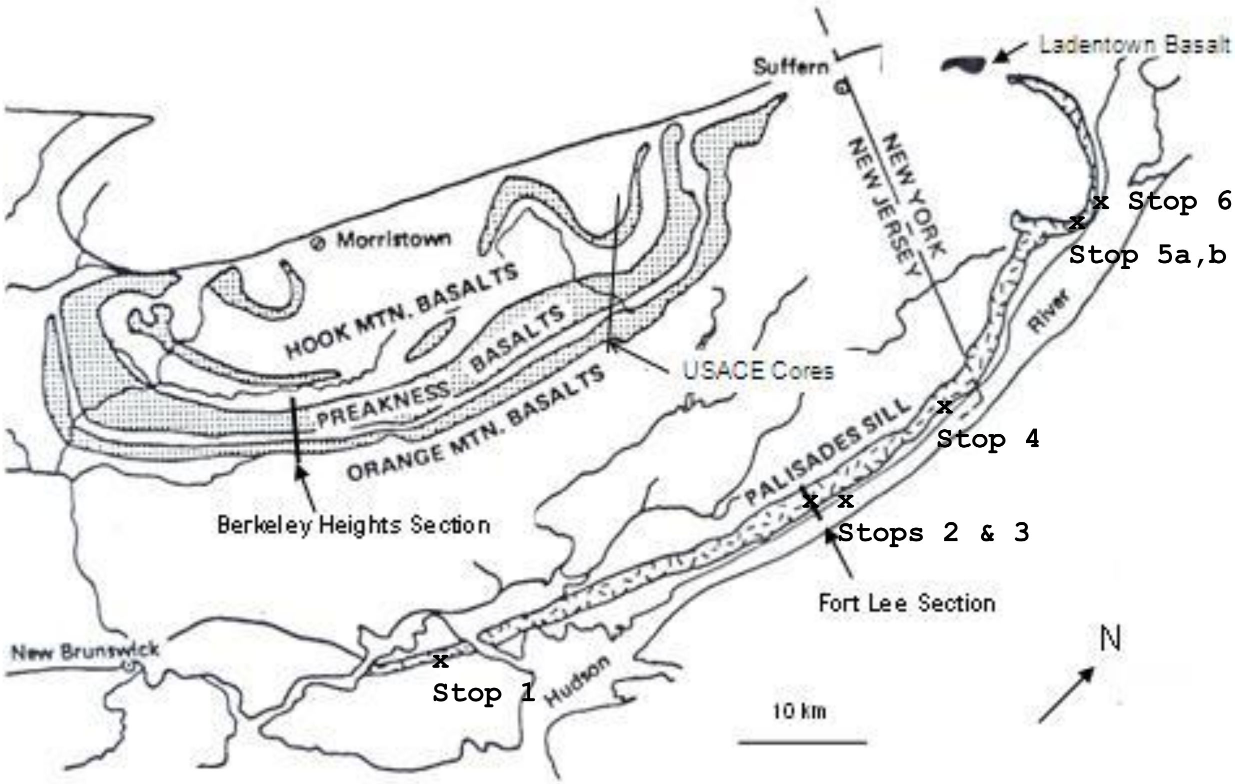

Figure 1. Distribution of early Jurassic igneous rocks throughout the northern Newark basin indicating the locations of data sources used by Puffer et al (2009) including the Berkeley Heights section, the US Army Corps of Engineers (USACE) drill-cores, the Fort Lee section, and Ladentown basalt exposures. Stop 1 is a partially fused xenolith exposure at Graniteville, Stop 2 is the olivine zone, Fort Lee, Stop 3 is a migmatite and trondhjemite exposure at the base of the sill near Ross Dock, Stop 4 is an exposure of cm-scale rhythmic banding at Alpine, Stop 5 is the Sandwich Horizon and some granophyres, and Stop 6 are exposures of the upper Palisades contact and some unusual rock types.

The Palisades system includes 16 additional early Jurassic diabase intrusive sills or sheets in the Newark Basin exposed west of the Palisades sill that have been identified by Gottfried et al. (1991a,b) as co-magmatic on the basis of similar chilled margin compositions. Husch (1992a) concluded that these 17 sheets constitute a single Palisades – Rocky Hill – Lambertville "megasheet" extending about 150 km from southern New York to Pennsylvania. He has shown that although the chill zone of each individual exposed portion of the megasheet is compositionally identical, the interior portions are highly variable. Steiner et al. (1992) use a cumulus-transport-deposition model to show that the Palisades responded to varying degrees of crystal settling, in situ crystallization, flow differentiation, and magma recharge resulting in distinct along-strike variations.

The intrusion of the first pulse of Palisades magma occurred at or very close to the Jurassic/Triassic boundary although the exact timing of the intrusion sequence is the subject of current research.

ENA and CAMP Classification of Palisades Magma

Weigand and Ragland (1970) were the first to recognize that eastern North American Mesozoic dolerite dikes plot as four distinct populations on TiO_2 – MgO – FeO_t variation diagrams. He named these the HTQ-type (high titanium quartz normative), the LTQ (low-titanium quartz normative), the HFQ (high-iron quartz normative) and OLN (olivine normative) magma types. Puffer et al (1981) applied this classification to the Watchung basalt flows of New Jersey and determined that the lower flows (Orange Mountain Basalt) are HTQ-type, most of the middle flows (Preakness Basalt) are LTQ-type and that the upper flows (Hook Mountain Basalt) are HFQ-type. Despite FeO contents below the range typical of HFQ, Tollo and Gottfried (1992) determined that the lower two of five Preakness flows qualify as HFQ-type on the strength of REE correlations with type sections. Gottfried et al (1991a,b) also found that chill-zone samples from each of the sills and dikes that make up the Palisades Intrusive System are HTQ-type. A series of papers by Puffer and others (1980-98) extended the HTQ-HFQ-LTQ classification to other ENA basalt formations including the Hartford, Culpeper, and Fundy Basins and to the Argana basin of Morocco and the Algarve basin of Portugal. Finally Marzoli and others (1999) expanded the classification to include Brazil, French Guiana, Surinam, Guyana, and parts of north-west Africa.

As the breadth of Ragland's applications increased Salters and others (2003) proposed these revisions: 1) LTi (low Ti) to now include the original OLN and some LTQ types and most CAMP dikes; 2) ITi (intermediate Ti, 1-1.5% TiO_2) to encompass HTQ-type and most CAMP basalt flows; and 3) HTi (high Ti) that links highly evolved basaltic rocks with 4-5% TiO_2, not common in North America, with similar varieties in Africa and South America. Note that some of the original LTQ and HFQ groups are included with the ITi group. However for purposes of distinguishing among Palisades and Watchung magmas the original Ragland nomenclature remains valid.

1. Geochronology

Dunning and Hodych 1990 on the basis of U/Pb dating of accessory minerals in the Palisades sill suggest intrusion occurred at ~201 Ma. This date agrees with $^{40}Ar/^{39}Ar$ dates (Hames et al., 2000) of plagioclase separated from the Orange Mt basalt (~201 Ma) but is 2 million years older than plagioclase from the Hook Mountain basalt (~199 Ma). However the analytical error is on the order of +/- 1.5 Ma. Much more precise techniques are available but depend on the occurrence of zircon. Blackburn et al (2009) have found zircon in the Preakness basalt and will shortly be publishing dates with analytical errors of +/- 0.2-0.25 Ma. In addition, a group led by Marzoli (in prep.) have new precise radiometric dates on Palisades and Watchung samples that will soon be available. These geochronological data have important implications for defining theTriassic-Jurassic boundary and the related mass extinction event caused by CAMP. In addition they bear directly on the length of time required for sills the size of the Palisades to fully evolve through complex multiple intrusion and crystallization steps.

If the Palisades sill was the conduit through which both Orange Mountain and Preakness basalts were extruded as proposed by Puffer et al (2009) the Palisades must have taken at least evolved for at least 260 Ky. Olsen et al. (2003) have shown on the basis of carefully measured Milankovitch cyclicity that the Feltville Formation separating the Orange Mountain basalt from the Preakness basalt represents about 260 Ky years of deposition. Puffer et al (2009) propose that intermittent magmatism (including Ladentown basalt extrusion) and hydrothermal activity kept a pathway unconsolidated and open to subsequent magma intrusions during the 260 Ky of Feltville deposition. Continuous pulse influx would also erode, assimilate, and eliminate any previous chill zones or any rock altered by previous vapor vents.

2. Correlation with Watchung Basalts

Part 1 Geochemical evidence

Puffer et al (2009) interpreted the Palisades sill as a progressively-inflated conduit for outpouring huge volumes of flood-basalt. The geochemical data are consistent with a Palisades structure fed by three compositionally distinct intrusion events. The first magma flowed through the sill and erupted near the northern terminus as three Orange Mountain basalt flows. Each of the three extrusive pulses is linked to discrete facies in the lower 150 m of the sill based on distinct geochemical reversals in vertical compositional trends. The end stage of each pulse is characterized by pyroxene phenocryst accumulations.

Magma from a second source inflated the sill by an additional 170 m after approximately 260 Ky of minor intermittent extrusive and intrusive igneous activity and sediment deposition (the Feltville Formation) onto the Orange Mountain basalt}. The second magma extruded as the highly fractionated 150 m thick Preakness basalt and comprises the central layer of Palisades diabase of similar composition. Subsequent extrusions of relatively thin Preakness flows (Magma 3) correlate with upper layers of the Palisades sill (Fig. 2).

Puffer et al (2009) provide geochemical evidence, including Cr distribution (Fig. 2), to document facies boundaries. Each of the Orange Mountain Basalt pulses is correlated to facies in the lower half of the Palisades sill (Fig 2). In addition, each Preakness basalt flow pulse correlates with representative diabase layers within the upper half of the sill (Fig. 2).

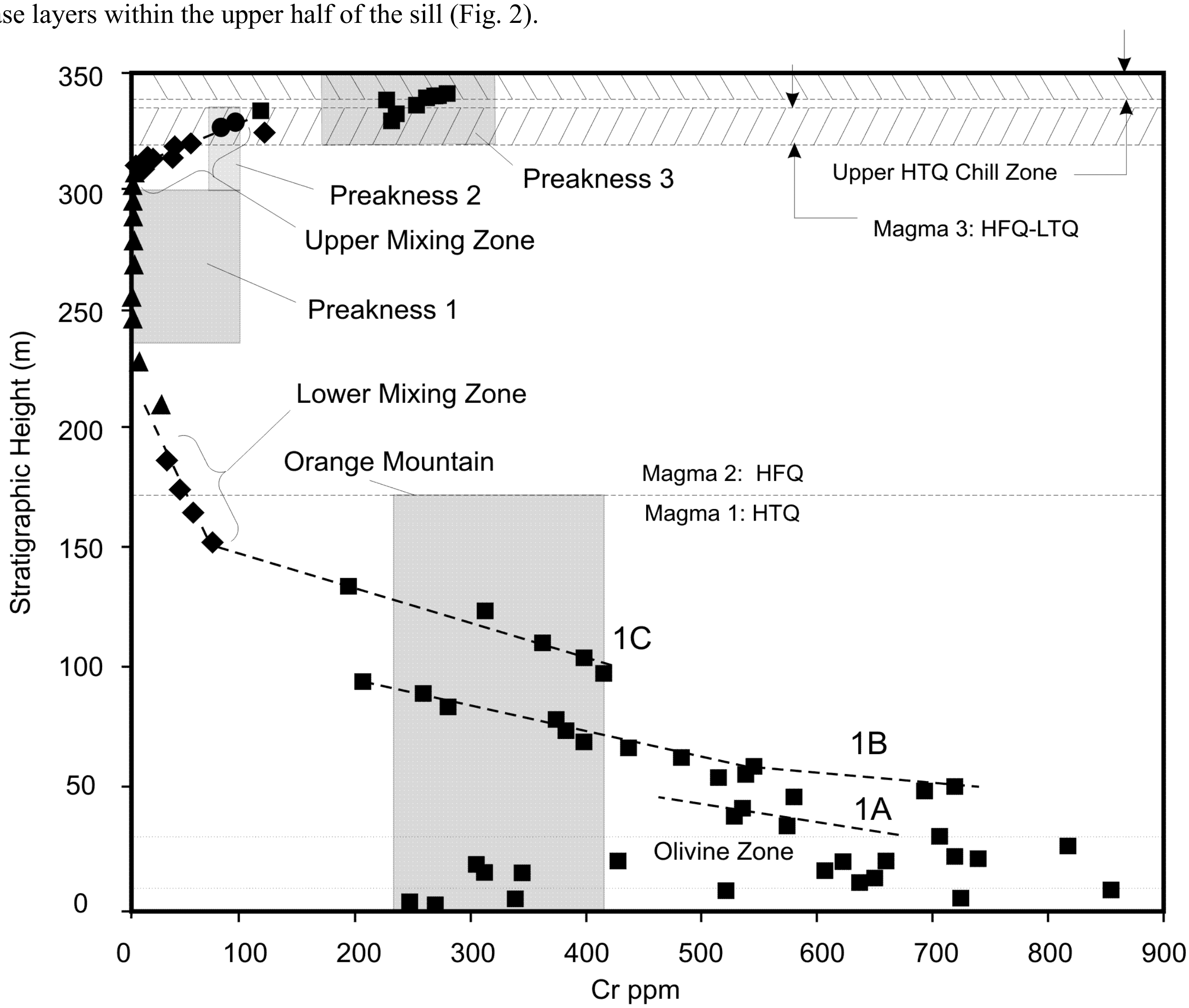

Figure 2. Cr content of the Palisades sill as a function of stratigraphic height (data points) together with Orange Mountain and Preakness basalt flow thickness and Cr ranges plotted as gray fields. Olivine zone (Hysalosiderite; Walker, 1969); 1A Pulse 1A of Magma 1; 1B Pulse 1B of Magma 1; 1C Pulse 1C of Magma 1; OMB Orange Mountain Basalt coeval with Magma 1; Preakness flow 1 coeval with Magma 2; Preakness flow 2 and Preakness flow 3 coeval with Magma 3. HTQ High Titanium Quartz Tholeiite; HFQ High Iron Quartz Tholeiite; LTQ Low Titanium Quartz tholeiite.

Part 2 Mineralogical evidence

Steiner, et al. (1993) have proposed that the 'olivine' layer is a restructured member of a disarticulated magma chamber formed at depth within the Palisades system. Although extensive compositional correlations have been outlined, there is very little comprehensive evaluation of either the series of petrographic facies within the diabase sheet or members of the correlative Watchung flow members. Steiner et al (2009) have established correlations with facies along the basal 50 meters of the Palisades with a comparable section of the Orange Mountain Basalt. For example, facies identified by Walker (1969) as chilled dolerite and early dolerite facies near the base of the sill contain~~s~~ glomeroporphyritic aggregates of augite, and orthopyroxene surrounded by reaction rims of altered olivine. These glomeroporphyritic aggregates are virtually identical in appearance to those that characterize the Orange Mountain Basalt.

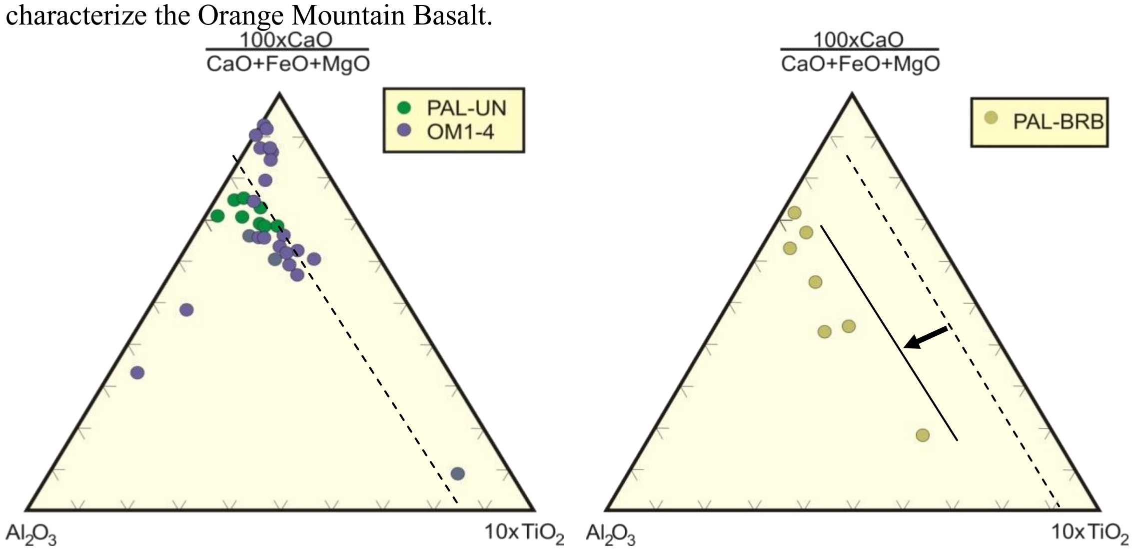

Figure 3. Diagram comparing (A) the augite composition from the lower 40 M of the Palisades with augite from the first of three Orange Mt basalt flows and with (B) augite from 45 m above the base of the Palisades. Note the distinct increase in alumina content.

Augite Chemistry - Steiner et al (2009) have shown that the Al content of the augite fraction in the Palisades sill shows a break at 50 m which is consistent with the bulk chemistry and x-ray diffraction data (Puffer et al, 2009). The variation in Ca ratio-Fe-TiO_2 in the lowermost OMB is consistent with the lowermost 40+ m in the Palisades and shows a stepwise increase from 15 relative wt. % Al at to 17 wt% at 45 m and then again conforms to the Palisades at 50+ m (Fig. 3). Correspondence in major element chemistry, petrographic fabric, the noted x-ray discontinuity and differences in augite chemistry support the conclusion that the Palisades acted as a feeder to the Orange Mountain Basalt and that the lowermost 50 m represents Pulse 1 of Magma 1.

3. In-situ Fractionation vs. Multiple Intrusion Pulses

Puffer et al (2009) interpret the distinct layering of the Palisades sill as injections of magmas that were largely pre-fractionated at deeper levels and then modified to varying degrees by in-situ processes. Most previously proposed Palisades models rely on transporting large quantities of pyroxene and plagioclase crystals long distances by settling or convection from one internal crystallization front across a high temperature interior to the opposite crystallization front. Injection of thinner largely pre-fractionated pulses removes these advective changes as an issue in the evolution of the Palisades (simplify these problems). In addition, Steiner and others (1992) have demonstrated though mass considerations that the cumulus composition of the lower Palisades is insufficient to produce a mass balance with the upper Palisades. Intrusion of magmas from independent sources as proposed by Puffer et al (2009) solves this paradox.

4. The Olivine Zone

A group including Steiner, Brock, and Puffer are currently working on a project pertaining to the olivine zone. The Steiner group has found enclaves of coarse-grained rock in an exposure of Orange Mountain Basalt at Garret Mountain, Paterson. The coarse grained rock is significantly more mafic than typical Orange Mountain basalt. This mafic rock may have been carried as xenoliths (Orange MT) and as a partially solidified magma mush (the Olivine Zone) from a deep source. In both cases it is unlikely that the mafic rocks represent shallow or in-situ olivine or pyroxene accumulation during fractionation.

5. Granophyres and the Sandwich Horizon

A group led by Karin Block is currently revising models for the development of granophyres within the upper Palisades sill and the 'sandwich horizon' of Shirley (1987). Walker (1969) describes silicic facies for the Englewood Cliffs section that occur approximately five kilometers to the north of Shirley's (1987) George Washington Bridge Section. These include fayalite granophyre, ferrodolerite, pegmatite dolerite, and granophyric dolerite, all residing at various stratigraphic levels. These facies are often juxtaposed to less silica-enriched rocks, consistent with a pulse model involving a somewhat chaotic mixing of magmas of possibly differing petrologic heredities. Of present interest are granophyres of Shirley's (1987) sandwich horizon which include Walker's (1969) granophyric dolerites.

The Palisades sandwich granophyres are texturally distinctive, late-stage silica and iron-enriched differentiation products (56-63 wt. % SiO_2; 14 to 16% FeO total), sharing features with the well-studied plagiogranites of mid-ocean ridge systems (Koepke et al. 2007). It may be argued that at least some granophyres in the Palisades, particularly those close to the upper and lower sill contacts, derive from felsic country rock assimilated into the magma during intrusion. This is supported by evidence for the partial melting of country rock at the lower contact with the Palisades (Benimoff and Puffer, 2000; Benimoff, Puffer and Sclar, 2000; Benimoff and Puffer, 2001, Benimoff and Puffer, 2007). We will examine this evidence at field trip Stop 3.

However, isotope evidence generated by the Block group indicates that the Palisades granophyres of the sandwich horizon are not primarily derived through assimilation of country rock. Neodymium isotope systematics unequivocally demonstrate that if country rock was eroded and incorporated into the Palisades magma, the amount of assimilated material was insufficient to influence magma composition to any significant extent. The new isotopic results demonstrate that granophyres from the 'sandwich horizon' of the Palisades Sill are products of magmatic differentiation and provide no evidence of a mixing relationship between sedimentary country rocks and ordinary diabase. Notably, the Nd-isotope composition of a diverse suite of Palisades rocks is nearly constant. Therefore, a multiple-pulse model for the petrogenesis of the Palisades sill requires a homogeneous magma source in terms of Nd-isotope composition. Nd and trace elements show that the Palisades are generally enriched and support Puffer's (2003) hypothesis that CAMP magmas may be products of a reactivated back-arc source.

The absence of a positive Eu anomaly in the Palisades rocks analyzed in this study contradicts compaction and in situ differentiation models proposed by Shirley (1989) and Philpotts et al. (2000). Nonetheless, a significant change in the trace element stratigraphic profile of the Fort Lee section that culminates in a maximum concentration in incompatibles at the sandwich horizon granophyres, is consistent with the evolution of a pre-differentiated second magma (Puffer et al. 2009) and provides adequate conditions for the sill to remain fluid over extensive time periods. This supports a recently proposed model of the Palisades as a composite intrusion that served as a feeder to the extrusive Watchung flood basalts west of the sill.

6. Trondhjemite and Syenite Intrusions

A series of papers by Benimoff, Puffer, and the late Charles Sclar have concluded that a network of trondhjemite intrusion into the Palisades sill are the result of fusion of Lockatong argillite and subsequent penetration into late joint systems. Occurrences of both Lockatong xenoliths and Lockatong beds in contact with the lower contact of the Palisades sill have been described by the Benimoff-Puffer-Sclar group and will be examined at field-trip stops 1 and 3.

In addition to trondhjemite, some syenite melt was generated at the lower contact of sill and dike members of the Palisades Intrusive System. Benimoff and Puffer (2005) conclude that the composition of the melt product depends largely on 1) the composition of the sediment that was melted and 2) on metametasomatic reactions that occurred before fusion. Figure 4.

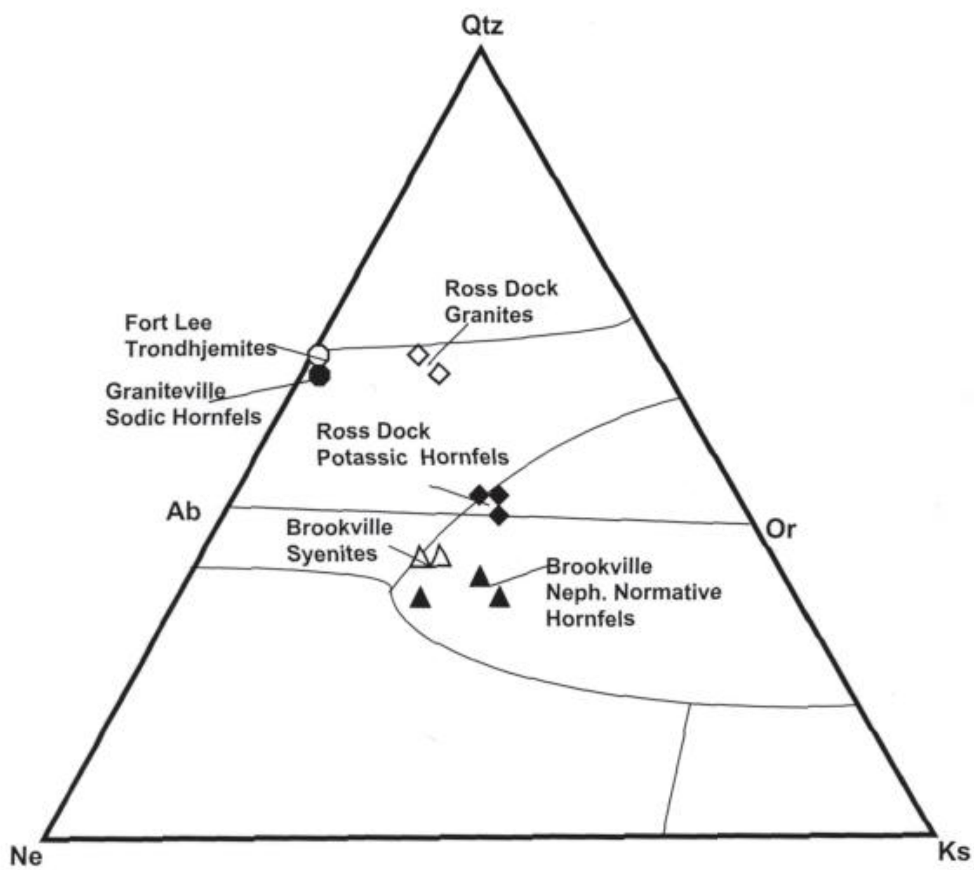

Figure 4 Quartz-Nepheline-Kalsilite phase diagram at 1 kilobar with trondhjemite, granite, syenite compositions together with their respective hornfels sources. Trondhjemites from Fort Lee (open circles) plot close to the eutectic point along the Ab-Qtz boundary. Granite from the George Washington Bridge site plot close to the thermal valley of the Quartz-Albite- Orthoclase system and syenites from Brookville plot close to the Albite-Orthoclase-Nepheline-Kalsilite minimum.

7. Palisades Magma Source

Most of the controversy pertaining to the source of Palisades (and by association CAMP magma) deals with the likelihood of a plume (hotspot) source vs. a fissure source related to the rifting or early brakeup of Pangea. Puffer (1992, 2001, and 2003) argues that decompression melting related to Pangean crustal thinning and rifting close to previous plate sutures is more consistent with the geologic evidence than plume or superplume magmatic activity.

Tectonic evidence for a non-plume source includes the fact that there is no hotspot tract. Instead, early CAMP magmatism, (HTQ or ITi-type) including the Palisades, extruded and intruded, along plate boundaries, and in most cases the same plate sutures associated with the Paleozoic assembly of Pangea. The underlying mantle source was, therefore, enriched during previous subduction.

Geochemical evidence includes the fact that initial Palisades magma resembles calc-alkaline or ARC-type magma in most respects including distinct negative Nb, and Ti anomalies on spider diagrams and a negative slope parallel to standard ARC magma Puffer (2001). In contrast Plume-type or Ocean Island Basalt is relatively enriched in REE's and high field strength elements. Additional geochemical evidence is provided by Rb, Sr, Nd and Sm isotopic data (Puffer, 1992; Pegram, 1983) that indicates early CAMP (Palisades) magma derivation from a source distinct from MORB but consistent with an enriched subcontinental mantle Strong support for a subduction enriched mantle source for HTQ magma is provided by Dorais and Tubrett (2008). They analyzed the cores of strongly zoned clinopyroxenes and found up to 1 wt% Cr_2O_3 and other data indicating that they are early crystallizing phenocrysts, not xenocrysts. Extended rare earth element diagrams for Cr-rich liquids in equilibrium with these cores show enrichment in incompatible elements similar to arc basalts. Their data indicate that the mantle source experienced subduction zone fluid metasomatism that was later modified by crustal contamination.

Puffer (2003) has also argued that an ARC source is consistent with a reactivation of the same magma source responsible for the Paleozoic andesites that extruded along advancing plates during the assembly of Pangea. This ARC source remained dormant until decompression associated with Pangean rifting. Finally, most CAMP magma extruded suddenly and ended quickly with relatively minor late magmatism unlike the prolonged several million year duration of typical plume and plume-tail magmatism.

Some of the current research that Steiner, Block, and Puffer are engaged in, particularly the micro-probe analyses of pyroxene and plagioclase phenocrysts in Orange Mountain and Palisades samples will add additional insight into magma source theory.

Field Trip Stops:

Stop 1. Xenolith fusion (trondhjemite) at Graniteville, Staten Island

(Forest Ave. between Van Name and Simonson Avenues south side), (Latitude 40.624689° ; Longitude -74.153697)

At this stop we will examine a xenolith of argillaceous Lockatong Formation enclosed in Palisades diabase that has undergone partial fusion to yield a trondhjemite. The sodium-rich slab-like xenolith of argillite is 30 m long,, 0.5 m thick and strikes N 30° E with a vertical dip. The xenolith was derived from Lockatong located below the sill. Completely surrounding the xenolith is a coarse-grained trondhjemite. Chemical analyses (Benimoff and Sclar, 1984) reveal that there was diffusion of ions across the liquid/liquid interface between diabase and trondhjemite melts. Fe, Mg, and Ca diffused into the trondhjemite, whereas Na, Rb, K, Ba and diffused into the diabase.

The diabase is composed dominantly of plagioclase ($An_{61}Ab_{38.8}Or_{0.2}$) and augite ($En_{34\text{-}44}Fs_{17\text{-}31}Wo_{35\text{-}42}$). The augite contains exsolution lamellae of pigeonite on (001), and typically exhibits simple contact twinning on (100). A granophyric intergrowth of quartz and K-feldspar is present in minor amounts. Grains of titanomagnetite with oxidation lamellae of ilmenite and discrete grains of ilmenite are common.

The trondhjemite is composed dominantly of quartz-albite granophyre containing large discrete crystals of albite and Ca-rich pyroxene. Minor constituents include interstitial calcite, titanite, ilmenite, optically homogeneous titanomagnetite, nickelian and cobaltian pyrrhotites, apatite, and sphalerite. The modal mineral percentages are clinopyroxene 38, albite 38, quartz 18, titanite 2.7, calcite 1.3, and opaques 2.0.

Petrographic examination shows that the xenolith is now a hornfels and exhibits a hornfelsic texture. The hornfels is composed dominantly of albite and quartz and subordinantly of calcite, titanite, apatite, ilmenite, and actinolite. The modal mineral percentages are albite 66, quartz 30, titanite 2.3, calcite 0.9, apatite 0.5, and actinolite 0.3. The bulk composition of the xenolith is variable, as shown in Table 1 of Benimoff and Sclar (1984) which is not unexpected for a meta-sedimentary rock. Normative albite ranges from 56.4 to 80.2 wt.%, whereas normative quartz ranges from 7.0 to 35.4 wt.%.

Stop 2. The Olivine Zone (Palisades Park, Fort Lee)

From River Road turn into Henry Hudson Drive; The olivine zone is on the left side of the road near the first left curve. (Latitude 40.846969°; Longitude -74.153697°

The olivine zone (hyalosiderite) occurs 7 to 20 meters above the base of the southern portion of the Palisades sill but is less well defined within the northern portion because it is replaced by a more hypersthenes-enriched facies with less olivine (altered to iddingsite) but with similar whole rock chemistry, particularly Cr/Mg ratios (Steiner et al, 1993). The northern end of the olivine layer is exposed at Nyack Beach State Park (Stop 6 of this field guide).

Stop 3. Trondhjemite and Syenite fusion (Ross Dock)

Continue on Henry Hudson drive and park at Ross Dock. Walk up to traffic circle and outcrop is just west of the circle at Latitude 40.857369° and longitude -73.959189°.

The chill zone at the base of the sill is clearly exposed along the park road above Ross Dock. The diabase here is aphyric except for glomeroporphyritic aggregates of pyroxene and plagioclase and contains very few xenoliths; characteristics shared by the Orange Mt basalt. The lower contact is largely parallel to the bedding planes of the underlying metasediments but is locally discordant. Flow of the first pulse of diabase through the Lockatong argillite has excavated a few channel-like cuts several meters across that truncate underlying Lockatong bedding plains at about 30^{o}. In addition, anticlinal dome-like structures consisting of Lockatong Formation that rise a few meters into overlying diabase are exposed here (Fig. 5). It is at these dome-like structures where fusion has occurred.

Figure 5 (on page 94). Lower contact of the Palisades Sill along the road to Ross Dock. Migmatites are present to the right of the meter stick in an anticlinal dome structure.

Four meters of the section directly below the Palisades contact where considerable fusion has occurred includes 0.3 m of “buff arkose” in contact with the diabase, underlain by 0.2 m of “bedded siltstone”, underlain by 2.9 m of “buff arkose” underlain by 1 m of “platy and bedded siltstone” and 0.5 m of “laminated siltstone”. These lithologies have been described by Olsen (1980) as meta detrital cycles and he has correlated them continuously for 12 km along the base of the sill. The uplift of the black “laminated siltstone” has brought it to close proximity to the sill contact. The domed structures may have involved movement of volatiles derived from brackish groundwater. The salt content of these volatiles may have helped flux the melting process. Each of the lithologies exposed at the stop 3 dome exposure have been chemically analyzed by Benimoff and Puffer (2000). Both the syenite and trondhjemite fusion products are sodic typically containing 4 and 7.5 % Na_2O respectively, but K_2O and Rb is highly partitioned into the syenite, typically containing 5% and 125 ppm vs. only 0.5% and 25 ppm for the trondhjemite. Both the syenite and trondhjemite have similar REE contents comparable to the Lockatong Argillite (Benimoff and Puffer, 2000). The syenite, trondhjemite, and Lockatong laminated siltstone each display negative Nb anomalies in contrast to the Palisades diabase.

Stop 4. Alpine

(near Exit 2 Palisades Interstate Parkway; close to Palisades Interstate Park Headquaters)

The central portion of the Palisades sill is exposed along an extensive section extending from about 60 m above the base to approximately the 150 m level. Portions of this section are characterized by cm-scale rhythmic banding (Fig. 6). Thin sections (Block, et al, 2004) reveal associations of plagioclase and CPX tend to be separated by finer-scale plagioclase chains consistent with a convective flow model. Thin sections also reveal that the rhythmic banding is complicated by a cryptic mm-scale banding.

Figure 6. Centimeter scale rhythmic banding in Alpine Section of the Palisades Sill.

Stop 5A. Coarse Augite Dolerite (Valley Cottage)

As described by Steiner (1989) this is one of the few localities not in someone's yard which shows coarse augite dolerite (granophyre). However, the exposure here is weathered. The iron-enrichment of the Palisades at this stop is due to abundant titanomagnetite in the groundmass that will attract a magnet. The titanomagnetite is often dendritic and is considered to occur as both a primary and a quench feature. Chemically and to a certain extent petrographically this coarse dolerite appears to be equivalent to the late stage ferrodolerite, fayalite granophyres and other facies of Walker (1969), except that the iron enrichment is not accompanied by iron rich ferromagnesian minerals such as ferroaugite or fayalite. Ferroaugite rims may occur, but the bulk clinopyroxene is clearly augite.

REE patterns (Steiner, 1989) indicate extreme enrichment and are consistent with the derivation of the coarse augite dolerite from pigeonite facies through crystal liquid fractionation.

Stop 5B. The Upper Contact (Route 303 and Lake Road in Valley Cottage)

Parking can be accommodated at the local deli, across the street at the Bank, or in the large Valley Cottage Parking lot one block west on Lake Road; the latter will accommodate buses.

One of a few rare outcrops of the upper contact of the Palisades is exposed near the intersection of Route 303 and Lake Road in Valley Cottage and has been described by Steiner (1989). Another upper contact exposed about 3.2 km to the south is also described by Steiner (1989). The Valley Cottage location marks a sharp boundary between baked lake sediments and the upper quench zone contact with the Palisades. NYSGA members on the trip are challenged to find the contact. Note that the bench or small ridge that runs roughly east west toward Rockland Lake (from the intersection toward the Chase bank looking across the structure) represents the contact metamorphic zone. This location is on the partially exposed 'ring-dike' structure at the northernmost termination of the Palisades that extends northward along the Hudson toward Haverstraw than arcs westward, circling back to this location comprising in map view a large circular structure.

The texture of the contact diabase is microporphyritic with augite microphenocrysts. Within 2 meters of the contact the texture is ophitic, and beginning about 5 meters south patches of interstitial mesostasis appear. Farther south the diabase appears to plunge beneath the sedimentary cover. About 1 km north of Lake Road the contact reappears on the upper portions of the exposed slope which is inset 60 meters east of route 303. The dolerite dips roughly west at about 45 degrees under a veneer of shales. The intrusive contact is, therefore, complex, winding in a curvilinear fashion along its margin the general form of poorly exposed coalesced domes or localized arches.

Stop 6. Nyack Beach State Park

Enter Nyack Beach State Park, curve around the toll booth and follow paved incline up the hill to the left. Turn left at the top of the hill approximately 100 yards to the circular turn around and park. Latitude 40.95305°; Longitude -73.920490°)

Steiner (1989) described in detail the geology of Nyack Beach State Park. The escarpment at the eastern edge of the park represents the western wall of an infilled stone quarry. On this rock face, at approximately 13 meters above the presently obscured basal contact, a subhorizontal "rotten zone" can be observed. This zone presumably represents the last vestige of the olivine layer referred to by Walker (1969). It appears to fade northward of the present location.

A close up view of the olivine zone reveals that the basal part is undulose and uneven. It is marked by nodules of basalt enclosed in a weathered granular matrix. An analysis of one of the olivine bronzite nodules yields 10 percent MgO. This percentage is high for most of the Palisades, but less than the 19 percent reported by Walker (1969) for the hyalosiderite facies.

Here, as elsewhere, it appears that cooling cracks are reasonably continuous through the olivine zone indicating that it belongs to the same cooling unit as the overlying dolerite.

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