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Evolution of late stage differentiates in the Palisades Sill, New York and New Jersey

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ABSTRACT

The Palisades Sill at Upper Nyack, NY contains evolved rocks that crystallized as ferrodiabase and ferrogranophyre and occupy 50% to 60% of the local thickness. $^{143}Nd/^{144}Nd$ isotope values for rocks representing Palisades diversity range between 0.512320 and 0.512331, and indicate a homogeneous source for the Palisades and little or no contamination from shallow crustal sediments. Petrographic analysis of ferrodiabase suggests that strong iron enrichment was the result of prolonged quiescence in cycles of magmatic input. Ferrogranophyres in the updip northern Palisades at Upper Nyack are members of a suite of cogenetic rocks with similar composition to 'sandwich horizon' rocks of the southern Palisades at Fort Lee, NJ, but display distinct mineralogical and textural features. Differences in textural and mineralogical features are attributed to a) updip (lateral) migration of residual liquid as the sill propagated closer to the surface; b) deformation caused by tectonic shifts; and c) crystallization in the presence of deuteric hydrothermal fluids resulting in varying degrees of alteration. A model connecting multiple magmatic pulses, compaction and mobilization of residual liquid by compositional convection, closed-system differentiation, synchronous with tapping of the sill for extrusion of coeval basaltic subaerial flows is presented. The persistence of a low-temperature mushy layer, represented by ferrogranophyres, supports the possibility of a long-lived conduit subject to reopening after periods of quiescence in magmatic input, leading to the extrusion of the multiple flows of the Orange Mountain Basalt and perhaps even subsequent Preakness Basalt flows, depending on solidification conditions. A sub-Newark Basin network of sills subjected to similar protracted input of pulses as hypothesized for the Palisades was likely responsible for 600 ka of magmatic activity required to emplace a third set of Watchung flood basalts, the Hook Mountain Basalt.

1. Introduction

Fractional crystallization of tholeiitic magma typically produces a small amount of felsic residue that remains trapped interstitially. As mafic components are removed from the magma, the granophyre fraction increases during the later stages of tholeiite crystallization to occupy approximately 7–12% of the rock body (Carmichael, 1964). In some cases, the volume of late-stage differentiates, and granophyre in particular, is significantly larger than what would be expected from simple fractional crystallization. The northern limb of the Palisades Sill of New York and New Jersey contains a thick layer of granophyre that occupies more than 25% of the intrusion thickness. The occurrence of voluminous granophyres in mafic intrusions has been attributed to a variety of processes such as contamination by anatexis of country rock and extreme fractionation. In this work, we report petrographic and geochemical results from analysis of a near-continuous granophyre-rich section of the Palisades Sill at Upper Nyack, NY to provide a basis for comparison to sections to the south, particularly the comprehensively sampled stratigraphic section at Fort Lee, NJ (Shirley, 1987). The latter has provided subsequent researchers with valuable geochemical and petrographic data for assessing a number of competing hypotheses (e.g., Latypov, 2003; Puffer et al., 2009). Samples from Upper Nyack were analyzed for major oxides, trace elements, and mineral chemistry to establish correlative horizons with other portions of the sill. To assess the influence of entrainment and assimilation of crustal rocks on granophyre production, Sm–Nd isotope analyses were collected on a set of 16 samples from throughout the Palisades in addition to Upper Nyack and nearby country rocks exhibiting varying degrees of contact metamorphism. We present evidence of lateral migration, episodic deformation, and metasomatism leading to the generation of a thick layer of evolved liquids. Lastly, we present a model that accounts for the observed features, and that ties late stage differentiates to coeval extrusives of the Newark Basin, the Watchung flood basalts.

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2. Background

2.1. A brief overview of granophyres

Granophyres are broadly used to describe felsic bodies occurring in mafic rocks. A "granophyre texture" consists of cauliflower-like intergrowths of quartz and feldspar associated with titanomagnetite and apatite. During fractional crystallization, these granophyric constituents increase in total volume as the mafic body evolves ultimately resulting in felsic rocks that can be compositionally described as analogous to granites, trondhjemites, diorites, tonalites, and monzonites. Some authors have extended the usage to include granophyres with intermediate to high silica (~56–73 wt.%) and high iron content (>10 wt.%), and are described as ferro- or melano-granophyres (McBirney, 1989).

Several hypotheses have been suggested as alternatives to simple fractional crystallization to account for granophyre horizons in mafic intrusions. The most common of these are: assimilation of siliceous country rock (Sierra Ancha diabase; Smith and Silver, 1975); compaction and filter pressing (Skaergaard intrusion; McBirney, 1995; Palisades sill; Shirley, 1987; Graveyard Point Intrusion; White, 2007); reaction of residuum with a) hydrothermal chloride-rich liquids (Stillwater complex; Czamanske et al., 1991), or b) iron-rich volatiles (Dillsburg sill; Hotz, 1953); and liquid immiscibility (Skaergaard intrusion; Jakobsen et al., 2005; McBirney and Nakamura, 1974; Naslund, 1983; Bushveld complex; VanTongeren and Mathez, 2012; VanTongeren et al, 2010; also in the North Mountain Basalt; Greenough and Dostal, 1992).

In hypabyssal intrusions similar to the Palisades, inordinately thick granophyres are attributed to other mechanisms. The granophyres of the Endion Sill are hypothesized to have accumulated by either of two ways: a) migration of late stage liquids updip, or b) as a separate felsic pulse unrelated to fractionation (Ernst, 1960). The idea of updip migration of residual magmatic liquids has also been proposed for the Plains sill (Poage et al., 2000), for the diabase sheet system of the Culpeper Basin (Froehlich and Gottfried, 1988; Woodruff et al., 1995), and the York Haven diabase sheet of Pennsylvania (Mangan et al., 1993), and the western portion of the Palisades intrusive system of western New Jersey and eastern Pennsylvania (Husch, 1992). We will show that some of these processes apply to the granophyres of the Palisades, particularly updip migration of residual fluids.

2.2. Geology and petrology of the Palisades Sill

The Palisades Sill is a large, shallow diabase body that intrudes sedimentary strata of the Newark Supergroup. The sill is a member of the Central Atlantic Magmatic Province (CAMP) associated with the rifting of Pangea in the late Triassic/early Jurassic (Marzoli et al., 1999, 2011). The sill is dated at 201 ± 1 Ma by U/Pb (Dunning and Hodych, 1990), 201.4 ± 2.6 Ma by $^{40}Ar/^{39}Ar$ (Turin, 2000), 200 ± 1 Ma by $^{40}Ar/^{39}Ar$ (Baksi, 2007) and 201.520 ± 0.031 by U/Pb (Blackburn et al., 2013). Marzoli et al. (2011) determined that the Palisades was subject to prolonged magmatic input yielding upper Palisades $^{40}Ar/^{39}Ar$ dates as late as 195 Ma.

The intrusion is shallow and tabular, ranging in thickness from 250 to 340 m, thinning northward along the western bank of the Hudson River. The sill is mostly concordant, dipping 10–15° W through Upper Nyack, NY (Fig. 1) and extending approximately 150 km along strike with estimated depth of emplacement of 3–4 km (Faust, 1975). The sill is in contact with late Triassic members of the Newark Supergroup (Olsen, 1980); the Stockton Formation at its base in its southern limb (Staten Island, NY and in New Jersey) and the Lockatong Formation at its northern limb (Rockland County, NY). 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 and then breaks out to extrude as basalt. In fact, some workers have hypothesized on the basis of geochemical (Husch, 1988) and magnetic data (Maes, 2006) that the Palisades magma originated at depth in the south near Staten Island and propagated northward toward the surface with each pulse. A map of the study region and focus areas for this study is shown in Fig. 1.

The Palisades has been a focal point for ongoing inquiry for over a century. This has been facilitated by well-exposed outcrops and large-scale heterogeneity progressively revealed over its long history of study. In the Palisades, and layered sills in general, mafic phases are dominant near the basal contact, with increasing fractions of felsic components toward the upper contact; for example see Gibb and Henderson (1992, 2006).

Early petrogenetic models of the Palisades focused on a lower olivine layer, and the preponderance of mafic constituents, in the lower portion of the sill, ostensibly interpreted as the result of in situ fractionation of a single event of magma following Bowen's reaction series (Lewis, 1908;

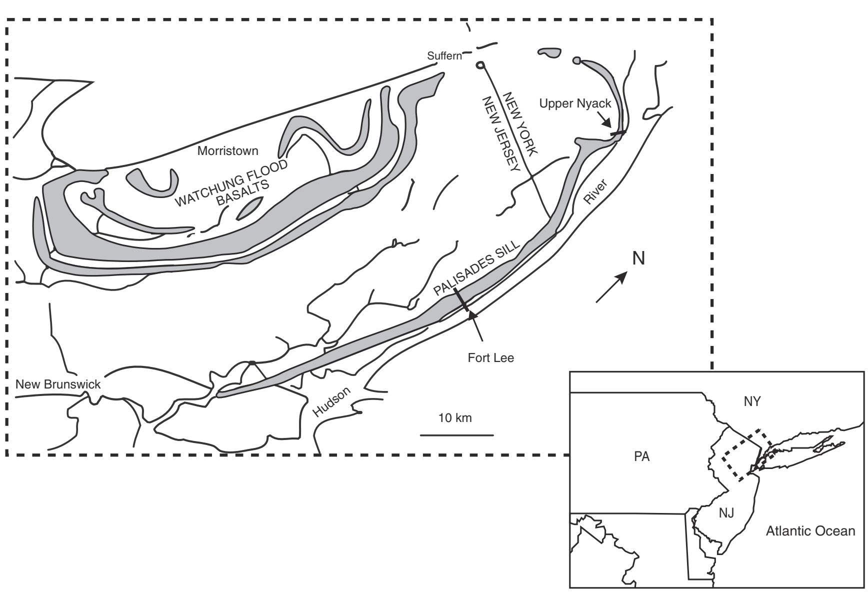

Fig. 1. Map showing location of Newark Basin tholeiites discussed in this study. Location of focus areas at Upper Nyack and Fort Lee are marked with arrows.

Walker, 1940). However, for most of the study history of the Palisades the working model that best explains the various geochemical and mineralogical features in the sill is based on input of multiple pulses of magma.

The first viable multiple pulse model was developed by Walker (1969). Walker analyzed the geochemistry and petrography of suites of specimens representative of variations along stratigraphy for exposures at a series of locations along strike from Kings Bluff to Haverstraw. His work revealed that the famous olivine zone extended for a limited southern portion of the exposed sill along strike. 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 above the basal contact to the input of three or four magma pulses. Shirley found that maximum concentrations in incompatible elements in the "sandwich horizon" granophyres occurred where the upper and lower solidification fronts met, and were caused by compaction and filter pressing that expelled more buoyant residual liquid upwards through the crystal mush.

A follow-up quantitative analysis of textural anisotropy in plagioclase chain networks (Gray et al., 2003), revealed that the sill was emplaced in its present dip orientation and that overall compaction in the sill was ~8%, resulting in down-dip slumping of the crystal mush. Evidence from AMS fabrics obtained through analysis of shape preferred orientation of magnetite and plagioclase in the Palisades (Maes, 2006) is consistent with the findings of Gray et al. (2003) regarding the sill's present orientation. However, the latter study did not find evidence of compaction post-emplacement.

A larger context to the crystallization of the Palisades was proposed by Husch (1990) who suggested 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 a dissonance with regard to expected fractionation trends. While the majority of the intrusion is dominated by pyroxene fractionation, as would be expected in a quartz tholeiite, he noted that production of an olivine zone would require a fractionation trend typically associated with olivine tholeiites. Instead of regarding the olivine layer as a second pulse that was Mg-rich and crystallized primary olivine, 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 elaborated on Husch's hypothesis. Steiner et al. (1992) proposed a cumulus-transport-deposition model that argues for multiphase fractionation induced by convective overturn, followed by deposition of cumulates through flow differentiation. Gorring and Naslund (1995) found that geochemical reversals in Mg#, Cr, and Ni trends in the lowermost 100 m in the sill were in fact markers of magma input events. They suggested that magma chamber recharge could account for heterogeneity in the layering of the Palisades. Most recently, Puffer et al. (2009) connected geochemical trends and reversals corresponding to discrete pulses in the Palisades with similar trends in two nearby flood basalts indicating that the sill therefore served as a conduit or feeder for prolonged extrusion during rifting of Pangea.

3. Materials and methods

3.1. Sampling

Upper Nyack samples were collected along route 9 W and in Upper Nyack State Park (UNSP) in Rockland County, NY. Rocks from approximately 6 m to approximately 32 m above the chilled margin were sampled at six locations along the base of the 50 m UNSP escarpment. Specimens were also collected across strike from 17 to 195 m. A third set was collected from 230 to 250 m relative height along route 9 W. A Google Earth file with sample locations and metadata is available in the Supplementary Materials (Palisades.kmz). The upper chill sequence is not exposed. Granophyre samples from the Fort Lee section were acquired at the map location of the sandwich horizon reported by Shirley (1987). Additionally, samples representative of major textural and compositional horizons of the sill from locations in Alpine, NJ and Piermont, NY were chosen for Sm–Nd isotope analysis. A complete list of samples analyzed, available metadata, major oxide and trace element chemistry is included in Table A1 in the Supplementary Materials.

3.2. Bulk rock chemistry

Major oxide concentrations were obtained through analysis of glass beads (Johnson et al., 1999) on a Philips PW 1400 X-ray fluorescence spectrometer at the Department of Earth and Atmospheric Sciences of The City College of New York except for samples as noted which were analyzed by fusion ICP-MS at Activation Laboratories, LTD in Canada or by microanalysis of polished glasses conducted on a Cameca SX-100 electron probe at the American Museum of Natural History operating at 15 kV accelerating voltage and 10 nA beam current. Trace element concentrations were obtained by ICP-MS at Activation Laboratories LTD, in Canada. The relative error is estimated at 2% for major oxides (up to 10% for Na_2O) and 1–15% for trace elements. Measured and certified values for trace element values of USGS standards BIR-1 and DNC-1 are included with the data.

3.3. Mineral chemistry and electron microscopy

Minerals were identified on the basis of composition for representative Upper Nyack and Fort Lee ferrogranophyres and Upper Nyack ferrodiabases. Quantitative mineral chemistry was obtained on polished thin sections of ferrogranophyre samples RL-2, RL-7 (Upper Nyack) and sample F-2 (Fort Lee) at the American Museum of Natural History on a 5-spectrometer Cameca SX-100 electron microprobe operating at 15 kV accelerating voltage and 10 nA beam current. Analyses were calibrated using synthetic and natural standards and the total error is estimated at 1–2%. Semiquantitative mineral identification on polished thin sections was determined on Upper Nyack ferrodiabase sample R-14, ferrogranophyres R-30, and RL-2, and Fort Lee ferrogranophyre F-4 on a Zeiss Supra 55 V scanning electron microscope (SEM) equipped with energy dispersive x-ray analyzer (EDS) operating at 15 kV accelerating voltage and 15 nA beam current with a spot size of 1 μm. ZAF correction was applied to EDS compositions and compared to compositions of analogous samples obtained by electron microprobe.

3.4. Isotope analysis

Nd isotopic compositions and Sm–Nd concentrations were measured on a VG 54-30 thermal ionization mass spectrometer (TIMS) at the Lamont-Doherty Earth Observatory run in dynamic mode on whole rock samples prepared using standard chemical preparation procedures. Sm concentrations were measured on a VG Axiom MC-ICP-MS. Nd isotopes and Sm–Nd concentrations used a mixed ^{149}Sm–^{150}Nd spike using the total spiking method, i.e., the Nd isotope ratio and concentration were measured on the same dissolution. $^{143}Nd/^{144}Nd$ ratios are corrected for instrumental mass fractionation relative to $^{146}Nd/^{144}Nd = 0.7219$ and normalized to a value of $^{143}Nd/^{144}Nd = 0.511860$ for the La Jolla standard which yielded a measured mean value of 0.511855 and external reproducibility of $2\sigma = \pm 0.000015$ ($n = 18$), which we take as the estimated error.

3.5. Solidification time calculation

Solidification time was calculated using the numerical solution of Shaw et al. (1977). A detailed procedure for the application of the model using the Crank and Nicolson (1947) implicit finite difference method is described by Philpotts and Ague (2009). The method employs a numerical solution to deriving solidification time by solving the one-dimensional form of Fourier's Law of Heat Conduction given by

$$\frac{dT}{dt} = k\left(\frac{d^2t}{dz^2}\right) \tag{1}$$

where T is the temperature, t is time, k is the thermal diffusivity (m/s^2), and z is distance across a grid with cell size δz. The temperature is obtained through calculation of heat flow across a series of cells. The amount of heat, Q, is determined by

$$Q = -\frac{K(\Delta T)A\delta t}{\delta z^2} \tag{2}$$

Where K is the thermal conductivity, ΔT is the change in temperature between adjacent cells, A is the cross-sectional area, which is derived from δt and δz. The change in heat content of a cell in the grid, δQ, depends on the change in temperature, δT, in the *ith* cell. The change in temperature, δT, is given by

$$\delta T = \frac{\delta Q}{C\rho V} \tag{3}$$

where C is the heat capacity, ρ is the density and V is the volume, and which for cells can be expressed as

$$\delta T_i = k\frac{\delta t}{(\delta z)^2}(T_{i+1} - 2T_1 + T_{i-1}) \tag{4}$$

and temperature is a function of δt and δz, chosen so that $k\,\delta t/(\delta z)^2 \le 0.25$. The implicit finite-difference method of Crank and Nicolson (1947) was applied to Eq. (4) to obtain the temperature for each cell in the grid and generate a geothermal gradient at t = 0. Solidification time for a basaltic pulse was determined by introducing a thermal perturbation to the geothermal gradient at the desired depth and running the numerical model to obtain the time elapsed before relaxation of the gradient to a particular temperature.

4. Results

4.1. Major oxide bulk chemistry

The bulk composition of the Upper Nyack suite is reported in Table A.1 (in the Supplementary Materials). Major oxide variations with stratigraphic height in the sill are plotted in Fig. 2(a–e) along with data from the section at Fort Lee (data from Shirley, 1987). SiO_2 concentration ranges from ~50 wt.% to ~53% for most samples from Upper Nyack with higher concentrations at 60 m, 180 m, and upwards of 195 m above the basal contact. Samples with SiO_2 concentrations lower than 50 wt.% at Upper Nyack correspond to rocks containing high concentrations of TiO_2 (Fig. 2b) and FeO_T (Fig. 2c), indicative of crystallization of titanomagnetite (discussed below in further detail). MgO concentration at Upper Nyack is highest from the basal contact to 25 m attaining a maximum of ~7 wt.%, then slowly decreases with stratigraphic height to produce an S-shape profile also found at Fort Lee (Puffer et al, 2009) that is typical of layered intrusions (see for example Gibb and Henderson, 2006). However, the trend is less prominent than the profile observed at Fort Lee (Fig. 2d). From 6 to 124 m, the majority of Upper Nyack samples have TiO_2 concentration between 1 wt.% to 2 wt.% and FeO_T values between 9 wt.% and 13 wt.%. These concentrations correspond to High-Titanium Quartz (HTQ; Weigand and Ragland, 1970) magma, which correlates with the Orange Mountain Basalt flow (Puffer et al., 2009) and Fort Lee rocks identified as Pulse 1 by Shirley (1987). At 84 m (sample R-14) and above 124 m at Upper Nyack TiO_2 increases, reaching values between 2 wt.% and 4 wt.% and FeO_T values of 14 wt.% to 18 wt.%, similar to the compositions approached by the iron-rich (14 wt.% to 16 wt.%) gabbroids and pegmatoids in the lowermost flow of the Preakness Basalt (Puffer and Volkert, 2001) and high-iron basalts of the third set of Watchung flows, the Hook Mountain Basalt (Fig. 3).

The concentration of K_2O at Upper Nyack is less than 0.9 wt.% from the basal contact to 160 m after which it increases sharply, reaching a maximum of ~3 wt.% (Fig. 2e), and indicating that approximately half the thickness of the Upper Nyack section consists of fractionation products. Together, major oxide variation indicates that most of the Upper Nyack Palisades is significantly more fractionated than sections south in New Jersey, such as in Fort Lee (Shirley, 1987), Englewood Cliffs, Weehawken, and Union City (Walker, 1969).

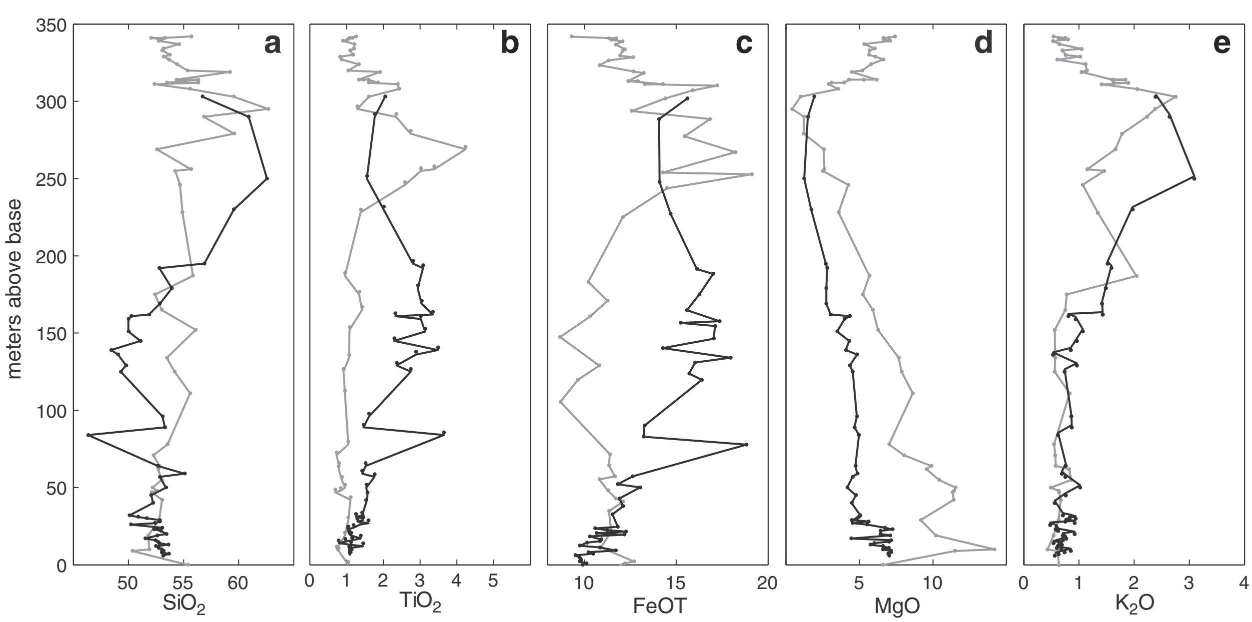

Fig. 2. Variation in concentration (wt.%) of SiO_2, TiO_2, FeO_T, MgO, and K_2O with stratigraphic height in Upper Nyack (black) and Fort Lee (gray; data from Shirley, 1987). Upper Nyack section exhibits high concentration of FeO_T and TiO_2 for more than 60% of its total thickness. High SiO_2 and K_2O from ~200 to 300 m in Upper Nyack constitute a much thicker horizon than at Fort Lee where similar rocks occupy a horizon from ~275 to 300 m.

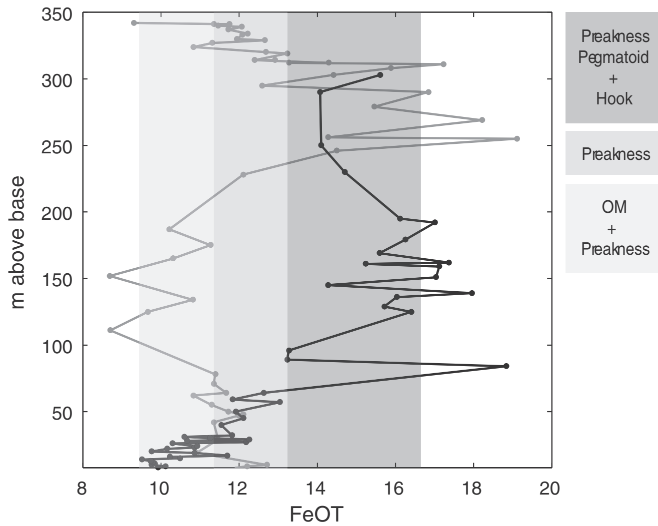

Fig. 3. FeO_T vs. stratigraphic height of Palisades rocks at Upper Nyack (black line) and Fort Lee (gray line) with shades areas designating the range of FeO_T in the Watchung flows. Watchung flows with lowest FeO_T content are LTQ magmas of the Orange Mountain Basalt (OM; data from Puffer, 1992) and parts of the Preakness Basalt (light gray shading; data from Puffer, 1992). Intermediate FeO_T compositions correspond to HTQ magmas that comprise the majority of the Preakness Basalt (medium gray shading). High FeO_T compositions fall in the range of Preakness pegmatoids (data from Puffer and Volkert, 2001) and the Hook Mountain Basalt (data from Puffer, 1992).

4.2. Trace element chemistry

Trace element concentrations for a subset of Upper Nyack samples and the two Fort Lee samples are reported in Table A.1 (Supplementary Materials). The primitive mantle-normalized trace element distribution of Upper Nyack diabase, ferrodiabase and Upper Nyack and Fort Lee ferrogranophyres are shown in Fig. 4. Diabase (dashed black lines), ferrodiabase (solid black lines) and ferrogranophyres (gray lines) follow a pattern of increasing concentration in HFSE and REE as the magma becomes more fractionated. Variations in concentration of incompatible elements with stratigraphic height produce profiles (not shown) that mimic K_2O behavior (see Fig. 2e). High Th/La ratios (0.15–0.22) and a marked positive Pb anomaly are indicative of a continental crust component in the magma and is a feature commonly found in continental flood basalts. Sr and, in some rocks, Eu in the Upper Nyack diabase exhibit a flat profile, which may indicate that either compaction of the mush was not as prominent in Upper Nyack as in Fort Lee or cumulus plagioclase re-equilibrated with a later, more differentiated magma. However, negative anomalies of both elements in ferrodiabase and ferrogranophyres reflect depletion of Ca in the magma as a result of plagioclase-dominated fractionation. The largely uniform, parallel pattern in incompatible elements suggests a common magma source or that the source magmas were homogenized during transit to the near surface.

The concentration of copper is highly variable near the basal contact and in the mid- to upper section where the sill is most evolved. The concentration is 150 ppm from 30 m to 124 m after which it builds up to reach a maximum of 380 ppm at ~200 m. Wide fluctuations of Cu at the base of the Palisades sill are shown in Fig. 5. Even wider fluctuations of Cu are found near the base of comagmatic Palisades offshoots such as the Arlington Sill (Puffer, 1998; Puffer and Graham, 2005) and other Eastern North America CAMP sills that are associated with Cu ore deposits and have been interpreted as hydrothermal (Robinson, 1988).

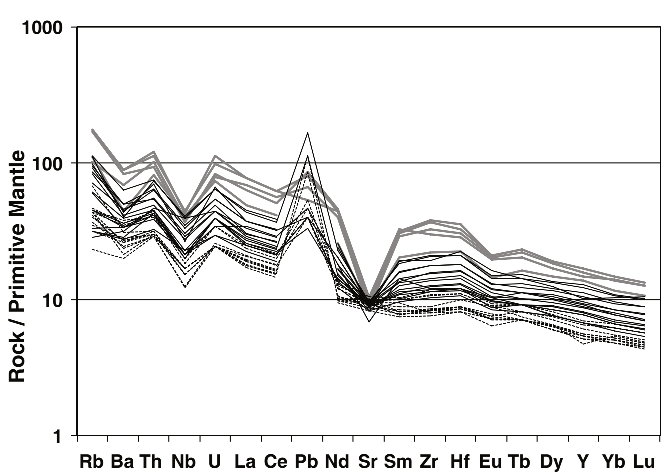

Fig. 4. Primitive mantle normalized trace element distribution in Upper Nyack diabase (dashed black lines), Upper Nyack ferrodiabase (solid black lines), and Upper Nyack and Fort Lee granophyres (gray lines). Similarities in the profiles indicate homogeneity in source magma and increases in concentration of nearly all the elements as the magma is progressively more fractionated. The pronounced Pb spike in the least fractionated rocks is indicative of continental material in the magma source and becomes less pronounced as the magma evolves. There is no positive europium anomaly in Upper Nyack diabase, indicating that filter pressing did not have a pronounced effect in Upper Nyack.

4.3. Sm–Nd isotopes

The 200 Ma age-corrected $^{143}Nd/^{144}Nd$ ratios in 10 samples of Palisades diabase and granophyres (Table 1) are within error of each other, falling within the narrow range 0.512320 to 0.512331 (average value = 0.512324) indicative of a common source for all of the Palisades samples. The εNd (200 Ma) values ranging from −1.0 to −1.2, are typical of continental flood basalts. Neodymium isotope ratios of country rocks and metasediment fall in the range expected for crustal sediments and reveal no mixing relationship with Palisades magma to produce granophyres (Fig. 6).

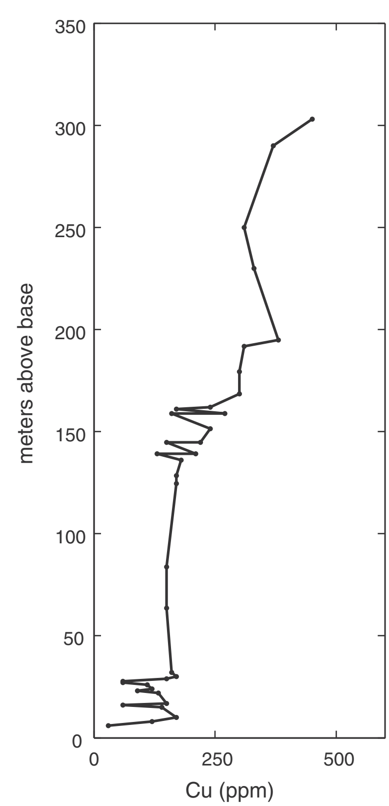

Fig. 5. Variation in copper concentration with stratigraphic height in Upper Nyack. Steady enrichment in Cu in reaching a maximum at ferrogranophyre horizon is indicative of a magmatic (hydrothermal) origin.

Table 1
Sm–Nd concentrations and isotopic results.

Sample	Rock type	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$^{143}Nd/^{144}Nd$	εNd
		ppm	ppm			(200 Ma)	
A-29	Diabase	3.07	12.5	0.1485	0.512514	0.512320	−2.4
A-RB	Diabase	3.22	13.0	0.1499	0.512522	0.512326	−2.3
KBPM-8	Diabase	2.82	11.6	0.1473	0.512514	0.512321	−2.4
C-23	Diabase	3.55	14.9	0.1438	0.512515	0.512326	−2.4
K-6	Diabase	4.83	20.6	0.1418	0.512516	0.512330	−2.4
R-29	Diabase	7.79	32.3	0.1459	0.512514	0.512323	−2.4
RL-2	Granophyre	11.7	50.3	0.1404	0.512511	0.512327	−2.5
RL-7	Granophyre	12.7	55.4	0.1390	0.512513	0.512331	−2.4
F-2	Granophyre	13.3	57.4	0.1403	0.512510	0.512326	−2.5
F-4	Granophyre	12.4	55.0	0.1364	0.512510	0.512331	−2.5
JJ4A	Hornfels	8.33	41.3	0.1220	0.512074	0.511915	−11
N-1	Hornfels	2.05	9.52	0.1298	0.512184	0.512014	−8.9
N-2	Hornfels	7.70	40.9	0.1138	0.512109	0.511960	−10
N-3	Shale	6.54	34.9	0.1133	0.512014	0.511866	−12
P-1	Hornfels	4.37	25.3	0.1042	0.512143	0.512007	−9.7
P-2	Sandstone	2.35	13.2	0.1077	0.512151	0.512010	−9.5

4.4. Petrography and mineral chemistry

4.4.1. Petrography

The rocks from Upper Nyack can be geochemically classified into three groups: ordinary diabase (9–13 wt.% FeO_T) in the lower one third of the section from 6 m to ~100 m, ferrodiabase (14–18 wt.% FeO_T) at 84 m and from ~124 m to ~200 m and ferrogranophyre (>14% FeO_T) from ~200 m to ~300 m. Thin section micrographs of samples representative of the three types and Fort Lee ferrogranophyres are shown in Fig. 7a–h. Diabase exhibiting typical subophitic texture with augite microphenocrysts and plagioclase laths, glomeroporphyritic clusters, and secondary titanomagnetite is shown in Fig. 6a and b, corresponding to sample R-6 (40 m). At 84 m where FeO_T reaches a maximum of 18%, the texture corresponds to a coarse ferrodiorite with abundant skeletal opaques, large euhedral plagioclase, and interstitial pyroxene (Fig. 7c and d). Higher in the section, (124 m to180 m) the ferrodiabase exhibits a similar texture to that observed at 84 m, however, there is evidence of alteration with hornblende replacement on pyroxene rims and partial sericitization of plagioclase. From 168 m to 250 m the most evolved differentiates are ferrogranophyres containing abundant interstitial myrmekite and opaques, and exhibiting evidence of hydrothermal alteration, shown in Fig. 7e and f. For comparison, micrographs of Fort Lee sandwich horizon sample F-4 (Fig. 7g and h) show significant deuteric alteration exemplified by pyroxenes almost entirely replaced by amphibole, sericitized plagioclase, and abundant myrmekite. The assemblages appear to have sheared during crystallization to produce a fabric reminiscent of metamorphic texture (Fig. 7h).

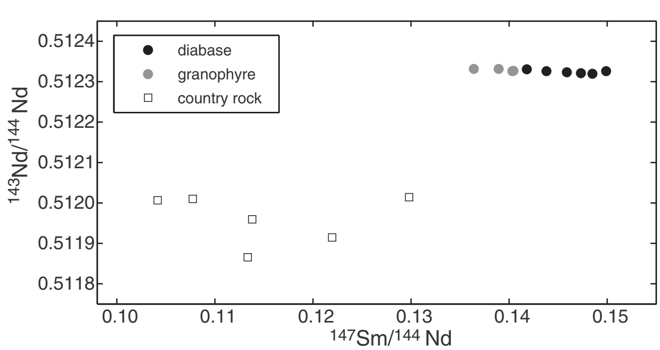

Fig. 6. Sm–Nd "isochron" plot showing sandwich granophyres (open circles), Palisades diabase (gray circles) and country rocks (filled circles). $^{143}Nd/^{144}Nd$ ratios are initial values at time of emplacement (200 Ma; Dunning and Hodych, 1990).

4.4.2. Electron microscopy and mineral chemistry

Mineral compositions analyzed by electron probe microanalysis and SEM-EDS are reported in Tables A.2 and A.3 (Supplementary Materials). Evolved iron-rich rocks dominate the Upper Nyack section starting at approximately 100 m above the base and encompassing ~30% of the intrusion and indicate the persistence of near closed-system fractionation conditions. Ferrodiabase sample R-14 contains opaques consisting of titanomagnetite with ferrian ilmenite lamellae surrounding inclusions of fayalite and quartz (Fig. 8a). Plagioclase is labradoritic and clinopyroxene is iron-rich, exhibiting some alteration to ferrohornblende. From ~200 m to 280 m (samples R-29, R-30, R-31) where the sill transitions from ferrodiabase to ferrogranophyre, the assemblages consist of ferroaugite with ferrohornblende rims, sodic plagioclase, apatite, and abundant interstitial myrmekite. (Fig. 8b; sample R-30). Skeleto-ilmenite remains of ilmeno-magnetite intergrowths are evidence of near complete leaching of the magnetite portion (Fig. 8c) of Fe–Ti opaques.

4.4.2.1. Comparison of sandwich horizon granophyres: Fort Lee and Upper Nyack. The final stages of crystallization, represented by Upper Nyack samples RL-2 and RL-7, and their analogs at Fort Lee, samples F-2 and F-4 are compositionally nearly identical (Table 2). However, the mineralogy and texture of ferrogranophyres at Upper Nyack is significantly different from Fort Lee (Fig. 9a–b).

Upper Nyack ferrogranophyres are finer-grained with crystal diameters in the range of hundreds of μm (Fig. 9a). The mineral assemblages at Upper Nyack include remnant ferroaugite often corroded or altering to Fe-biotite (annite), supporting the presence of higher temperature (magmatic) fluids post-crystallization. The mesostasis consists of pockets of oligoclase and myrmekite with accessory titanomagnetite and apatite. Ferrohornblende is a metasomatic product of pyroxene alteration. Plagioclase is pervasively sericitized. Fayalite alteration leads to annite + quartz, which is stable at 590–610 °C (Dachs and Benisek, 1995) under QFM fO_2 buffer conditions. This is consistent with the titanomagnetite–ferrian ilmenite exsolution also observed throughout the Upper Nyack section that corresponds to stability temperatures lower than 800 °C.

In contrast, ferrogranophyres at Fort Lee are coarse-grained, containing mm-size crystals and exhibiting signs of extensive metasomatic alteration (Fig. 9b). Deuteric assemblages consist of quartz, microperthitic anorthoclase, remnant plagioclase, and ferroaugites altered to amphibole. Microanalysis reveals that amphiboles are primarily ferrohornblendes with significant alteration to ferroactinolite. Microaplite (aggregates of K-feldspar, oligoclase, quartz myrmekite) occur in response to pressure

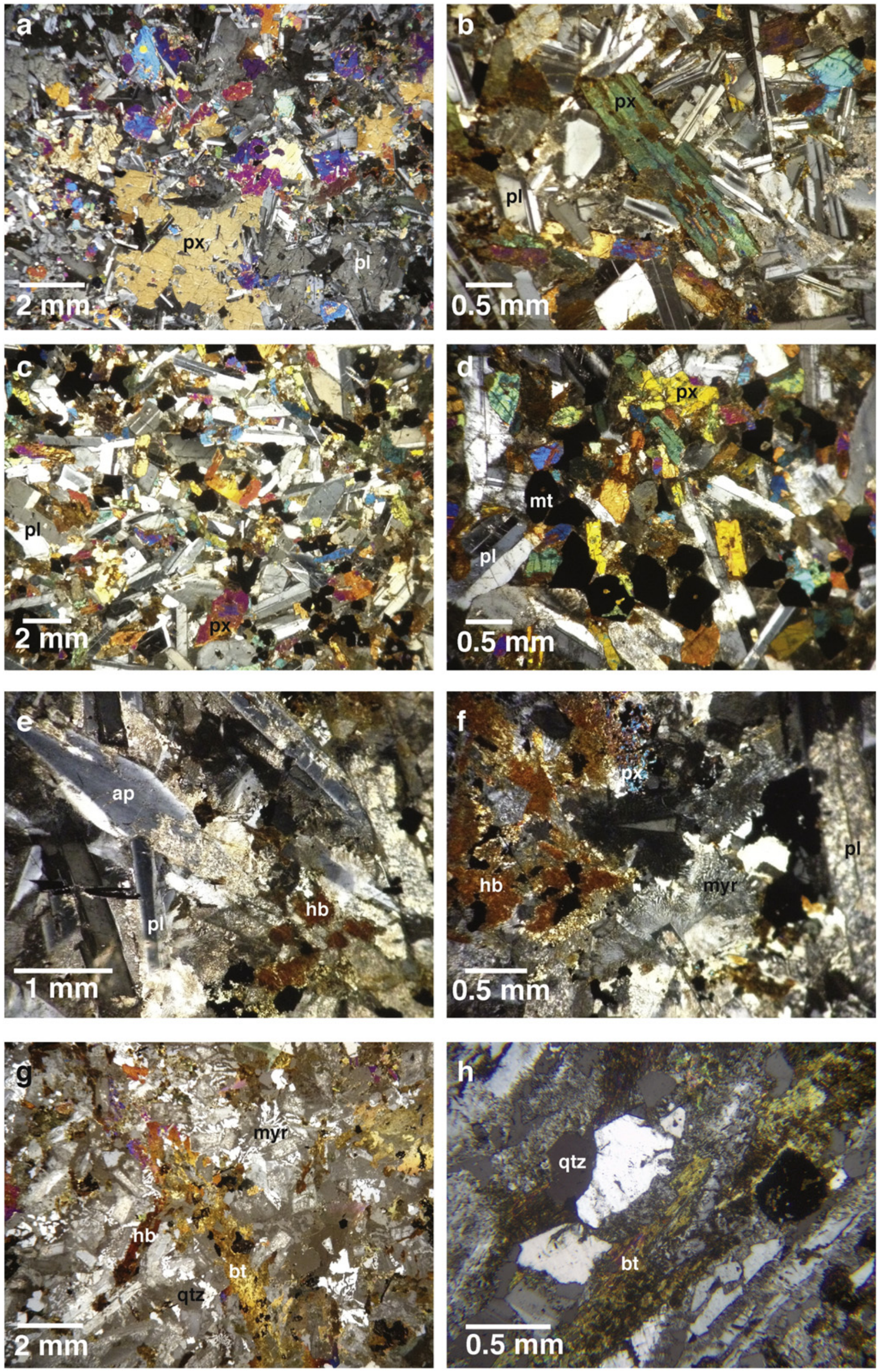

Fig. 7. (a–h). Representative thin section micrographs of Upper Nyack diabase, ferrodiabase, ferrogranophyres, and Fort Lee ferrogranophyres. a–b. Sample R-6 (diabase) exhibiting typical subophitic texture with minor interstitial opaques. c–d. Sample R-14 (ferrodiabase) exhibiting abundant skeletal opaques (magnetite) and near-equal amounts of pyroxene and plagioclase; some alteration of pyroxene at the rims is present. e–f. Sample RL-2 (ferrogranophyre) exhibiting large elongate plagioclase, partially sericitized; large apatite crystals, abundant myrmekite is present throughout the sample and pyroxene is almost entirely replaced by hornblende. g–h. Sample F-4 (ferrogranophyre, Fort Lee) is characterized by assemblages typical of crystallization under hydrothermal conditions; sericitized plagioclase, quartz, myrmekite, biotite, and amphibole are present throughout; microfabric in h. indicates shearing during the last stages of crystallization. Mineral abbreviations: plagioclase (pl), pyroxene (px), magnetite (mt), hornblende (hb), biotite (bt), quartz (qtz), myr (myrmekite).

quench. Together, the assemblage is here interpreted as the result of hydrothermal or metasomatic alteration post-crystallization.

The great majority of the opaques found concentrated in the ferrogranophyre is a second generation of Fe–Ti oxides precipitated out of deuteric fluids that postdate the primary precipitation of titanomagnetite. Iron leached from the ilmeno-magnetites in ferrodiabase was carried by the same deuteric fluids that partially hydrated the primary silicates of the ferrodiabase (plagioclase and pyroxene), altering them

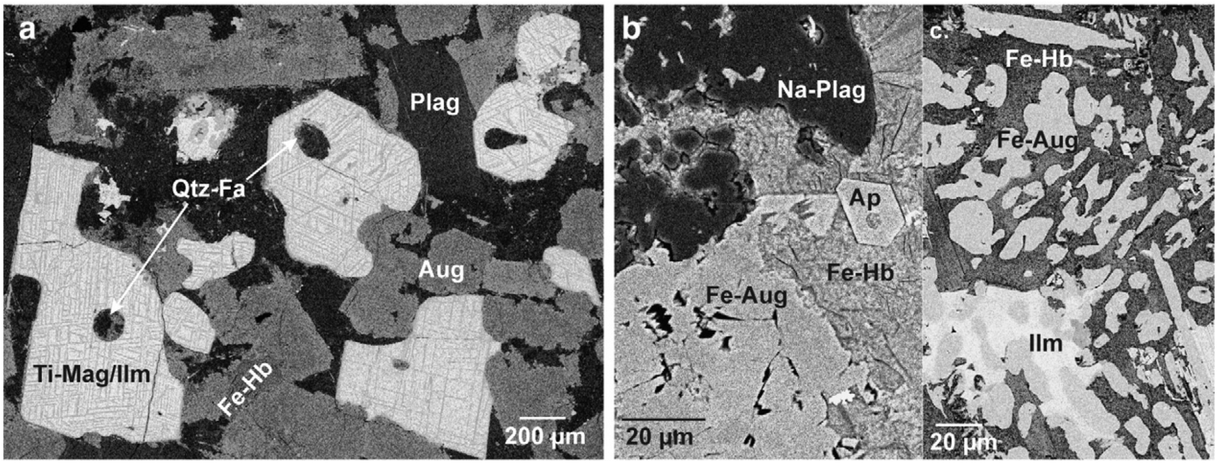

Fig. 8. (a–c). Scanning electron micrographs and mineral identification by EDS in Upper Nyack ferrodiabase and ferrogranophyre samples. a. Ferrodiabase sample R-14 (FeO_T = 18 wt.%) contains titanomagnetite grains (large white grains) with abundant ilmenite exsolution (darker crosshatch lamellae) with fayalite (Fa; lighter gray) and quartz (Qtz; black) inclusions. Some evidence of ferroaugite alteration to ferrohornblende is evident. b. Ferrogranophyre sample R-30 exhibiting abundant ferroaugite, ferrohornblende enclosing accessory apatite, and sodium plagioclase. c. Ferrohornblende after ferroaugite accompanied by remnant ilmenite after hydrothermal leaching of titanomagnetite in ferrogranophyre sample R-30.

into sericite and amphibole. The second generation of Fe–Ti oxide is easily distinguished from the primary magnetite on the basis of contrasting titanium contents. The secondary magnetite contains only 3% TiO_2 consistent with sub-igneous temperatures, below the 600 °C magnetite–ulvospinel solvus, while the primary magnetite contains 8% TiO_2, which together with coexisting ilmenite is consistent with 800 °C temperatures (Buddington and Lindsley, 1964). Similar iron–titanium oxide relationships were reported by Davidson and Wyllie (1968) in the diabase and granophyres of some eastern Pennsylvanian sills including the Dillsburg sill.

5. Discussion

5.1. Updip migration of fractionated liquids

At Upper Nyack ~50% of the sill thickness is comprised of fractionated liquids, with half of those being granophyres, precluding a mass balance with local cumulates. At this location, the sill occupies a higher stratigraphic level than the Fort Lee and other southern sections as it cuts across strata toward the surface. Furthermore, the late stage rocks at Upper Nyack have a distinct mineralogy from those at Fort Lee and comprise a larger fraction of the local sill thickness. In fact, the volume and mineralogy of rocks crystallized during the later stages varies greatly along the strike of the intrusion. Combining the petrographic and geochemical data from Fort Lee (Shirley, 1987 and this study), and Upper Nyack with data reported for Palisades exposures of the middle and upper horizons in Union City and Englewood Cliffs, NJ, reveals a broad cross-sectional trend corresponding to a northward increase in the fraction of evolved liquids occupying the total sill thickness (Fig. 10).

The mineralogy of late stage rocks varies greatly, and includes diagnostic late stage minerals such as quartz, hornblende, and biotite, variously identified as ferrohypersthene dolerite, fayalite granophyre, granophyre dolerite, and ferrodolerite (Table 3; data from Walker, 1969) and corresponding to rocks containing FeO_T >14 wt.% or SiO_2 >53 wt.%. Therefore, the increase in abundance of fractionated liquids northward along strike may be the result of pooling as buoyant, volatile-rich fluids that migrated updip (Fig. 11). Similar observations were reported by Husch (1992) for the diabase at Rocky Hill and in the Lambertville sill, both of which are members of the greater Palisades–Gettysburg sheet. Husch (1990) speculated that, for the Palisades sill, repeated inflation and injection of magma resulted in propagation of the sill away from its feeder, forcing residual liquid to migrate laterally and toward the surface. He described this process as “lateral flow differentiation” and, in conjunction with hydrothermal transport of fluids and residue, is also cited as a mechanism for the accumulation of granophyres in the York Haven diabase, a member of the greater Palisades-Gettysburg sheet (Mangan et al., 1993). In addition, lateral migration and filter pressing of late stage liquids was invoked by Froehlich and Gottfried (1988) to explain the pervasive lack of mass balance in the Culpeper Basin, Virginia. We interpret the granophyres of the Upper Nyack section as an extreme development of approximately the same process.

In Fort Lee, compaction and filter pressing led to expulsion of residue that accumulated as a sandwich horizon on the basis of a positive Eu anomaly in the cumulate rocks of the lowermost pulse (Shirley, 1987) and compression of plagioclase chain networks (Gray et al., 2003). However, there is no Eu anomaly at Upper Nyack (Fig. 4), suggesting that compaction may have had a lesser impact on expulsion of residue, or a different process contributed in the expulsion of interstitial residuum at this location. Srogi and Lutz (1996) showed that silicic residual liquid (58–73 wt.% SiO_2) can be efficiently transported away from a 75% crystallized mush by compositional or gravity convection induced by additional pulse influx. Srogi and Lutz (1996) also showed that this process is manifested in a scattering of Ba concentration relative to

Table 2
Major oxide composition and CIPW norms of selected Palisades granophyres. F-2 and F-4 are from Fort Lee, NJ, RL-2 and RL-7 are from Upper Nyack, NY.

	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
$Al2O_3$	11.41	11.71	11.68	11.69
FeO_T	15.61	14.07	14.7	14.1
MgO	1.94	1.49	1.73	1.25
CaO	4.75	3.07	5.64	3.3
Na_2O	1.2	1.42	0.37	1.6
K_2O	2.39	2.64	1.97	3.09
P_2O_5	2.78	1.97	3.0	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	15.6	11.64	18.26
Albite (Ab)	10.15	12.02	3.13	13.54
Anorthite (An)	5.42	2.37	8.4	3.45
Hypersthene (Hy)	30.1	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

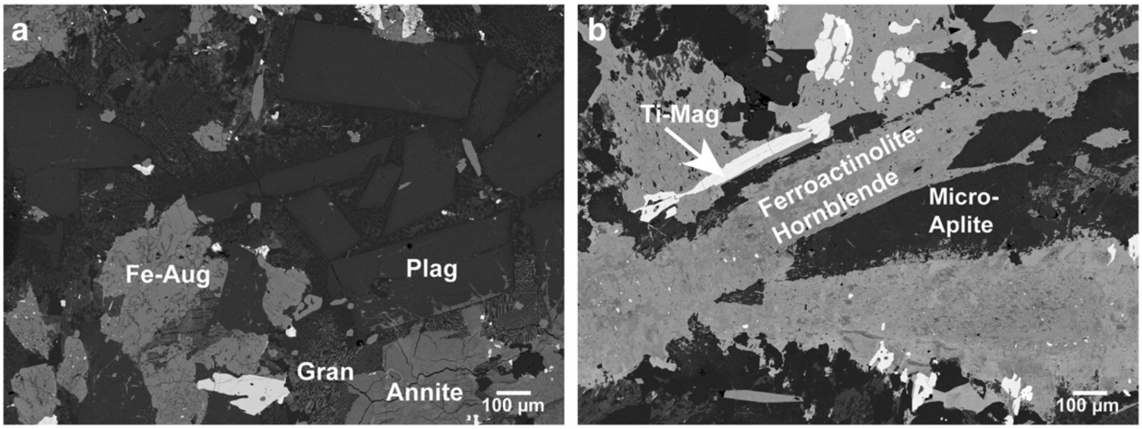

Fig. 9. (a–b). Scanning electron micrographs of ferrogranophyres in Upper Nyack and Fort Lee; Mineral identification by electron microprobe and EDS. a. Upper Nyack sample RL-2 exhibits crystal diameters of 100 to 400 μm, extensive quartz-albite granophyre (microaplite), and annite after biotite; b. Fort Lee sample F-4 exhibits mm-sized ferrohornblende with extensive metasomatic alteration to ferroactinolite. Microaplite is indicative of crystallization under hydrothermal conditions.

SiO_2, which we observed in our samples (Table A1; Supplementary Materials), and indicating a lack of equilibrium between the mush and residual liquid.

In addition, an absence of mass balance has been attributed to fractional crystallization and updip accumulation of residue, as reported for the Endion Sill, Duluth, Minnesota (Ernst, 1960), where more than half of the sill's thickness is composed of silicic rocks. The data presented here support the application of the Ernst (1960) interpretation to the Upper Nyack section.

5.2. Deuteric transport and alteration

The petrography of Upper Nyack granophyres supports crystallization under hydrous conditions that led to extensive crystallization of microaplite myrmekite. During fractional crystallization, magmatic volatiles carry residuum upward in the crystal mush, causing it to accumulate with the upper solidification front. However, the differences in mineralogy and texture in the ferrogranophyres of Upper Nyack and Fort Lee, signal that the two ferrogranophyres (Fig. 9) have been subjected to contrasting degrees of hydrothermal alteration and deformation in near-solidus conditions or post-crystallization. Similar observations have been made by Hotz (1953) and Gottfried et al. (1968) in the Dillsburg Sill. They found ample evidence of accumulation of residue through fractionation and also the presence of coarse and fine-grained

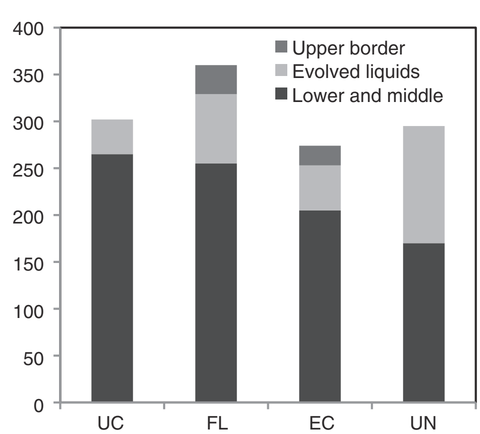

Fig. 10. Graph depicting increase in thickness of Palisades evolved liquids northward along the strike. Rocks identified as evolved liquids on the basis of petrography and total iron oxide (FeO_T > 14 wt.%) as reported in the literature and data from this study. UC is Union City, NJ, Fort Lee is Fort 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. UC and EC data is from Walker (1969); Fort Lee data from Shirley (1987); and UN (this study).

granophyres, such as those observed in Fort Lee and Upper Nyack, respectively. This signals the widespread redistribution of volatile-rich fluids enhanced hydrothermal circulation and alteration post-crystallization. Reheating of the sill through fresh addition of magma would have provided additional volatiles that contributed to alteration of granophyres post-crystallization, and produced iron enrichment throughout the Upper Nyack section.

Hydrothermal transport of iron was experimentally demonstrated by Martin and Piwinskii (1969) and was in all likelihood responsible for the network of magnetite veins in the Palisades-related Snake Hill dike (Puffer and Peters, 1974). A characteristic of the Snake Hill magnetite is the low (0.5 wt.%) sub-igneous TiO_2 content and the absence of co-existing ilmenite. In conjunction with anomalously high Cu concentration (400 ppm) at the level of the sandwich horizon in Upper Nyack (Fig. 5) and in other neighboring members of the CAMP, deuteric fluids appear to have significantly contributed to iron enrichment in the northern Palisades.

5.3. The role of deformation

The active extensional environment of the Newark Basin during intrusion of the Palisades may have also contributed to the accumulation of thick granophyres. Sheared or foliated textural fabric such as observed for Fort Lee (Fig. 7h) has been observed by Dick et al. (1991), Natland et al. (1991), and Natland and Dick (2001) in the upper 500 m of gabbros from Hole 735B in the Mid-Atlantic Ridge, which is attributed to "synkinematic deformation". In this process, the low porosity of adcumulates is overcome through deformation and fracturing, enabling the ascent of buoyant residuum and providing a path for basalt extrusion. In Hole 735B high iron differentiation caused by magmatic overpressure ends with a felsic product manifested as trondhjemite veins at the upper border that resemble a network of trondhjemite veins 0.2 to 1 m thick penetrating the Palisades near Fort Lee. The deformed rocks record discontinuous temperature stamps ("discontinuous crystallization"; after Bowen, 1920; also, "punctuated differentiation"; after Marsh, 1996). This process is considered pivotal to forming oceanic crust and may be important to the extrusion of voluminous basalts in extensional continental settings.

New injections of magma reopened the mostly crystallized Palisades over a protracted period, similar to the process of composite emplacement of magmas observed in the Beacon Sill (Zieg and Marsh, 2012). The low temperature assemblage of the granophyre close to "petrogeny's residua" of Bowen and Tuttle (1950) would remain at near solidus temperatures during hydrothermal conditions perpetuated by continued magmatism in the upper crust. Subsequent injection cycles capable of remelting or resorbing low temperature mineral

Table 3
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	

assemblages would displace interstitial residue updip by compositional convection (Srogi and Lutz, 1996) and by compaction of the crystal mush (Zieg and Marsh, 2012). Furthermore, a pathway for internal injection of multiple magma pulses could be maintained along sheared, low strength crystal mush zones in the interior of the Palisades as evidenced by cataclastic fabric and foliation of granophyres (Fig. 7h). In Upper Nyack, iron enrichment likely occurred during closed-system conditions that persisted during quiescent periods in the eruptive cycle. Mobilized volatiles would result in an extensive hydrothermal flow captured by altered minerals as far down as 84 m above the basal contact and pressure quench textures evident in Fort Lee and, in Upper Nyack granophyres (Fig. 7e–f.)

The persistence of a thick silica-rich layer in the Palisades with relatively low solidus temperatures may be indicative of the general role of evolved products of basaltic intrusion in the extrusion of flood basalts. The relationship of the Palisades as the coeval intrusive analog of the first set of Watchung flows, the Orange Mountain Basalt, is well established (Blackburn et al., 2013; Puffer, 1989; Puffer et al., 1981). However, though established geochemically (Puffer et al., 2009) the connection to the second set of flows is more tenuous due to a ~2.5×10^5 year gap between Palisades and Preakness ages (246 ka; Blackburn et al, 2013; 260 ka, Olsen et al., 1996). To examine the temporal feasibility of connecting the Palisades with the later Watchung flows, a one-dimensional numerical model (Shaw et al., 1977; see Methods section for details) was applied at time increments (δt) of 50 years and corresponding depth increment (δz) of 0.014 km. Starting with a geotherm of 20 °C, ten batches of basaltic magma with a thermal conductivity of 2.51 Wm^{-1} K^{-1}, were intruded at a depth of 4 km to achieve a total sill thickness of 400 m. Each pulse was allowed to cool to 800 °C before re-injection of subsequent pulses directly above previously emplaced magma. The total solidification time was determined to be ~6×10^3 years. However, deficiencies of applying this model include its failure to consider the role of deformation in addition to the assumption that each sequential pulse begins to cool as soon as the previous pulse reaches 800 °C. The model doesn't adjust for the duration of each pulse-flow event through the entire sill and across the full extent of the Newark Basin toward the edge of the CAMP boundary as estimated by McHone (2000), nor does it account for long periods of quiescence between re-injection events. While it is difficult to estimate the magnitude and variability of effusion rates, considerable time could be added to the 6×10^3 year calculation.

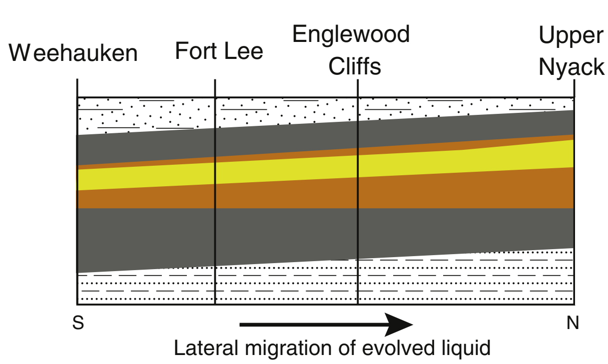

Fig. 11. Cartoon depicting the accumulation of evolved liquids updip and thickening of the total fraction of late-stage differentiates northward in the Palisades.

Considerably younger Palisades ages of ~197 Ma and ~195 Ma found for samples at 100 and 30 m, within the core of the Palisades were interpreted by Marzoli et al. (2011) as evidence of late injection of magmas transmitted via very low angle fault planes, supporting an extremely long time-scale of reactivation of the Palisades and related CAMP intrusives. Reopening of the sill through injection of magma into channels kept open during hydrothermal activity in conjunction with ongoing extension may have periodically fractured the sill reconciling the 10^4–10^5 time gap. As the only large intrusion in the Newark Basin geochemically correlated to the Preakness Basalt (Puffer et al., 2009), the Palisades is a compelling candidate despite a 250 ky time gap per the ages of Blackburn et al. (2013).

Connection of the early Palisades ages with the later extrusive flows requires processes that lengthen the time span for the formation of a composite intrusion or links the source of the Palisades with the source of the extrusives. The close geochemical resemblance between Upper Nyack ordinary diabase and the Preakness Basalt, and between Upper Nyack ferrodiabase and high-iron tholeiites of the CAMP, e.g., the third set of Watchung flood basalts, the Hook Mountain Basalt (Puffer and Volkert, 2001) and the Butner diabase of the Deep River Basin (Blackburn et al., 2013), strongly suggests that similar physical conditions may account for the geochemically correlative members and the unusually iron-rich rocks seen in some extrusive CAMP members. Shallow mafic sills such as in the Snake River Plain (Shervais et al., 2006) and in the Ferrar Dolerites (Marsh, 2004) have been found to be a part of a network of intrusions that feed extrusive flows. Similarly, it is likely that a network of interconnected sills and deeper magma chambers existed beneath the Newark Basin with the ability to store vast quantities of mush for as long as 10^5 to 10^6 years. Annen et al. (2006) modeled the effect of a series of small intrusions emplaced at the boundary of the upper and lower crust and found that the crust retains the memory of thermal anomalies for several million years, leaving it primed for remelting if subsequent magmatism occurs. In conjunction with thermal power generated by deeper source magma chambers the most evolved residual liquids in the Palisades may remain at near-solidus temperatures for as long as 10^4–10^5 years (Hawkesworth et al., 2000, 2004) and perpetuate a network of hydrothermal veins and vents that would have remained active during periods of relative eruptive quiescence. For Newark Basin magmatism to extend over 6×10^5 years with extrusive flows separated by more than 2×10^5 years as measured by U/Pb zircon dating (Blackburn et al., 2013) the existence of a long-lived source is clearly required.

5.4. Cyclical accumulation of late stage liquids and prolonged extrusion

A general conceptual model of the role accumulation of late stage liquids, periodic reinjection of magma in feeder sills similar to the Palisades, in the prolonged extrusion of flood basalts, e.g., the Orange Mountain Basalt is presented (Fig. 12). An initial pulse (L1) of magma is partially emplaced as a shallow intrusion and may erupt at the surface. The intruded pulse differentiates to produce cumulate and a differentiate (L1d/C1). A portion of the differentiate (L1d) may erupt at the surface while the remaining liquid follows a tholeiitic line of descent leading to evolved liquids (L1e) and eventually a granophyre (L1g) that segregates from the crystal mush by compaction and filter pressing (Gray et al., 2003; Shirley, 1987). The remaining silicic fraction serves as a path that can be reopened by subsequent pulses (Zieg and Marsh,

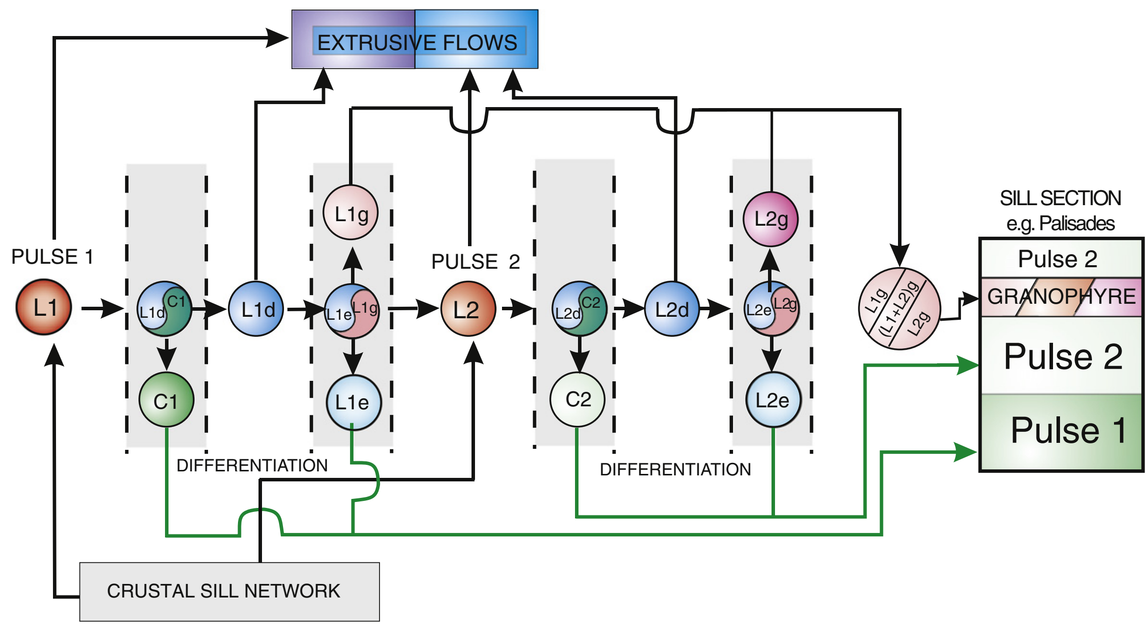

Fig. 12. Two-pulse model showing extrusive output to the Watchung Series, residuum accumulation in the sill, and the evolution of a composite granophyre. Pulse 1: Pulse 1 magma (L1) differentiates to produce a cumulate (C1) and differentiate (L1d). Residue is expelled from the mush through compaction and filter pressing and updip migration, and cooling to produce an evolved iron-rich liquid (L1e) and granophyre (L1g). Pulse 2: Pulse 2 (L2) reopens the sill partially mixing with the mush or resorbing the granophyric remnant (L1g). A second cumulate (C2) undergoes compaction to expelling a residue. The second injection event reheats existing mush and mobilizing trapped residuum by compositional convection to further accumulate evolved liquid. Composite granophyre: A horizon of iron- and silica-rich residuum located where the solidification fronts meet exhibits differing mineralogical and textural histories resulting from interaction with hydrothermal fluids and provides a long-lived weak layer subject to reopening in response to rifting and subsequent magmatic events.

2012). A second pulse (L2), mixes with the fractionated Pulse 1 (L1e/L1g). Compaction of the mush along with gravity convection (Srogi and Lutz, 1996), mobilize residual liquid from the mush, transporting residue updip and away from the feeder. The second set of differentiates (L2d) and evolved liquids (L2e/L2g) proceed as in the case of L1d. The process continues for subsequent pulses resulting in reworking and reheating of previous pulses that propagate the sill and facilitate the upward transport of residue in the magmatic column. For bowl-shaped sills or discordant tabular intrusions such as the northern limb of the Palisades, this results in accumulation of the residual liquid at shallower levels. In cases where pyroxene fractionation dominates the resulting late stage liquids are more silica-rich and iron-poor, which may be represented by the latter stage Upper Nyack rocks present between 200 m and 300 m above the basal contact.

6. Conclusions

A thick horizon of iron-rich evolved magmas in the Palisades at Upper Nyack occupies more than half the local thickness of the sill. The Nd-isotope composition of the granophyres is nearly identical to the rest of the Palisades, indicating that assimilation of country rock was negligible and that fractionation-related processes dominated during the evolution and crystallization of felsic late stage rocks. A lack of mass balance between evolved liquids and ordinary cumulates support the expulsion of residual liquid via compaction and lateral migration of the evolved liquid northward and closer to the surface. Subsequent magmatic pulses reheated the mush, mobilizing copper, iron and volatiles that resulted in extensive metasomatic alteration and deposition of secondary magnetite precipitated by deuteric hydrothermal fluids as they interacted with the final products of crystallization. Reheating and deformation as a result of rifting facilitated the migration of fractionated magma and trapped residuum upwards in the mush column to the top of the pile with each incremental magmatic pulse. The process is similar to deformation of residuum in mid-ocean ridge gabbros that enable magma to travel to the surface during continued growth of the oceanic crust. In the Palisades, each added magma pulse pushed the remaining melt laterally and updip, shearing the residuum before it completely solidified, resulting in accumulation of ferrogranophyre where the sill is closest to the surface. The low-temperature assemblages of the accumulated residue and long-lived hydrothermal conditions indicate that the horizon may have been able to persist as a weak layer conducive to penetration by later pulses, conditions likely to have occurred throughout a sub-Newark Basin network of upper crustal intrusions that provided a means for extrusion of flood basalts of the Watchung flows through 600 ka.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.lithos.2015.05.018. These data include Google map of the most important areas described in this article.

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