Transmission of Flood Basalts through a Shallow Crustal Sill and the Correlation of Sill Layers with Extrusive Flows: The Palisades Intrusive System and the Basalts of the Newark Basin, New Jersey, U.S.A.

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ABSTRACT

The Palisades Intrusive System consists of a 350-m-thick early Jurassic sill together with thinner comagmatic sills and dikes exposed within the Newark Basin of New Jersey and New York. The Palisades System is overlain by flood basalt that is interbedded with early Jurassic redbed formations. New and recently published data indicate that some of the basalt flows correlate with geochemically defined layers within a central well-exposed sill portion of the Palisades System at Fort Lee, New Jersey. Our interpretation views the sill as a progressively inflated conduit through which huge volumes of flood basalt flowed. The geochemical data are consistent with a Palisades sill fed by three compositionally distinct intrusion events. The first magma flowed through the sill and broke out near the northern end as three Orange Mountain basalt flows. Each of the three extrusive pulses is identified within the lower 150 m of the sill on the basis of distinct geochemical reversals. The end stage of each pulse was characterized by pyroxene phenocryst accumulation within the sill. Magma from a second source inflated the sill by an additional 170 m after approximately 260 k.yr. of minor intermittent igneous activity interbedded with sediments deposited above the Orange Mountain basalt. The second magma extruded as a highly fractionated 150-m-thick Preakness basalt flow and crystallized as a 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. We interpret the distinct layering of the Palisades sill as injections of magmas that were largely prefractionated at deeper levels and then modified to varying degrees by in situ processes.

Online enhancements: appendix tables.

Introduction

In addition to the Palisades sill and Newark Basin flood basalt sequence, thick layered sills occur as integral parts of most, if not all, flood basalt provinces. Some of these sills were sites where fractionation, contamination, or other processes may have controlled the composition of overlying comagmatic flows. For example, Shervais et al. (2006) proposed that cyclic chemical variations among the Snake River basalts of eastern Oregon and Idaho reflect fractionation and/or recharge cycles in a 10-km-thick series of sill-like intrusions imaged seismically at approximately 12–22-km depth. In addition, Durand and Sen (2004) concluded that the chemically evolved Grande Ronde basalt of the Columbia River Group is the product of fractionation, magma mixing, and degassing in a shallow intrusive network before eruption.

However, the Palisades sill is not thick enough and does not contain enough cumulate to have significantly influenced the huge outpourings of flood basalts that extruded across the Newark Basin and beyond. This is supported by the fact that the basalts of the Newark Basin are virtually identical to the dike-fed basalts of the Hartford Basin of Connecticut (Puffer and Philpotts 1988), which are not underlain by shallow sills. Instead, magmas that intruded into the Palisades sill are similar to the overlying basalts, both of which may be

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fractionation crustal contamination products of thicker and deeper magma chambers.

Our article does not address the initial source or deep crustal plumbing of Palisades magmas but does focus on three perplexing issues that relate to the association of sills with flood basalts: (1) the extent to which shallow sills were conduits through which flood basalts were transmitted, (2) the degree to which any sill layering was the product of in situ fractionation versus multiple intrusion of dissimilar magma pulses, and (3) the degree to which individual sill layers can be stratigraphically correlated with comagmatic basalts flows.

With respect to the first issue, flood basalts are typically modeled as products of dike-fed fissure eruptions. However, the shallow crustal pluming directly beneath flood basalts can be complex and can include an important role for sills. Thomson (2007) presented three-dimensional seismic imaging of a complex array of intersecting dikes and concave-upward sills with flat, central, deep portions surrounded by steeply inclined peripheries beneath the Faroe-Shetland flood basalts of the northwest European continental margin. He was able to trace magma flow from a feeder dike into a sill with a branching and climbing structure and then from the sill edge to a volcanic ridge. He was also able to image sills that merge with and feed overlying sills.

The northern edge of the Palisades sill also becomes inclined to the intruded strata, similar to typical saucer-shaped sills. Magnetic, gravity (Kodama 1983), and geochemical evidence (Puffer et al. 1982; Ratcliffe 1988) clearly demonstrates a northern surface breakout position for the Palisades sill where it is physically connected to some outpourings of basalt (Ladentown basalt). However, we will demonstrate that the entire 150-m-thick sequence of Orange Mountain basalt and the entire 320-m-thick sequence of Preakness basalt probably also flowed through the Palisades sill on their way to the surface.

With respect to the second issue, layering within thick diabase sills has been typically interpreted as the result of various closed-system, in situ fractionation processes such as crystal settling, convective flow, filter pressing, and Soret diffusion. However, during the last few years several thick-layered sills have been interpreted or reinterpreted as products of multiple magma injections or as part of magmatic mush column conduit systems (Marsh 2004) on the basis of a variety of evidence. Some notable examples include (1) the Shiant Isles main sill, NW Scotland, on the basis of geochemical evidence, particularly compositional reversals (Gibb and Henderson 2006); (2) the Graveyard Point sill in the western Snake River Plain, on the basis of abrupt chemical and mineralogical discontinuities between layers plus a lack of mass balance between the bulk sill and its chilled margins (White 2007); (3) the Muran sill of Dronning Maud Land, Antarctica, on the basis of chemical distinctions between a homogeneous lower zone and a geochemically differentiated upper zone (Vuori and Luttinen 2003); (4) the Insizwa sill of the Karoo Province, South Africa, on the basis of the anisotropy of magnetic susceptibility evidence (Maes et al. 2008); and (5) the Nipigon diabase sill associated with the Midcontinent Rift large igneous province (LIP), on the basis of crystal size distribution analysis (Forsha and Zieg 2006).

Several researchers have presented evidenced that the Palisades sill is also composite. Most recently Gorring and Naslund (1995) used compositional reversal near the base of the Palisades sill to demonstrate that at least two pulses of a similar (high-titanium quartz tholeiite–type) magma intruded the sill. However, they interpret most internal layering, as do most Palisades researchers, including Walker (1969) and Shirley (1987), as the product of in situ fractionation. We also recognize that an important in situ fractionation process took place within the Palisades sill (Steiner et al. 1992; Block et al. 2007) but will provide a new interpretation that most large-scale layering was caused by multiple injections of three dissimilar magmas on the basis of all available geochemical evidence, both new and previously published.

The third issue (correlation of layers with basalt flows) is rarely addressed. Seifert and Olmsted (2004) conclude on the basis of geochemical evidence that the sills of the North Shore Hypabyssal Group correlate with the "type 4" basalts that are common throughout the diverse North Shore Volcanic Group within the Midcontinent Rift of Minnesota; however, individual sill layers are not correlated. Ratcliffe (1988) used geochemical data to correlate the Ladentown and Orange Mountain basalts of New Jersey with portions of the Palisades sill; however, again, interior Palisades layers are not correlated with individual flows. We agree with the tentative correlations of Ratcliffe (1988) and provide new evidence that the lower Palisades layers correlate with Orange Mountain and Ladentown flows, whereas the upper Palisades layers correlate with Preakness flows. We will also present geochemical-based stratigraphic evidence that intermittent flow of hot magma throughout the Orange Mountain and Preakness extrusive cycle

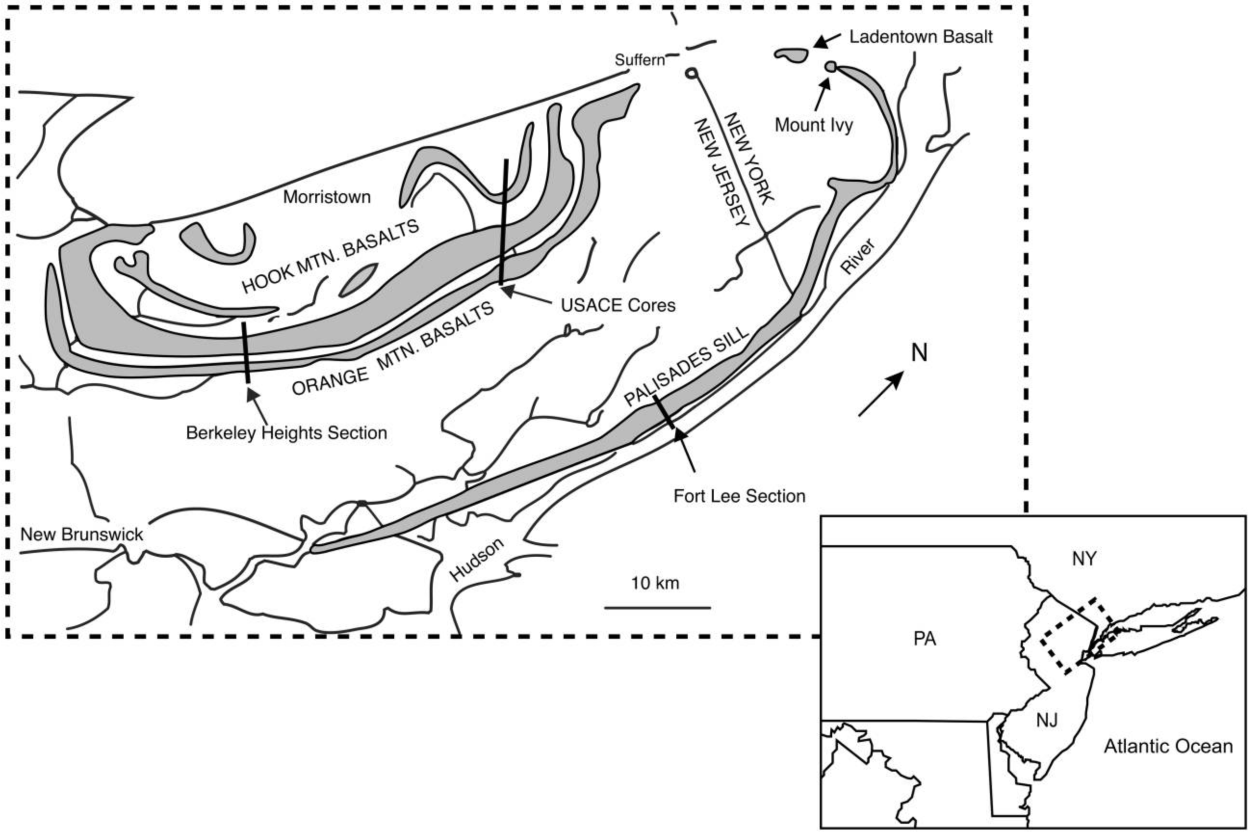

Figure 1. Distribution of early Jurassic igneous rocks throughout the northern Newark Basin indicating the locations of data sources, including the Berkeley Heights section (Puffer 1992; Puffer and Volkert 2001; new data), the U.S. Army Corps of Engineers (USACE) drill cores (Tollo and Gottfried 1992), the Fort Lee section (Shirley 1987; Gorring and Naslund 1995; new data), and the Ladentown basalt exposures (Ratcliffe 1988; new data). The location of the Newark Basin basalts discussed in this study relative to eastern North America is shown in the inset.

enabled the Palisades sill to remain above solidus temperatures for approximately 260 k.yr.

We present a new and comprehensive overview of the geochemical basis for the correlation of the Newark Basin flood basalts with individual horizons in the Palisades by using the well-exposed Fort Lee section in New Jersey (fig. 1) as a type section. The Palisades Intrusive System of New Jersey and New York (Puffer and Husch 1996) includes the Palisades proper (the historical section extending from approximately the George Washington Bridge to Haverstraw, New York, along the Hudson River) and 16 additional early Jurassic diabase sheets exposed throughout the Newark Basin. However, the Hudson River sheet is thicker (300–400 m) than the other diabase sheets. The present overview is intended as a model for the plumbing system associated with rifting margins where flood basalt magmas have been produced. Although several exposures along the Hudson River have been studied, sections through and close to Fort Lee, New Jersey (fig. 1), have undergone multiple studies, including detailed, closely spaced sampling and analyses (Walker 1940, 1969; Pearce 1970; Shirley 1987; Gottfried et al.1991*b*; Gorring and Naslund 1995). We propose that this portion of the sill provides the best evidence that the intrusive system is the probable conduit through which multiple pulses of magma were extruded into the Mesozoic Newark Basin. We suggest that the distinct compositional character of each intrusive pulse is regulated by deep chamber processes associated with the rifting event.

Stratigraphy and Petrology

The igneous rocks of the central Newark Basin (fig. 2) include the Palisades Intrusive System and three basalt formations (the Orange Mountain

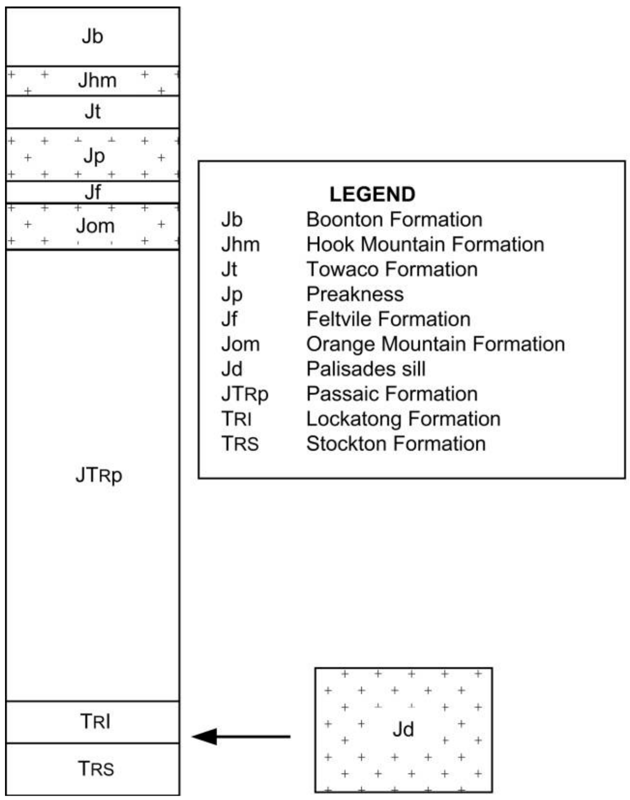

Figure 2. Stratigraphy of the Triassic and Jurassic rocks of the Newark Basin, New Jersey and New York. The Orange Mountain, Preakness, and Hook Mountain basalts are referred to by Olsen (1980) as the basalt formations of the Newark Basin but are informally known as the Watchung basalts.

basalt, the Preakness basalt, and the Hook Mountain basalt) that stratigraphically overlie the Palisades intrusions. These extrusive units are interbedded by redbed sedimentary rock units deposited in a shallow-water or subaerial environment containing dinosaur, reptile, and plant remains (Olsen et al. 2003). Basalt and diabase formations are also exposed throughout eastern North American (ENA) Mesozoic basins located north and south of the Newark Basin (Puffer 1992) and throughout the Central Atlantic Magmatic Province (CAMP; Marzoli et al. 1999).

The Palisades Intrusive System. The Palisades Intrusive System consists of an early Jurassic composite sill together with a network of thinner comagmatic sills and dikes exposed within the Newark Basin of New Jersey and New York. The Palisades sill portion of the system is mapped by Drake et al. (1996) as early Jurassic 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 360–400 m thick (Drake et al. 1996) but is typically just over 300 m thick.

The Palisades System includes 16 additional early Jurassic diabase intrusive sills or sheets in the Newark Basin exposed west of the Palisades sill, identified by Gottfried et al. (1991*a*, 1991*b*) as comagmatic on the basis of similar chilled-margin compositions. Husch (1992) 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. He proposed that geochemical variations correlate with distance from a western source and proposed that the effects of lateral flow differentiation increase toward the east. Steiner et al. (1992) used 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 Orange Mountain Basalt. The Orange Mountain basalt (140–180 m thick) is a uniformly fine-grained quartz tholeiite composed of calcic plagioclase and clinopyroxene, with minor orthopyroxene crystals located at the center of glomeroporphyritic clusters. The formation consists of three flows of uniform compositions characterized by vesicular flow tops separated by weathered zones and thin discontinuous beds of reddish-brown siltstone. The maximum thicknesses of the three Orange Mountain flows measure about 80, 40, and 60 m (Puffer and Student 1992) but total about 150 m at Berkeley Heights (fig. 1).

The Preakness Basalt. The Preakness basalt (280 m thick at Berkeley Heights) is a fine- to coarse-grained aphyric quartz tholeiite composed mainly of calcic plagioclase and clinopyroxene, but unlike the Orange Mountain it is very heterogeneous. The Preakness basalt consists of two major flows characterized by vesicular flow tops and three minor upper flows. The first flow ranges in thickness from 127 to 157 m and contains thick, discontinuous, coarse-grained gabbroid layers, described by Puffer and Volkert (2001). This first flow is overlain by a 2–8-m-thick reddish-brown siltstone bed. The second flow is about 60–80 m thick and is overlain by a reddish-brown siltstone bed about 1 m thick. The upper three flows are thin, discontinuous, and not well exposed, with a combined thickness of about 45 m (Puffer and Volkert 2001). An additional Preakness flow occurs at the base of the formation throughout the northern portion of the Newark Basin. This basal flow is about 10 m thick and is distinctly vesicular to scoraceous. The chemical composition of the 10-m basal flow is virtually the same as the lower 10 m of the overlying 127–157-m flow (Tollo and Gottfried 1992). The paleomagnetic polarity of the 10-m basal flow, however, contrasts with the upper Preakness flows but correlates with the first of two thick Holyoke flows exposed within the Hartford Basin (Kent and Olsen 2008). The Preakness basalt is petrologically and geochemically almost as diverse as the Palisades intrusions.

The Hook Mountain Basalt. The Hook Mountain basalt (110 m thick) is a fine-grained to locally coarse-grained amygdaloidal quartz tholeiite composed mainly of plagioclase, clinopyroxene, and iron-titanium oxides. The Hook Mountain basalt consists of three major flows, characterized by highly vesicular to amygdaloidal flow tops. The stratigraphic relationship of the Hook Mountain basalt to the other igneous and sedimentary units in the Newark Basin is illustrated in figure 2. However, stratigraphic evidence (Olsen et al. 2003) indicates that Hook Mountain basalt did not extrude until about 0.6 Ma after the Palisades sill intruded, making a comagmatic correlation with Palisades dolerite much less likely than with Orange Mountain or Preakness flows.

ENA Correlatives. In addition to the Newark Basin, ENA basalt flows similar to the Orange Mountain basalt are found in the Fundy, Hartford, Gettysburg, and Culpepper basins (Puffer 1992) and tend to become thicker and more abundant toward the north. Basalt flows similar to the Preakness basalt, however, are not found north of the Hartford Basin and tend to become thicker toward the south. The distribution of Preakness-like flows generally correlates with the distribution of thick diabase sheets similar to the Palisades. With the exception of the Holyoke basalt of the Hartford Basin, each Preakness-like basalt formation is located near a thick diabase sheet. Such thick sheets are rare north of the Newark Basin but are common in the Gettysburg Basin (Smith et al. 1975) and the Culpeper Basin (Froelich and Gottfried 1988) to the south. For example, a Preakness-like Sander flow measuring 230 m thick is located near the 366-m-thick Belmont sill of the Culpepper Basin. Apparently, the physical conditions conducive to the development of thick sheets such as the Palisades enhance the development of unusually thick flows such as the lower Preakness flow.

Geochemical Data

Analytical Procedure. All rock samples represented in tables A1–A4, available in the online edition or from the *Journal of Geology* office, except for samples L-2 and MI-1KB, were analyzed at the Rutgers University Geochemistry Laboratory, using a Rigaku 3030 x-ray fluorescence (XRF) spectrometer. Care was taken to avoid weathered samples during collection, and steel equipment that might have led to Cr contamination was avoided. The data are averaged from three separate analytical runs of the same disk through the instrument. The XRF instrument was calibrated with several USGS rock standards, including BHVO-2, W-2, AGV-2, GSP-2, BIR-1, and G-2. Precision was based on 10 runs of basalt standard BCR-2 that were not used to plot the calibration curve. The results were consistently reproducible to well within 1.5 relative percent, except for Ba, Ni, Cr, and Y (3.0, 4.5, 2.3, and 5.0 relative percent, respectively).

Bulk analyses for samples L-2 and MI-1KB were conducted on borate-fused pellets prepared by the method of Johnson et al. (1999) on a Phillips PW 1400 XRF spectrometer calibrated to standards BHVO-2, W-2, AGV-2, GSP-2, BIR-1, and G-2 at the X-Ray Laboratory of the City College of New York. Trace and rare earth elements represented in table A5, available in the online edition or from the *Journal of Geology* office, were analyzed by inductively coupled plasma mass spectrometry at Activation Laboratories (Ontario).

Analytical Results. The analytical data presented in tables A1–A5, combined with previously published data, are the geochemical basis of our research. The analytical results of Orange Mountain basalt (table A1) sampled along the Berkeley Heights section (fig. 1) from map locations described by Puffer (1992) closely agree with the analyses of Tollo and Gottfried (1992) from the U.S. Army Corps of Engineers (USACE) drill core (fig. 1) and illustrate the high degree of chemical uniformity among Orange Mountain flows. The Orange Mountain data presented in table A1 are also compared with the published data of Gorring and Naslund (1995), Gottfried et al. (1991*a*, 1991*b*), and Shirley (1987) pertaining to the lower layers of the composite Palisades sill. Data from Shirley (1987) were downloaded from PetDB (http://www.petdb.org; Lehnert et al. 2000).

The analyses of the Preakness basalt (flow P-1, table A2; flows P-2 and P-3, table A3) sampled along the Berkeley Heights section (fig. 1) from locations described by Puffer and Volkert (2001) and Puffer (1992) also closely agree with the analyses of Tollo and Gottfried (1992) from the ACE drill core (fig. 1) and confirm a very high degree of chemical diversity among Preakness flows. The Preakness data of tables A2 and A3 compare closely with published data pertaining to mid- and upper layers of the Palisades sill (Shirley 1987; Gottfried et al. 1991*a*, 1991*b*) and indicate the potential for geochemical correlations.

The new analyses of the Palisades sill near Fort Lee (table A4) collected 0.2–2 m above the base of the sill (table A4) are compared with Orange Mountain basalt compositions from the Berkeley Heights section and further support geochemical correlations. Our new analyses of Ladentown basalt (tables A1, A5) and Palisades diabase at Mount Ivy (tables A4, A5) indicate virtually identical compositions that are also compared with Orange Mountain basalt and the Palisades chill zone at Fort Lee to show that they are fractionation products of Orange Mountain magma.

Intrusion-Extrusion Correlations

The correlations proposed here argue that the interior portions of the Palisades sill maintained a long-lived crystal mush replenished by multiple magma pulses over a long-standing inflationary period. Our proposals are consistent with Gibb and Henderson's (1992) observation that fluid dynamic theory together with abundant petrographic and geochemical data yield strong evidence that thick sills are rarely intruded as single-pulse events. We agree with their conclusion that sills are open-system conduits for through-going pulses that can be active over a protracted interval of time.

Our correlation proposals are based largely on geochemical evidence, particularly the distribution of incompatible elements Ti and Fe plotted against compatible elements Mg and Cr and plotted against stratigraphic position. Trace element distribution patterns were also examined.

Mg, Fe, and Ti Distribution. Weigand and Ragland (1970) recognized four populations of ENA Mesozoic dolerites based largely on Ti, Fe, and Mg content. The four populations were designated high-titanium quartz tholeiite (HTQ), low-titanium quartz tholeiite (LTQ), high-iron quartz tholeiite (HFQ), and olivine-normative tholeiite (OLN). Tollo and Gottfried (1992) recognized three of these magma types among the basalts of the Newark Basin, HTQ Orange Mountain basalt, HFQ lower Preakness basalt, LTQ upper Preakness basalt, and HFQ Hook Mountain basalt, and interpreted them as separate magma batches. More recently, these population designations have been reassigned to new classification systems that pertain to the entire CAMP LIP, particularly Marzoli et al. (1999) and Salters et al. (2003); however, the Weigand and Ragland (1970) classification, as revised by Ragland et al. (1992), remains valid as it pertains to eastern North America.

Gottfried et al. (1991*a*, 1991*b*) classified each of the 17 intrusions in the Newark Basin as members of the HTQ population, including the Palisades sill, based largely on chill zone compositions. The HTQ tholeiites are characterized by a very narrow range of TiO_2 (1.0%–1.3%) and MgO (7.0%–8.0%), which agrees with each of four Palisades chill zone samples collected within 2 m of the lower exterior contact and analyzed by Shirley (1987), five samples analyzed by Gorring and Naslund (1995), and six samples from the lower 2-m chill zone of the Palisades at Fort Lee (this study; table A4).

Each of these chill zone samples together with each of the 15 samples of Orange Mountain basalt from Berkeley Heights (table A1) plot within a very tight cluster of HTQ data (fig. 3). We interpret this close overlap as evidence of a comagmatic relationship and designate the magma as "magma 1."

None of the samples from the interior of the Palisades or from the Preakness basalt plots within the HTQ cluster. However, each sample from the lower half of the Palisades sill, within 150 m above the base, plots along a titanium-enrichment trend that intersects the HTQ field (fig. 3).

The Palisades sill layer above the 150-m level up to the 319 level plots along a scattered titanium-enrichment trend that overlaps the equally scattered first (P-1) Preakness flow (fig. 3). This second trend line is not a linear extension of the magma 1 trend and is designated magma 2. Most of the P-1 Preakness samples along the magma 2 trend plot within the HFQ magma field. We therefore agree with Tollo and Gottfried's (1992) HFQ designation for the Preakness P-1 flow and propose that the overlapping interior Palisades layer is comagmatic. Considerable scatter among P-1 flow and mid-Palisades samples is interpreted as the result of complex contamination and in situ fractionation processes. "Sandwich horizon" samples (fig. 3) are from a geochemically anomalous granophyre layer, containing less than 1.0% MgO and less than 1.0 ppm Cr, that may have been affected by hydrothermal alteration or contamination (Benimoff and Puffer 2007). Most other mid-Palisades and

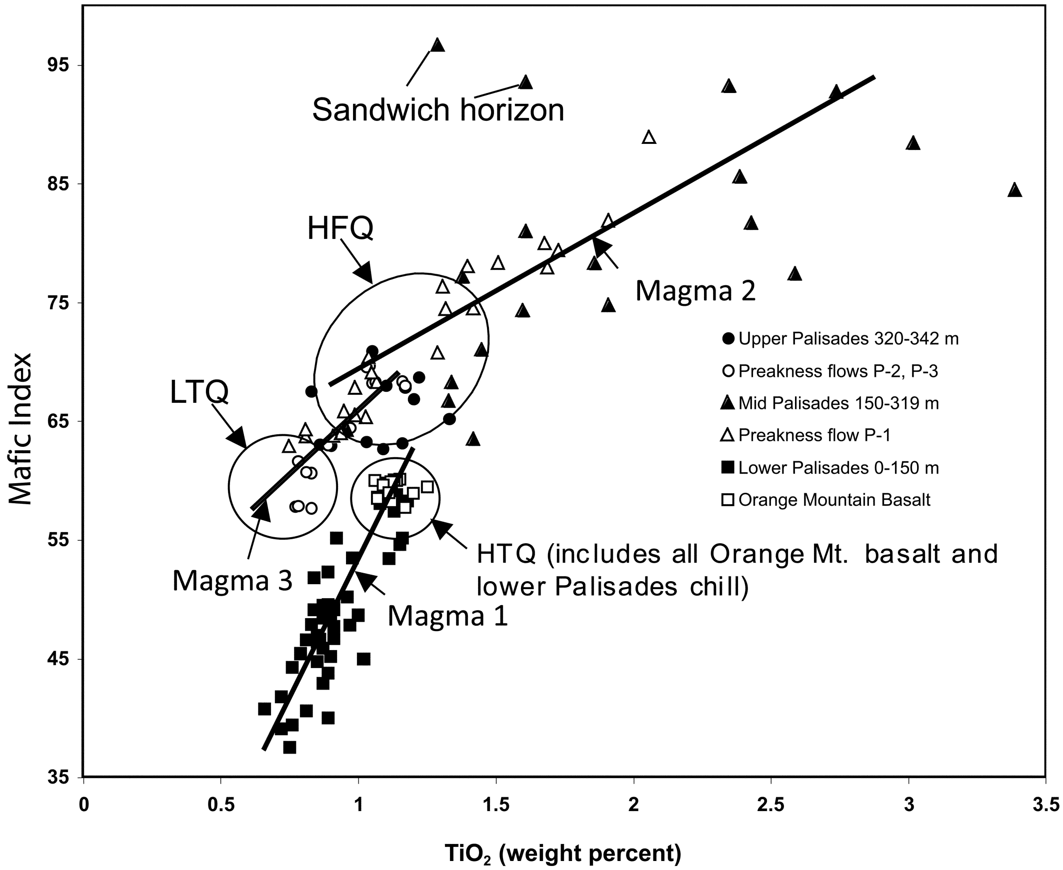

Figure 3. Plot of Palisades mafic index and TiO_2 composition of Palisades dolerite, Orange Mountain basalt, and Preakness basalt, with high-titanium quartz tholeiite (HTQ), high-iron quartz tholeiite (HFQ), and low-titanium quartz tholeiite (LTQ) field boundaries as defined by Weigand and Ragland (1970) and modified by Ragland et al. (1992). Mafic index $= Fe_2O_3^t \times 100/(Fe_2O_3^t + MgO)$. Palisades data from 0 to 100 m above the base after Gorring and Naslund (1995), from 100 to 350 m above the base after Shirley (1987) and lower chill zone new data (table A4, available in the online edition or from the *Journal of Geology* office); Orange Mountain basalt after new data (table A1, available in the online edition or from the *Journal of Geology* office); Preakness basalt data after Puffer (1992), Puffer and Volkert (2001), and new data (tables A2, A3, available in the online edition or from the *Journal of Geology* office). Least squared trend lines are plotted through proposed magmas 1–3.

Preakness P-1 flow samples that plot outside the HFQ range are pegmatoid samples that are the products of in situ fractionation (Steiner et al. 1992; Puffer and Volkert 2001) or iron-enriched granophyre layers described by Block et al. (2007). Although the degree of compositional scatter among mid-Palisades samples exceeds scatter among Preakness P-1 flow samples, the high degree of overlap among P-1 flow and mid-Palisades samples is clear (fig. 3) and supports a second comagmatic relationship.

The magma source of the upper Preakness flows was interpreted by Puffer and Philpotts (1988) and by Tollo and Gottfried (1992) as an LTQ source. Indeed, each of the upper Preakness flow samples (P-3) plots within the LTQ field (fig. 3). However, most samples from the upper Palisades layer located just below the upper chill and samples from the P-2 flow plot between the LTQ and the HFQ fields. These intermediate compositions are consistent with our interpretation that some residual HFQ magma mixed with a late intrusion of LTQ magma.

Chromium Distribution. Perhaps the most compelling evidence in support of our proposed correlations is presented in figure 4. Although three contrasting magmas from independent sources are proposed, some mixing of these magmas is evident.

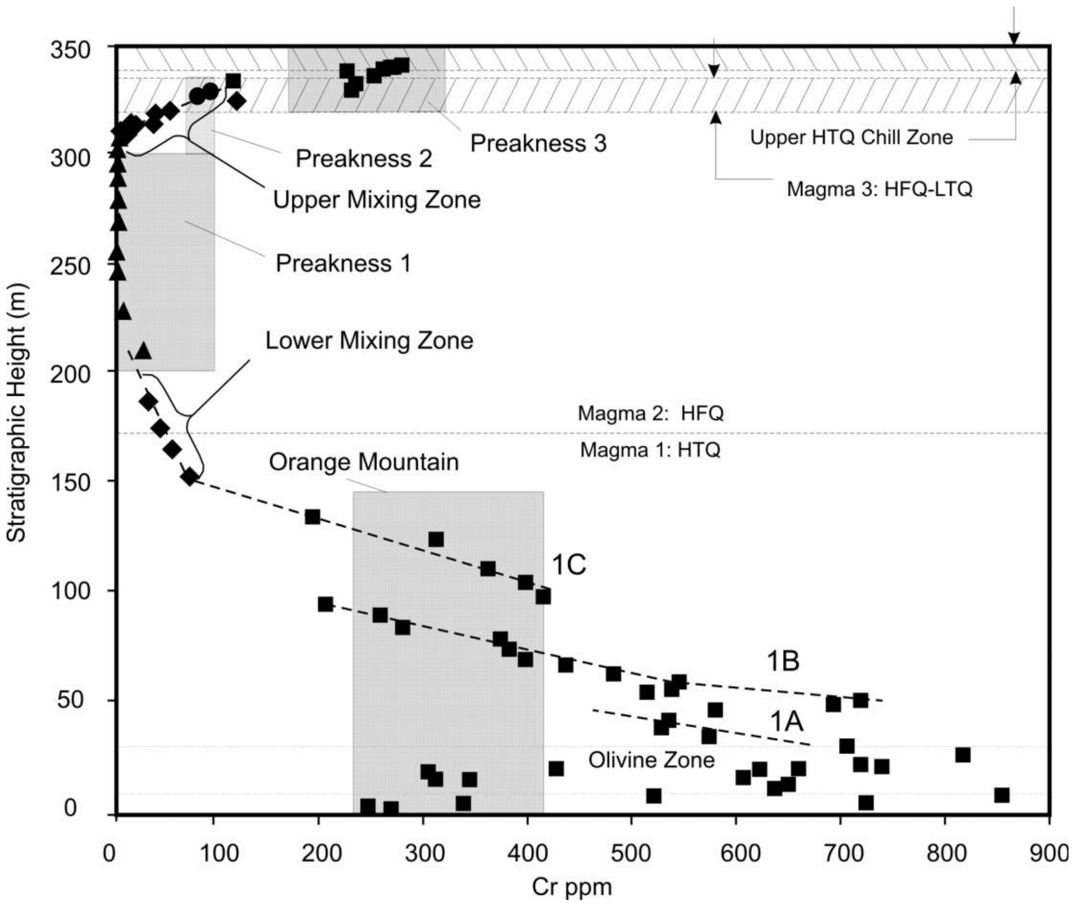

Figure 4. Cr content of the Palisades sill as a function of stratigraphic height (*data points*) together with Orange Mountain and Preakness basalt flow thickness and Cr ranges (*gray areas*). *Olivine zone* (Hysalosiderite; Walker 1969), *1A*, pulse 1A of magma 1; *1B*, pulse 1B of magma 1; *1C*, pulse 1C of magma 1. Orange Mountain basalt coeval with magma 1, Preakness flow 1 coeval with magma 2, and Preakness flows 2 and 3 coeval with magma 3. *HTQ*, high-titanium quartz tholeiite; *HFQ*, high-iron quartz tholeiite; *LTQ*, low-titanium quartz tholeiite.

Magma 1. Starting at the base of the Palisades sill, the Cr concentrations are somewhat erratic within the lower (HTQ) portion of the sill but display two abrupt reversals that divide the lower 150 m into three parts (1A–1C; fig. 4). We interpret these three parts as the first three pulses of Palisades magma, each of which broke through to the surface to extrude as three Orange Mountain basalt flows. The base of the first pulse (1A) is the chill zone that is virtually identical to the composition of the Orange Mountain basalt (tables A1, A5). The top of the first pulse is marked by a geochemical reversal at the 45-m level (fig. 4), interpreted by Gorring and Naslund (1995) as evidence of a second HTQ pulse of magma. We agree, however, that the composition of most of the first pulse (1A) is much more mafic than the first Orange Mountain flow. The mismatch is due to the intrusion of the olivine zone as the first pulse of Orange Mountain extrusive activity was subsiding. The olivine zone probably represents late pyroxene and olivine cumulate from a deeper magma source that was not carried to the surface and has no clear extrusive expression. The pyroxene and olivine crystal mush represented by the olivine zone was probably too dense and viscous to extrude and may have temporarily plugged extrusive fissures. Husch (1990), Steiner (1992), and Gorring and Naslund (1995) present evidence indicating that the olivine zone is very unlikely to have developed as an in situ fractionation product.

The absence of a mafic flow resembling the olivine layer among the Orange Mountain flows is a feature also found in the massive Ferrar (McMurdo Dry Valleys) System. In that system, a high concentration of Opx in the basal sill (20% MgO) is not seen in associated lavas or in the upper sills (Marsh 2004).

The second and thinnest of three Orange Mountain flows correlates with the second and thinnest Palisades magma 1 intrusive pulse located 45–95 m above the base of the sill (1B; fig. 4). The top of this second Palisades pulse is marked by a clear compositional reversal located at the 95-m level (fig. 4). Although the 95-m level is interpreted by Gorring and Naslund (1995) as being due to low-angle faulting, there is no clear evidence of a fault along the Fort Lee traverse. Fault planes and slickensides are not observed at the 95-m sample site.

We correlate the third Orange Mountain flow with the Palisades layer defined by the compositional reversal at the 95-m level and by distinct compositional changes near the 150-m level (1C; fig. 4). Samples above the 150-m level begin a gradual upward enrichment in iron, reaching 19.1% Fe_2O_3 255 m above the base (Shirley 1987). In addition, a grain size change is seen at the 150–200-m mixing level. The lower HTQ Palisades layers are distinctly finer grained than the overlying HFQ layer.

Support for the interpretation of three magma 1 pulses intruded through the lower half of the sill is the high degree of chemical similarity of the lower chill zone when compared with samples from several levels above the base (fig. 4). For example, the TiO_2 and MgO composition of Palisades sample 80-41 from the 134-m level is 1.07 and 7.67 (Shirley 1987), respectively—virtually the same as chill zone chemistry. Figure 4 indicates that a 250–400-ppm Cr range is duplicated at three levels within the lower Palisades, in each case overlapping the 250–400-ppm range of the Orange Mountain basalt. This layering is completely inconsistent with a single progressively fractionating HTQ magma and the development of the upper Palisades as its fractionation product. Instead, we propose that the upper Palisades is the product of second and third magmas that correlate with Preakness flows of similar composition. The second magma was highly fractionated (and/or contaminated) before it intruded into the Palisades sill and extruded as the first Preakness flow.

The Magma 1-2 Contact. If the second Palisades magma (fig. 4) correlates with Preakness flows, as we have proposed, the contact near the 150-m level may also represent a 260-k.yr. hiatus. Olsen et al. (2003) have shown on the basis of carefully measured cyclic stratigraphy that the Feltville Formation separating the Orange Mountain basalt from the Preakness basalt (fig. 2) represents about 260 k.yr. of deposition. The lower layers, therefore, had presumably crystallized into solid rock before the second magma was intruded along its upper contact. However, intermittent HTQ magmatism and hydrothermal activity during the 260-k.yr. hiatus may have kept a pathway unconsolidated and open to subsequent magma intrusions. Ratcliffe (1988) presented evidence that Ladentown basalt flows (fig. 1) chemically correlated with Orange Mountain basalt and were extruded at mid-Feltville stratigraphic positions. If intermittent surges of HTQ magma throughout the 260-k.yr. hiatus occurred, an igneous pathway would have been available to subsequent pulses. Consequently, rock at the 150-m level might be expected to reveal some fine-grain chill zones.

However, the thickness of the first pulse of the second magma was about 160 m, about the same as the thickness of the first Preakness flow (fig. 4). If the area covered by the first Preakness flow was close to the area covered by the Orange Mountain basalt (11.3 km^2), a massive volume of about 2.4 km^3 (McHone 2003) of magma flowed through this pathway. Continuous pulse influx at high velocity is necessary for about 150 m of magma to cover such a large area. Continuous pulse influx would also thermally erode and assimilate some overlying and underlying magma 1 rock, thus eliminating previous chill zones or any rock altered by previous vapor vents.

Magma 2. The thickness, pegmatite-enriched petrology, and geochemical similarity of the mid-Palisades layer and Preakness basalt flow P-1, including Cr content (fig. 4), is striking. The average and range of the Cr content of Preakness flow P-1 plotted onto figure 4 are consistent with our proposed correlation, in each case overlapping mid-Palisades compositions.

Magma 2 resides over the interval 210–300 m above the base of the Palisades sill (fig. 4) bracked by mirror image mixing lines (a lower mixing zone extending from 150 m and 90 ppm Cr to 250 m and 10 ppm Cr and an upper mixing zone extending from 300 m and 5 ppm Cr to 320 m and 80 ppm Cr).

The upper contact of the magma 2 layer is marked by an abrupt change in chemical composition at the 320-m level. In particular, the TiO_2 concentration decreases from 1.91% at the 319-m level to only 1.05% at the 320-m level and then continues to decrease to LTQ levels of only 0.86% at the 327-m level and 0.83% at the 329-m level (Shirley 1987). However, other components, including Cr, begin a more gradual change at the 300-m level (fig. 4), due in part to mixing of magma 2 with magma 3. The upper mixing zone (fig. 4) is a com-

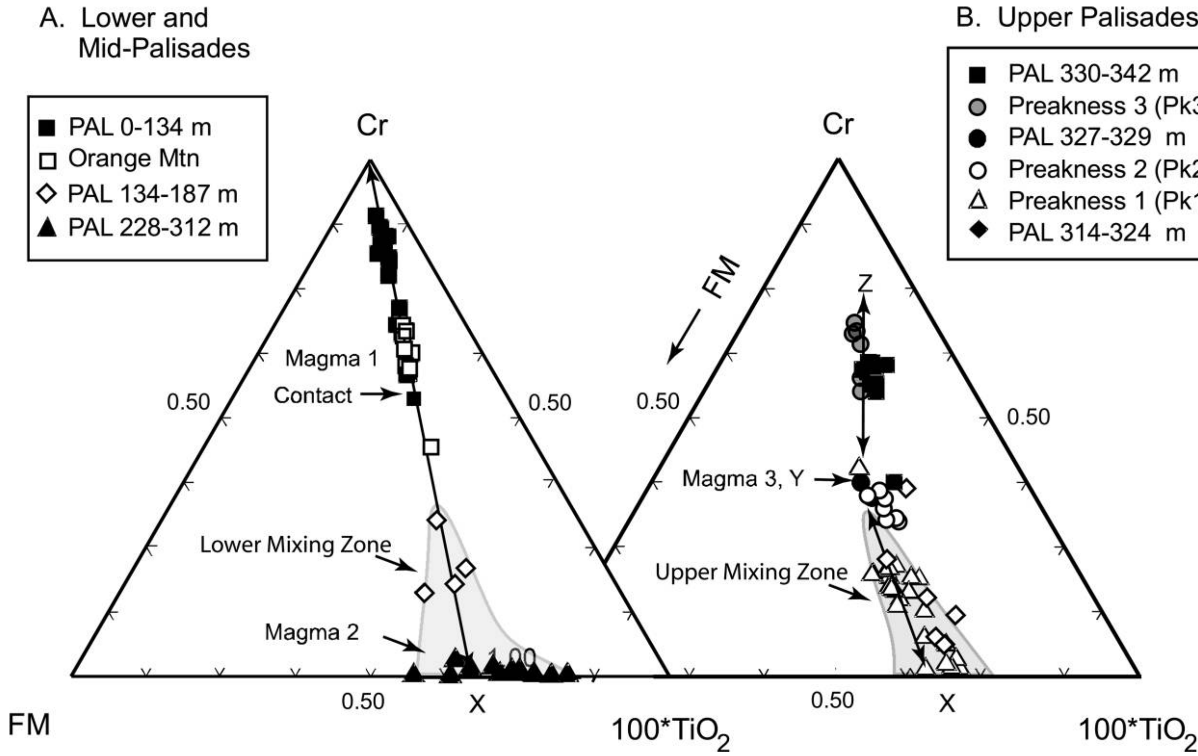

Figure 5. Element variation within the Palisades sill, divided into two series at the magma 3 stratigraphic level (PAL 312–314 m) at the Fort Lee section, compared with the flood basalts of the Newark Basin. *A*, Lower and mid-Palisades section at Fort Lee comprises magmas 1 and 2 as presently defined and mixing lines. *Cr-contact* (lower chill contact, Fort Lee), magma 1 data from Shirley (1987) comprises the lower Palisades section, PAL 0–134 m, representing mixing with orthopyroxene-enriched cumulus, and from Gorring and Naslund (1995), PAL 0–105 m (*filled squares*), and the comagmatic Orange Mountain flows (*open squares*; table A1, available in the online edition or from the *Journal of Geology* office). *Contact-X*, mixing line connecting magmas 1 and 2. Magma 2 data from Shirley (1987), PAL 228–312 m (*filled triangles*), and in lower mixing zone (*open diamonds*). *B*, Upper Palisades section at Fort Lee extending from 314 m to the upper contact at 342 m (PAL 314–324 m), including magma 3 and mixing lines. *X-Y*, mixing line between magma 2 (*shaded area*) and magma 3 (at *Y*) that transects data for Preakness 1 (*open triangles*) and portions of Preakness 2 (*open circles*). *Y-Z*, mixing line between magma 3 (at *Y*) to midrange of the Palisades mixing line (*Cr-contact*) that intersects field for Preakness 3 (*gray circles*). The upper Palisades near the upper contact at 330–342 m (*filled squares*) plots close to the initial line Cr-contact for the lower section Palisades, representing original magma 1.

posite of (*a*) the residue from the mixing of magma 1 and magma 2 as magma 2 invaded residual magma 1 and (*b*) a mixing of this residue and the last magma, magma 3. Magma 3 is plotted as two circles (fig. 4) at about 335 m and 80 ppm Cr. This complex mixing pattern is also illustrated in figure 5*B*.

Magma 3. Magma 3 followed magma 2 after a second, although much briefer, period of sedimentation. The first Preakness magma 2 flow is separated from the overlying sequence of relatively thin magma 3 flows by about 2 m of sandstone, siltstone, and mudstone. This 2-m layer represents a much briefer period than the 137–148-m thickness of the Feltville Formation (Olsen 1980) deposited between magma 1 and the first Preakness flow. Instead of only one very thick pulse, magma 3 delivered at least four upper Preakness flows to the surface. The first of these flows is a hybrid or mixed HFQ-LTQ flow (P-2), followed by three LTQ flows. These multiple magma 3 pulses resulted in the thin intrusive layering defined by multiple minor reversals in fractionation trends and contrasting grain size throughout the upper 25 m of the Palisades sill. In general, the grain size of these thin upper layers is distinctly finer than that of the magma 2 layer.

The upper boundary of the titanium-depleted (magma 3) layer is marked by a return to compositions typical of the (magma 1) lower chill zone (fig. 4). The Cr content jumps from 90 ppm at the 329-m level to 226 ppm at the 330-m level (Shirley 1987). These elevated Cr levels are maintained up to the upper contact at 342 m.

Resemblance to Shiant Isles Sill. The distribution of Cr through the Palisades cross section (fig. 4) plots as an irregular S-shaped pattern. Similar S-shaped Cr and MgO patterns were plotted for the Shiant Isles main sill, NW Scotland, by Gibb and Henderson (2006). They propose that the lower part of the sill was first formed by an initial magma input and then the sill was later inflated by a second input of magma of contrasting composition and phenocryst content. They (and also Marsh 1996) suggest that this general process could apply to most other thick (>50-m-thick) sills showing strong internal discontinuities in composition. They point out that whenever the chemistries of large mafic sills are investigated in detail, they turn out to be products of multiple intrusions. Gibb and Henderson (2006) rely heavily on compositional breaks in cross-section fractionation trends as evidence of multiple intrusions. Similar fractionation reversals are found in the lower Palisades sill, 45 and 95 m above the base (fig. 4).

In cases where later magmas are more evolved than previous magmas, such as upper Shiant Isles and upper Palisades sill magmas, compositional breaks occur as gaps or abrupt changes instead of reversals. The abrupt compositional change 150 m above the base of the Palisades sill (fig. 4) is interpreted in this article as evidence of intrusion of a second, more evolved magma.

Fe-Mg (FM), Ti, and Cr Distribution

When Cr is plotted against both TiO_2 and FM ($100 \times FeO/FeO + MgO$), three trend lines again emerge (fig. 5) in confirmation of the above observations (lines Cr-X, X-Y, and Y-Z). The lower 150 m of Palisades consistently overlaps the Orange Mountain basalt along a very narrow, almost straight line through magma 1 that plots directly away from the Cr point of the triangle to the lower contact of the Palisades sill (fig. 5*A*, *line segment Cr-contact*). This almost straight line field includes the pyroxene-enriched olivine zone and establishes its comagmatic relationship with the Orange Mountain basalt. This line represents an orthopyroxene cumulus-enrichment line and is well defined despite the numerous reversals shown in the lower 150 m in figure 4.

The four samples on the lower magma 2 mixing line from the mid-Palisades 134 to 187 m above the lower contact plot directly on or close to this straight line (fig. 5*A*, *Cr-X*). This mixing line extends toward the highly fractionated magma 2. The magma 2 field is defined by the cluster of mid-Palisades samples from 228 to 312 m above the base, plotted near the base of the shaded triangular area of figure 5*A*, centered at point X, and the cluster of Preakness samples that overlaps this triangular area plotted on figure 5*B*.

The upper mixing zone of magma 2 is a composite, as discussed relative to figure 4, of the original mixing along Cr-X and the magma 3 (fig. 5*B*, *Y-X*). Note that the former is represented primarily by Palisades samples (*diamonds*), whereas the latter better defines the Preakness 1 series (*open triangles*).

Preakness 2 (*open circles*) and the Palisades 3 facies at 327–329 m above the lower contact (*filled circles*) define magma 3. Preakness 3 aligns well with the Palisades data at the upper 330–342-m layer and lies exactly on the line magma 3 (Y-Z). The line Y-Z creates an angle with X-Y.

The most straightforward way to explain these divergent trends is to invoke three independent magmas. The Palisades and the variable compositions of all the Preakness flows is therefore consistent with the injection of three magmas and the resulting complex mixing patterns.

Trace Element Distribution

Figure 6*A* is a primitive mantle–normalized (Sun and McDonough 1989) trace element distribution diagram that illustrates the high degree of geochemical resemblance between Orange Mountain basalt and the chill zone composition of the Palisades sill. Figure 6*A* compares the average composition of Orange Mountain basalt (table A1) with sample 80-B1 collected from the base of the Palisades sill at Fort Lee, as analyzed by Shirley (1987). Reanalysis of sample 80-B1 by Gottfried et al. (1991*a*, 1991*b*) confirms Shirley's data and supplies additional trace element data. The virtually identical composition of Orange Mountain basalt and the Palisades chill zone is compelling evidence of a comagmatic (magma 1) relationship.

The chemical composition of the Ladentown basalt (fig. 1) is also plotted in figure 6*A* for comparison. The Ladentown basalt plots as a line close to and parallel to the Orange Mountain–Palisades chill zone line and is interpreted as an HTQ basalt that has been slightly fractionated. There is virtually no noticeable petrographic distinction between the mineralogy and the texture of the Orange Mountain and Ladentown basalts.

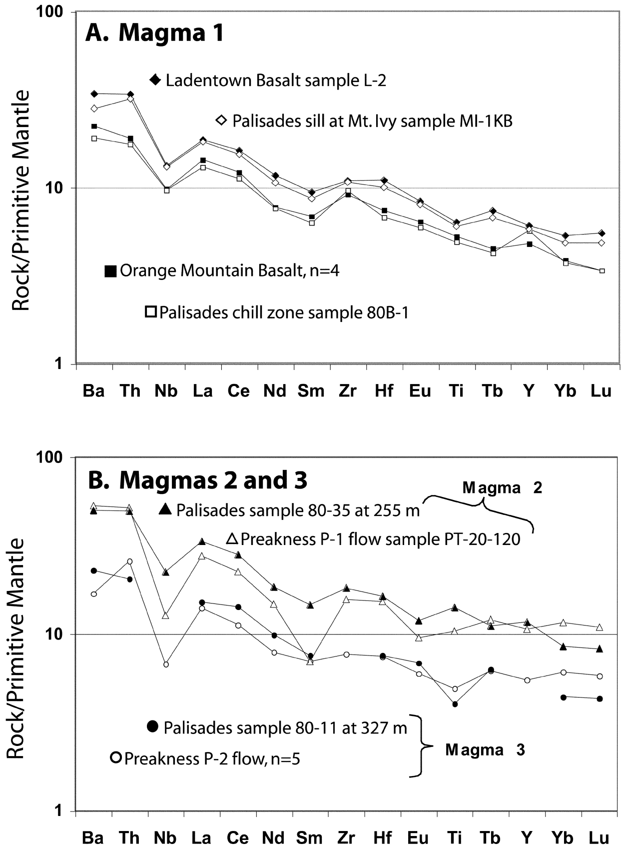

Figure 6. Rock/primitive mantle–normalized (Sun and McDonough 1989) diagrams. *A*, Magma 1, average Orange Mountain basalt (table A1, available in the online edition or from the *Journal of Geology* office, $n = 15$; table A5, available in the online edition or from the *Journal of Geology* office, $n = 4$) and lower Fort Lee contact chill zone of Palisades sill sample 80B-1 (Shirley 1987; except Nb, Zr, and Y after Gottfried et al. 1991*a*), Ladentown basalt sample L-2 (tables A1, A5), and Palisades sill sample MI-1KB from Mount Ivy (tables A4, A5). *B*, Magma 2, Palisades diabase sample 80-35 from 255 m above the lower Fort Lee contact (Shirley 1987; except Nb, Zr, and Y after Gottfried et al. 1991*a*) and Preakness basalt sample PT-20-120 (Tollo and Gottfried 1992); magma 3, Palisades diabase sample 80-11 from 327 m above the lower contact (Shirley 1987) and Preakness basalt flow P-2 (Preakness P-6, $n = 5$; Tollo and Gottfried 1992).

Additional support for an Orange Mountain–Palisades chill zone correlation is the close geochemical resemblance of the Ladentown basalt and a fine-grained, slightly vesicular sample of Palisades diabase collected at its breakout position at Mount Ivy (fig. 1). The close geochemical resemblance of extrusive Ladentown basalt to intrusive Palisades diabase from Mount Ivy (fig. 6*A*) suggests a comagmatic relationship and is consistent with the continuous subsurface physical connection of the Palisades sill to the Ladentown basalts observed by Kodama (1983) based on magnetic and gravity evidence. An open-system or flow-through relationship between the Palisades sill and basalt is, therefore, well established.

Figure 6*B* illustrates the high degree of geochemical resemblance between Preakness basalt and interior layers within the Palisades sill. Magma 2 samples include a highly fractionated, pegmatitic sample of Preakness basalt (sample PT-20-120; Tollo and Gottfried 1992) from the P-1 flow and a coarse-grained sample of Palisades ferrogabbro (sample 80-35; Shirley 1987) of similar composition. Both samples contain less than 6 ppm Cr.

Magma 3 is represented by the average composition of Preakness flow P-2 (sample average P-6, $n = 5$; Tollo and Gottfried 1992) and a fine-grained sample of Palisades diabase from the 327-m level (Shirley 1987); Cr contents are 72 and 78 ppm, respectively. Throughout the Palisades the overall degree of geochemical correlation with chemically diverse Preakness flows is nicely predicted by chrome content.

The intrusive-extrusive correlations of magmas 2 and 3 (fig. 6*B*) are remarkably close, considering the possibility of intralaboratory error. The intrusive and extrusive magmas plotted in figure 6*A* represent in initial Palisades chill zone, and the extrusive comagmatic Orange Mountain flows exhibit only a small degree of in situ fractionation. In contrast, figure 6*B* represents interior Palisades layers and the interiors of thick, extrusive flows that have undergone extensive in situ fractionation (Puffer and Volkert 2001). However, fractionation processes that took place within the sill were relatively efficient compared with fractionation occurring within rapidly solidifying flows. This disparity in fractionation efficiency led to a divergence of the most incompatible elements (particularly Nb through Nd) compared with the most compatible elements (Yb and Lu). The most incompatible element content of the Palisades layers, therefore, is slightly enriched compared with extrusive correlatives.

Magma Sequence

The proposed sequence of magmatic activity is depicted in figure 7. The first phase of activity (magma 1) initiates the Palisades sill, inflating it to a thickness of 150 m while simultaneously extruding as Orange Mountain basalt. Late magma 1 activity continues upward through the lower

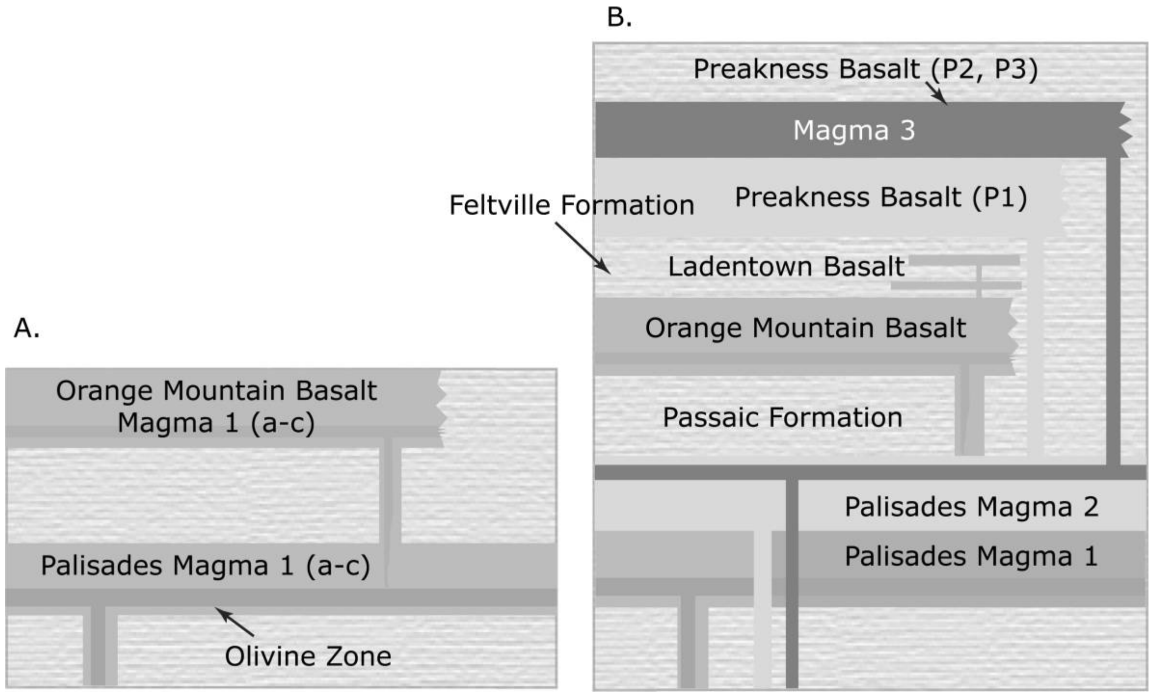

Figure 7. Diagram illustrating the movement of magmas through the Palisades Intrusive System and onto the surface as basalt flows.

Feltville siltstone to erupt near Ladentown (figs. 1, 7). Apart from late intermittent magmatic activity located near Ladentown (fig. 1), the main phase of magma 1 activity intruded as three pulses, each of which was characterized by late accumulation of pyroxene phenocrysts, a common feature among mafic intrusions (Simkin 1967; Steiner et al. 1992; Marsh 1996; Gibb and Henderson 2006). Portions of each of the three Palisades layers at the base of the sill are enriched in pyroxene phenocrysts, although in diminishing concentrations as the northern extrusive breakout position is approached (Walker 1969; Block 2006), a feature typical of saucer-shaped sills. In contrast, the three Orange Mountain basalt layers (representing the leading or early portion of each pulse) contain sparse pyroxene phenocrysts. However, portions of each of the three lower Palisades layers closely resemble Orange Mountain basalt (fig. 4).

The thin intermittent extrusions of magma 1 exposed near the northern breakout located near Ladentown, New York (Puffer et al. 1982; Ratcliffe 1988), may have kept an igneous pathway open for several thousand years. Intermittent pyroclastic activity probably also occurred during this interval on the basis of thin altered tuff layers found interbedded with redbed sediments (P. E. Olsen, personal communication, personal observations). Shallow magmatic systems that remain active for durations exceeding 260 k.yr. may not be unusual, for example, the Yellowstone and Reykjanes Ridge systems.

The intrusion of magma 2 (fig. 7) inflated the Palisades sill by an additional 170 m while extruding as a lower Preakness basalt flow about 160 m thick. The intrusion would have occurred at the boundary of the upper and lower solidification front of the last magma 1 pulse. The force of the 170-m-thick intrusion was presumably capable of eroding much of the residual magma 1 crystal mush and perhaps stoping away the upper entablatures of previous pulses, leaving only upper chill zones and hardened lower colonnades intact. The late intrusive stage of the magma 2 layer is not pyroxene phyric but instead displays iron enrichment (up to 18% total FeO) typical of HFQ magmatism.

Magma 3 pulses also intruded into the crystal mush at the boundary of the upper and lower solidification front of previous intrusions. Magma 3 intrusions, although thinner than the magma 2 pulse, were also presumably capable of stoping upper magma 2 layers while extruding as a sequence of basalt flows (P-2 and at least three P-3 Preakness flows). These upper Preakness flows are poorly exposed but do not display weathered flow tops and were probably extruded in rapid succession.

Summary and Discussion

The mineralogy and textural characteristics of diabase sheets reflect a complex series of formative events, including partial melting at the source, decompression melting during ascent, flow differentiation, and in situ processes. A sheet with multiple injections additionally involves mixing between magmas, as long as the magma system remains sufficiently fluid to support diffusive and convective interchange. This study suggests that the Palisades sill is in major aspect a composite of remnants, as well as of internal processes, deposited as a succession of through-going magmas migrated upward to form the overlying flood basalts of the Newark Basin. These units interacted by mixing, resulting in gradational boundaries between initially compositionally discrete magmas and, to a lesser scale, between pulses from the same magma. In addition to the compositional variability induced by in situ magma mixing, magma pulses can carry along cumulus and wall rock material, resulting in mixing lines with magma, such as that noted for the lower Palisades in the Fort Lee section (olivine zone) and the Orange Mountain basalt (fig. 5*A*, *mixing line contact-Cr apex*). This is not to suggest that in situ processes are not key to interpreting local layering phenomena, such as the dramatic fluctuations in modal mafic minerals in the lower horizon discussed by Gorring and Naslund (1995) and in an overlying horizon by Block et al. (2004, 2007).

This reevaluation of the Palisades-Watchung System represents a confirmation of the model of Gibb and Henderson (2006) for the production of S-shaped internal layering within sills through the process of multiple magma injections. It extends the argument by showing that correlations in the injection character within a sill extend to its extrusive equivalents. In this study, sheet-to-eruptive correlations are supported, using chrome abundance values at key horizons in the sill that relate to comparable variability in extrusive flows. Specific observations in support of this include the following.

1. Magma 1. There are three HTQ Orange Mountain basalt flows and three proposed lower Palisades diabase layers (this study) of similar relative thickness. Importantly, the Cr enrichment in the Palisades, reflected dramatically in the olivine zone (pulse 1A, fig. 4), has its correlation in the lowermost Orange Mountain basalt, a correlation not previously recognized in studies of this system. This supports arguments by Steiner and others (1992) and Gorring and Naslund (1995) that a significant inclusion of material into the primary magma occurred before emplacement, and this complex material is present cryptically in the Orange Mountain basalt, based on the exceptional overlap of data in ternary plots such as figure 5*A*. An Orange Mountain–lower Palisades correlation is therefore supported by the overlapping geochemistry of the lower chilled contact and pulses 1A–1C along the very narrow Cr-mixing line of the Palisades sill and the Orange Mountain basalt series (fig. 5*A*). Comparisons with titanium, magnesium, nickel, and other metals yield the same result.

2. Magmas 2 and 3. Magma 2 is represented by the Cr-depleted layer at an approximate elevation of 228–312 m in the Fort Lee Section together with mixing zones that extend the magma 2 boundaries to 150 and 320 m (fig. 4). Lacking in internal chill zones, the exact boundaries of the internal contacts in the Palisades are somewhat subjective. The case in point is that each of the magmas 1–3 represent mixed magmas, in contrast to the magma contacts. The mixing line between pulse 1C and magma 2 (134–187 m; fig. 5) exemplifies the character of mixing as presently proposed.

Correspondingly, Preakness flow 1 overlaps with the slightly elevated Cr composition of magma 2 and represents mixing with magma 3. Preakness flow 2 is on the same mixing line (fig. 5) but is enriched in magma 3. Preakness 3 is comprised primarily of magma 3 but resides on a mixing line with the initial magma 1 (fig. 5*B*, *line Y-Z*, where Z is on line contact-Cr). Therefore, present arguments underscore the mixed character of the magmas comprising the flood basalts of the Newark Basin.

3. It is presently emphasized that the pre-Palisades heredity described in this work is not intended to minimize the later in situ processes that occurred in the sill, particularly related to the rhythmic and modal layering recognized by Goring and Naslund (1995) and Block (2004, 2007). Internal fractionation clearly produced iron-enriched pegmatoids in the sill (Block 2007) and in the Preakness flows (Puffer and Volkert 2001).

4. The time duration is consistent with mixing in the sense that the long intervals between separate intrusion events resulted in a significant amount of mixing between magmas, possibly due to thermal erosion and assimilation associated with each additional pulse.

Redbed sediment deposition below and above the first Preakness flow provided ample time for magma source changes to occur within a dynamic tectonic setting. However, the shared intrusive pathway through the Palisades sill permitted some mixing of these diverse magmas, as reflected in compositional overlap among adjacent igneous units. Despite this mixing, contacts between diverse units are marked by distinct compositional gaps or reversals.

5. 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. Our proposed injection of thinner, largely prefractionated pulses removes these advective changes as an issue in the evolution of the Palisades. In addition, Steiner and others (1992) have demonstrated through mass considerations that the cumulus composition of the lower Palisades is insufficient to produce a mass balance with the upper Palisades. Our proposed intrusion of magmas from independent sources solves this paradox.

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