

The Palisades Sill, New York and New Jersey
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General Geology of the Palisades Sill: The Palisades sill is a Mesozoic tholeiitic intrusion approximately 300 m thick, that extends in outcrop for 80 km in a north-south direction along the western side of the lower Hudson river (Fig. 1, Walker, 1969), and may connect under cover with the Rocky Hill and Lambertville sills to the south for a total strike length of 150 kms (Husch, 1992). The east-west extent of the sill is unknown, but if it were circular in plan view it would represent over 1750 km³ of magma. Field relations, petrography, and petrology have been described by a number of authors (Lewis, 1908; F. Walker, 1940; K. Walker 1969; K. Walker, et al., 1973; Shirley, 1987; Husch, 1990, 1992; Steiner et al., 1992).

The Palisades sill has an extensive differentiation sequence from Mg-rich gabbro at its base to Fe-rich diorite at approximately the 250 m level. The roof sequence, although much thinner than the floor sequence, is increasingly differentiated from the roof downwards (Fig. 2). The main constituents of the sill are plagioclase and pyroxene (augite, orthopyroxene, and pigeonite), which together make up over 90% of the primary phases; olivine, amphibole, ilmenite, magnetite, and minor amounts of biotite are additional phases. Igneous layering within the sill is restricted to thin (cm-scale), faint layers best seen on weathered outcrops. Calculated solidification times for the sill are on the order of 1000 years (Shirley, 1987; Gorrington & Naslund, 1995).

Mineral compositions vary from the base of the sill upwards (and from the roof downwards) reflecting the increasing differentiation of the Palisades magma (Fig. 3). Plagioclase compositions vary from An₇₈ to An₂₈; augite from

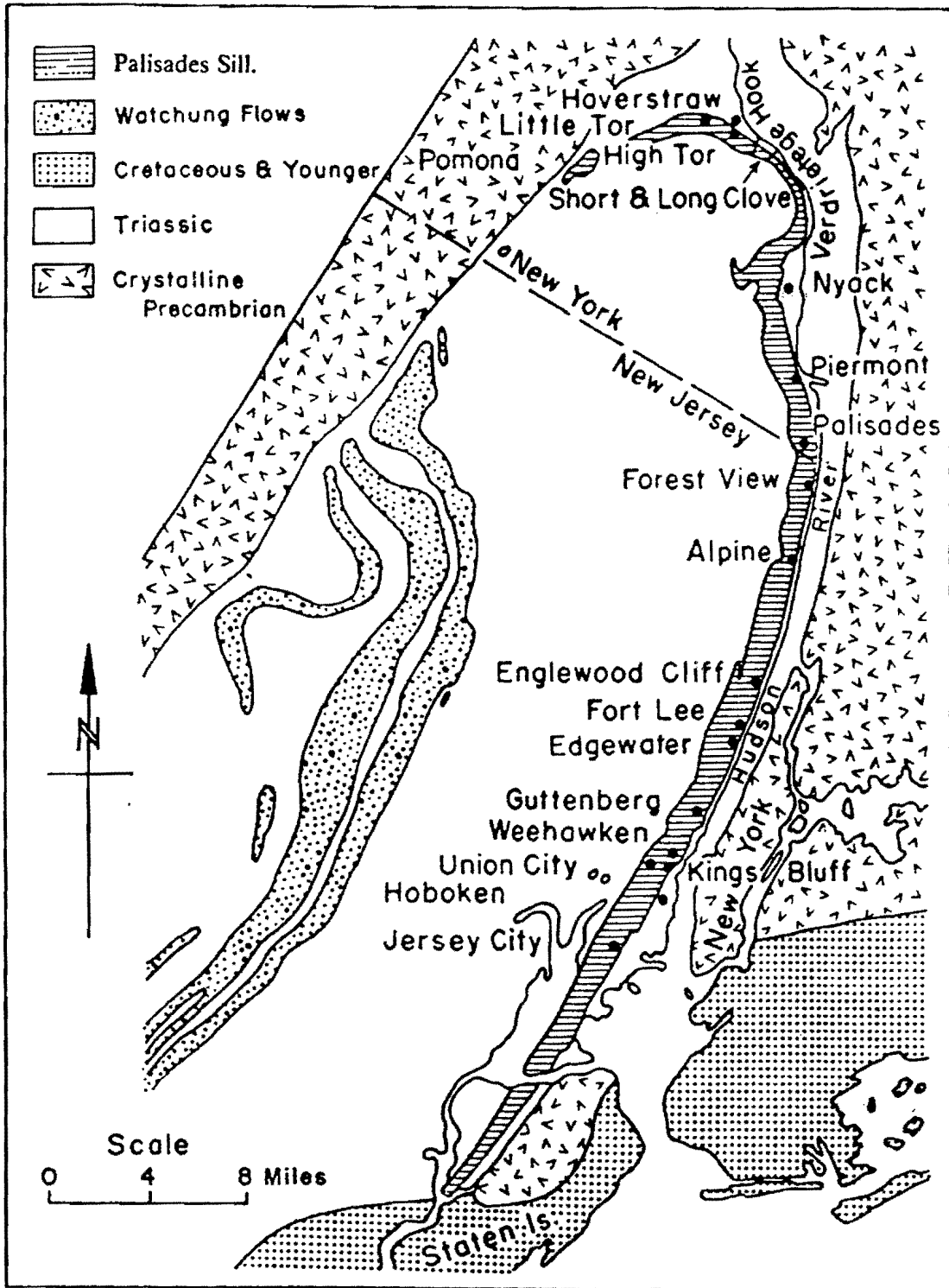


Fig. 1 Map showing the present outcrop pattern of the Palisades sill (from Walker, 1969).

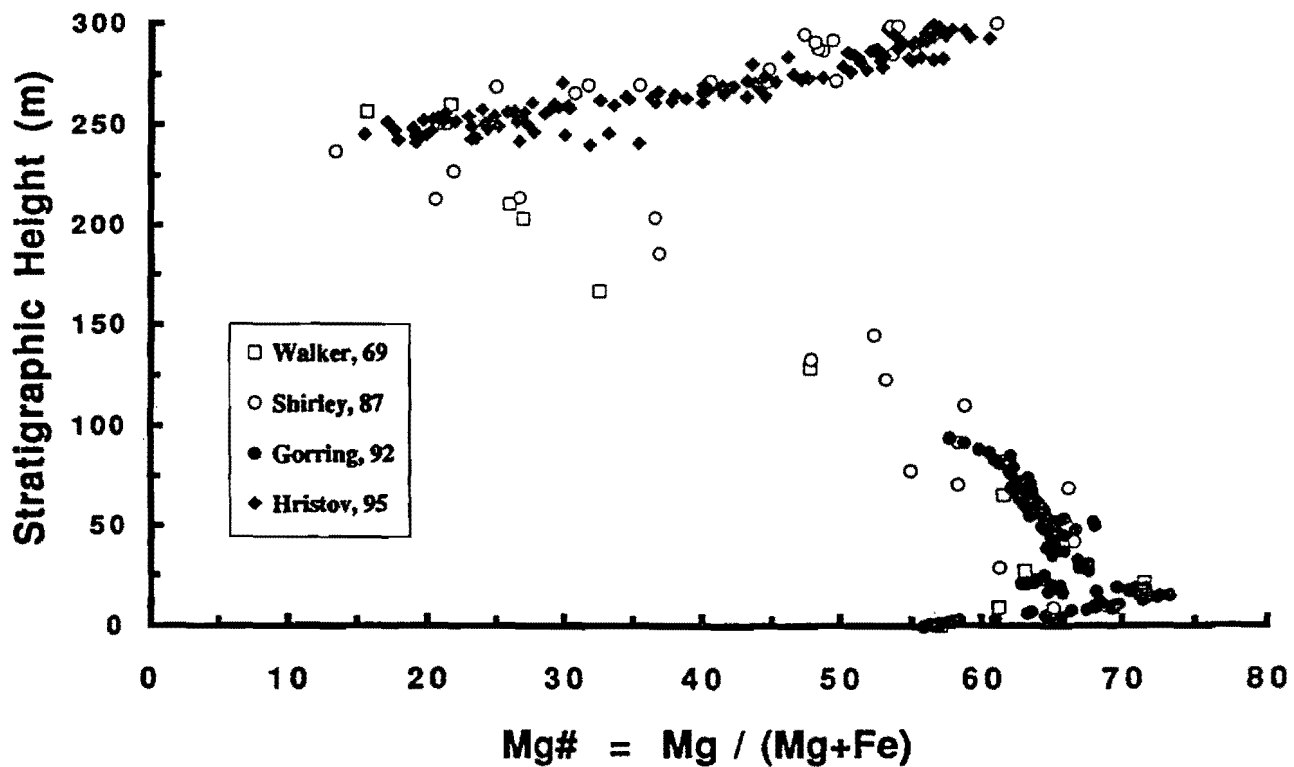


Figure 2 - A plot of Mg# vs. stratigraphic height for the Palisades sill section in Fort Lee, NJ. Data points are from Walker (1969), Shirley (1987), Gorrington (1992), and Hristov (1995).

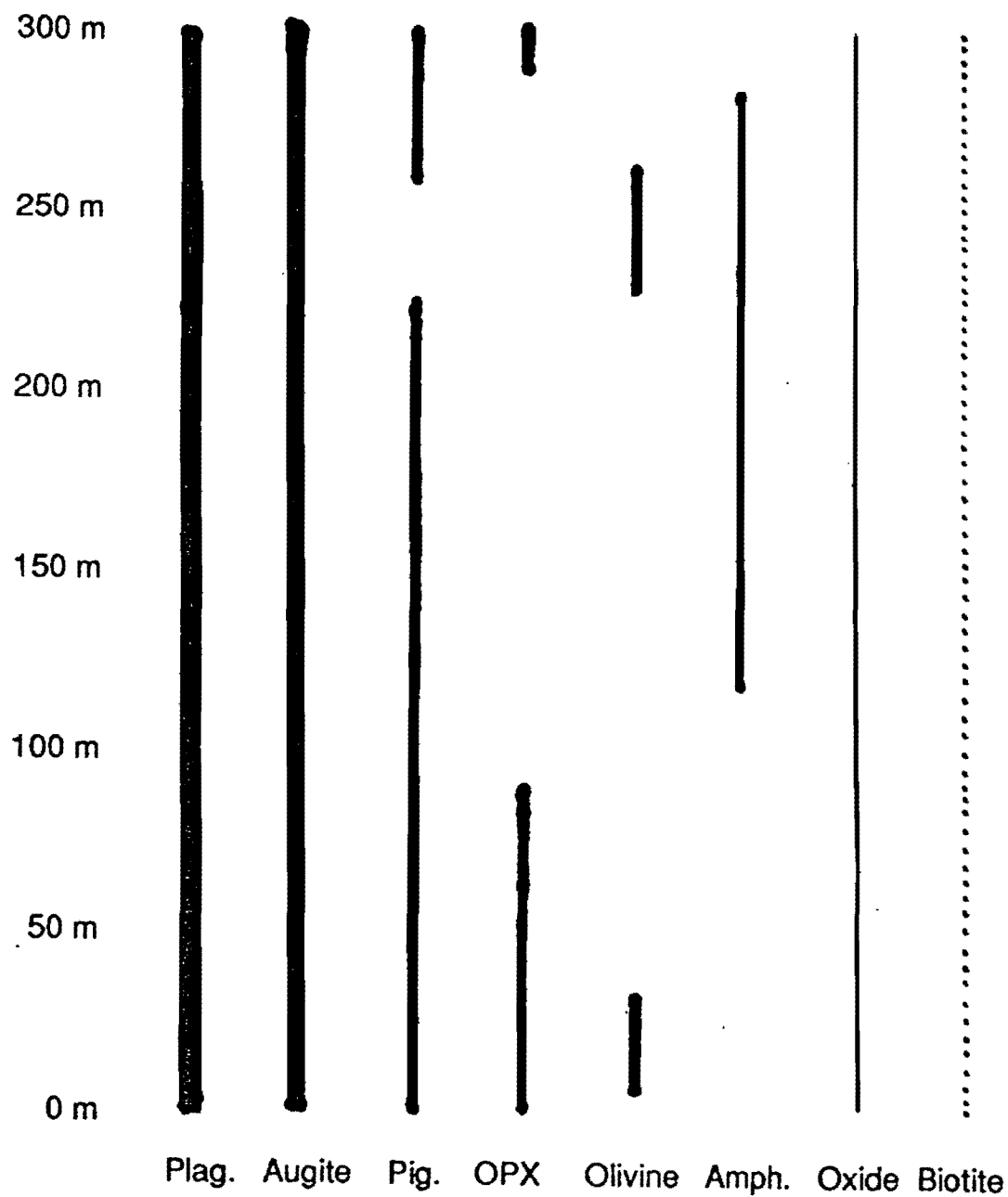


Fig. 3 Distributions of the major mineral phases of the Palisades sill vs. stratigraphic height in the sill (modified from Walker, 1969). Heavy lines indicate abundant phases, light lines indicate less abundant phases, and dotted lines indicate trace phases. Plag = plagioclase; Pig = pigeonite; OPX = orthopyroxene; Amph = amphibole.

$Wo_{38}En_{51}Fs_{11}$ to $Wo_{38}En_{10}Fs_{52}$; pigeonite from $Wo_8En_{54}Fs_{38}$ to $Wo_{12}En_{34}Fs_{54}$; orthopyroxene from $Wo_4En_{78}Fs_{18}$ to $Wo_3En_{55}Fs_{42}$ and from $Wo_3En_{34}Fs_{63}$ to $Wo_4En_{26}Fs_{70}$; and olivine from Fo_{77} to Fo_{55} and from Fo_{13} to Fo_5 (Walker, 1969; Walker *et al.*, 1973; Gorrington, 1992; Hristov, 1995). The plagioclase, pyroxenes, and olivine of the sill are all strongly compositionally zoned (Walker, 1969; Gorrington, 1992; Hristov, 1995) with augite typically zoned 20 to 25% in Mg# (Mg# = $Mg/[Mg+Fe]$) from core to rim, orthopyroxene 15 to 20% in Mg# from core to rim, and plagioclase in excess of 25 An% within crystal cores, with rims up to 50 An% poorer than cores. Many individual grains have relatively homogeneous central cores that make up 25 to 75% of the area surrounded by strongly zoned rims.

The base of the sill is sharply defined by a very fine-grained to glassy, phenocryst-free chilled margin against the country rock. Above the chilled margin, the grain size gradually increases upward in the sill from ~2 mm to over 10 mm at the 250 m level. The lower 2.5 m of the sill is a fine grained, compositionally homogeneous, dolerite which appears to represent liquid solidified in situ with no significant addition or loss of crystals. Approximately 10m above the base of the sill is the well known olivine-rich horizon which is thought to have formed during the emplacement of the magma as a result of initial magma inhomogeneities, or the nearly simultaneous emplacement of two magmas of contrasting compositions. Geochemical data suggest that there were at least two additional pulses of magma injected into the chamber at the 27m and 45m levels. These later pulses are marked by small but abrupt regressions in the generally decreasing Mg/Fe trend, abrupt increases in Ni, Cr, and modal orthopyroxene, increases in the Cr_2O_3 contents of augite and orthopyroxene, and abrupt decreases in grain-size (Gorrington & Naslund, 1995).

Shirley (1987) has modeled the effects of intercumulus melt migration and compaction in the partially solidified Palisades sill. His model suggests that the rocks originally accumulated on the floor of the magma chamber along with 50 to 60% interstitial magma. Some of this interstitial liquid was subsequently forced upward through the crystal mush by compaction, reducing the final proportion of "trapped" liquid to between 40 and 50 %.

Steiner *et al.* (1992) present a "cumulus-transport-deposition" model for the

crystallization of the Palisades sill based on a section through the sill in Upper Nyack, NY. The model proposes that "crystals collect in convection cells or like environments at deep levels within the sheet" and are then subsequently "remelted, resorted, and/or recrystallized during epizonal emplacement due to: magma decompression, shallow level flow differentiation, and magma-wall rock interactions" (Steiner *et al.*, 1992). In this model the first 2.5% crystallization is dominated by olivine (olivine : plagioclase : augite, 100 : 0 : 0), the next 20.5% by augite (16 : 34 : 50), and the next 26% by plagioclase (10 : 60 : 30). The substitution of orthopyroxene for olivine in the model does not significantly affect the overall fit with the observed Palisades trends; the first crystallization episode (0-2.5% crystallization) has a better fit using olivine; the second and third episodes (2.5-23% and 23-49%), however, have better fits using orthopyroxene (Steiner, *et al.*, 1992).

Magma-chamber recharge: Overall there is a general decrease in Mg#, Cr, Ni, and modal orthopyroxene, and a general increase in grain size and modal plagioclase with increasing stratigraphic height in the sill. Petrographic and geochemical anomalies in this general trend, however, are observed at the 10 m, 27 m, 45 m, and 95 m stratigraphic levels (Figs. 4, 5, and 6).

The anomaly at 10 m is the well known olivine horizon. Sections through the horizon at both Fort Lee and Alpine had similar profiles with a gradual increase in olivine and MgO content from the 2 m level up to the lower part of the horizon at about 10 m, and a sharp decrease in olivine and MgO at the upper contact of the horizon at approximately 20 m. No abrupt lower contact was observed at either locality. Within the olivine horizon at both localities, there are two distinct maxima in olivine content separated by an interval with lower olivine and higher augite content. These maxima are clearly apparent in the trend for MgO, Ni, and Co which peak at the olivine maxima, and Cr which peaks in the augite-rich interval. Calculations based on cooling rates, crystallization rates, crystal settling rates, and magma emplacement rates suggest that the olivine horizon probably formed during the initial filling of the chamber as a result of inhomogeneity in the source magma.

The anomalies at 27 m and 45 m probably represent magma chamber recharge during which more primitive magma ponded on the floor of the magma

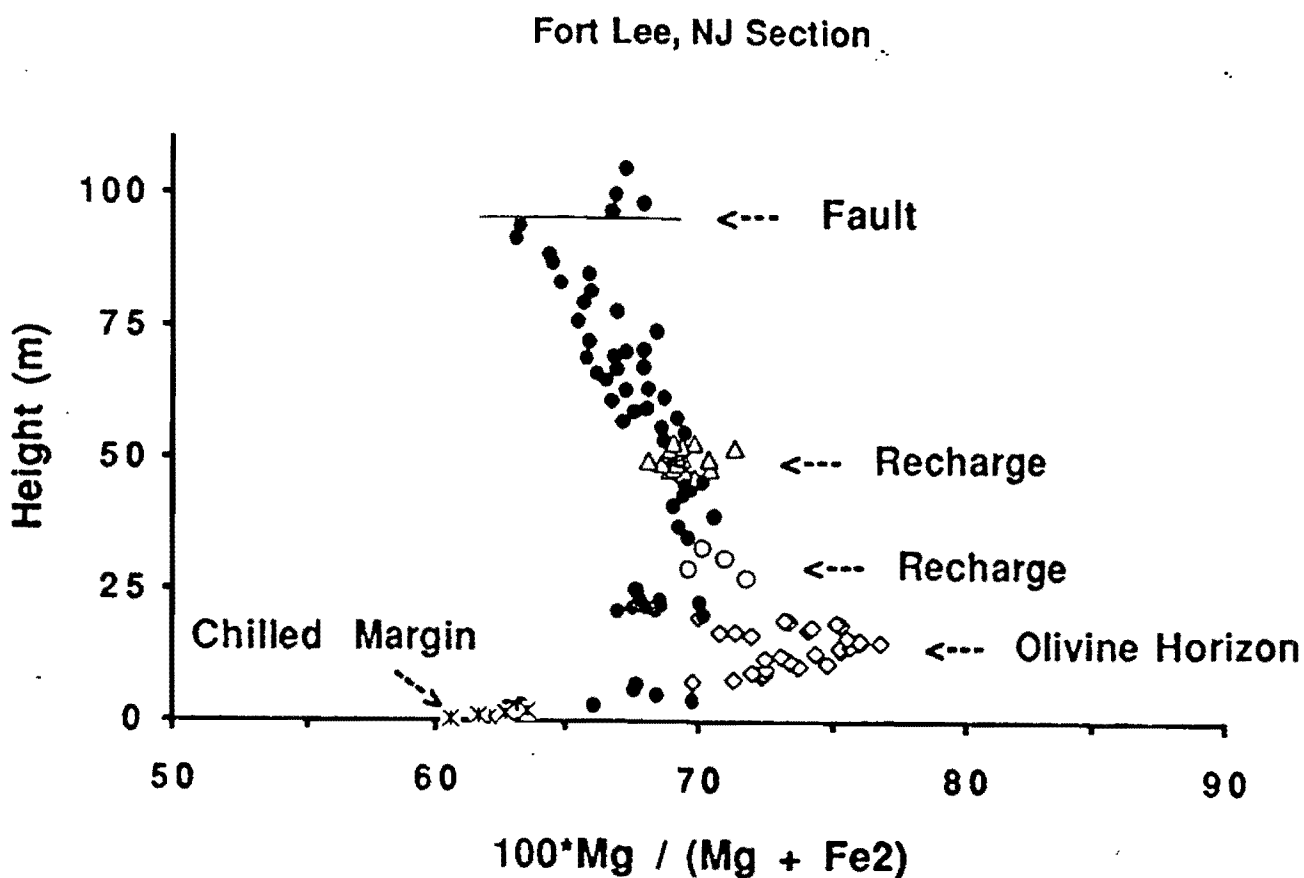


Fig. 4. Plot of Mg# vs. Stratigraphic Height for the Fort Lee, NJ section, showing the location of geochemically anomalous horizons at 10 m (open diamonds), 27 m (open circles), and 45 m (open triangles). Filled circles represent diabase samples from the sill that are not associated with geochemical anomalies, and asterisks represent chilled margin samples.

$$F' = 0.5 \cdot (Fe+Mg) + 2 \cdot Ca + 3 \cdot Na$$

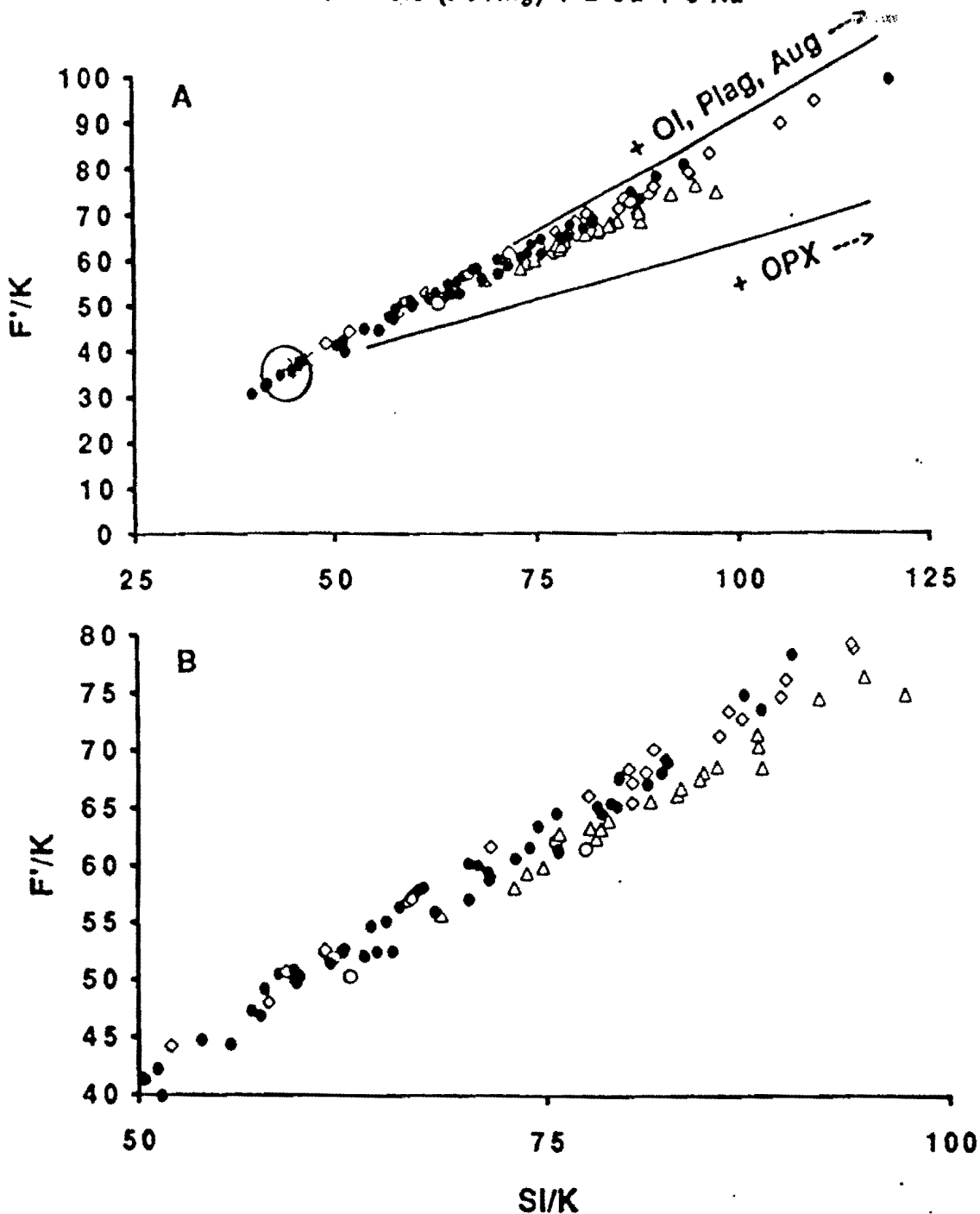


Fig. 5a. Pearce Element Plot of F'/K vs. Si/K where $F' = 0.5 \cdot (Fe+Mg) + 2 \cdot Ca + 3 \cdot Na$ for the Fort Lee, NJ section. The fractionation of olivine, augite, or plagioclase will cause a linear trend with a slope of 1.0, the fractionation of orthopyroxene will cause a linear trend with a slope of 0.5, and the fractionation of Fe-oxides will cause a linear trend with a slope of ∞ . The plot assumes an augite of composition $Ca_{0.67}(Fe, Mg)_{1.33}Si_2O_6$. The six chilled margin samples are circled. Symbols as in Figure 4.

Fig. 5b. Enlargement of the central part of 5a showing the separate trend for samples from the anomalous horizons at 27 and 45 m.

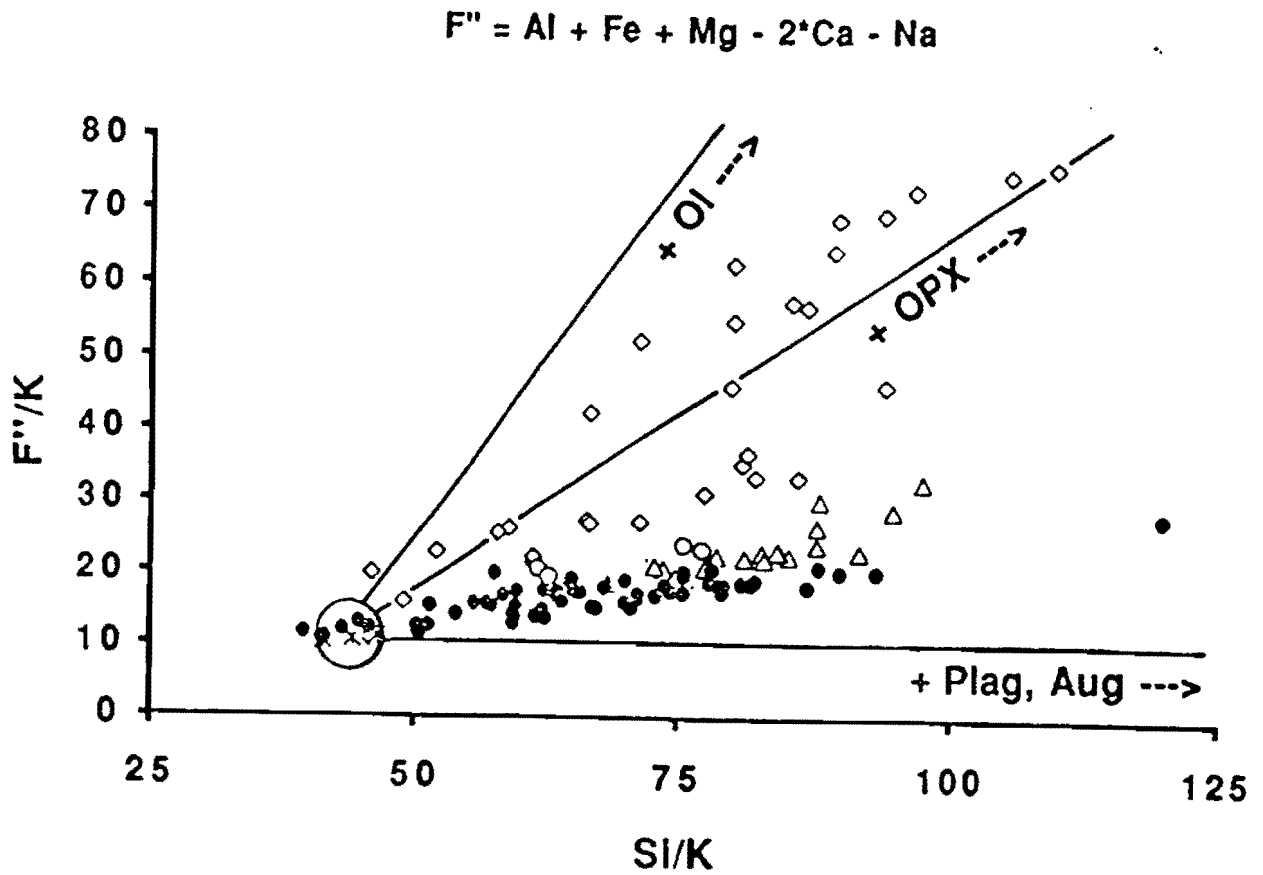


Fig. 6. Pearce Element Plot of F''/K vs. Si/K where $F'' = Al + Fe + Mg - 2 \cdot Ca - Na$ for the Fort Lee, NJ section. The fractionation of augite or plagioclase will cause a linear trend with a slope of 0.0, the fractionation of orthopyroxene will cause a linear trend with a slope of 1.0, and the fractionation of olivine will cause a linear trend with a slope of 2.0. Symbols as in Figure 4.

chamber and/or hybridized with the resident magma in the chamber. Both horizons are marked by abrupt but narrow intervals of increased Mg# and Cr contents, and higher percentages of cumulus orthopyroxene. The anomaly at 45 m is marked by an abrupt decrease in grain size for plagioclase and augite, and was observed in both the George Washington Bridge section and the Ross Dock section indicating that it extends for at least 500 m laterally. The anomaly at 95 m, which had been identified by a previous investigator as a recharge horizon, is the result of normal faulting.

Diabase samples from the roof sequence appear to represent nearly 100% solidified ("trapped") liquid from which plagioclase, augite, and orthopyroxene have been lost. In this regard they are a complement to the floor samples which appear to be where these minerals have accumulated. Minor geochemical anomalies in the roof section at 296m, 293m, and 283m, appear to correlate with the anomalous horizons in the floor sequence at 10m, 27m, and 45m, respectively.

Layering: Although the sill appears to be homogeneous on a hand specimen scale, faint Cm-scale layering is visible on some weathered surfaces. Two 20-Cm rhythmically layered sequences have been examined in detail; one section from the 10 m level, and another from the 70 m level (Fig. 7). Although layering is only faintly visible in outcrop, both sections have significant modal variations in the form of layers 1 to 3 cm thick. Layer boundaries are gradational, and parallel to the dip of the sill. In the section at 10 m: plagioclase varies from 35 to 55%; augite from 20 to 45%; hypersthene from 5 to 25 %; olivine from 0 to 10 %; and opaques from 1 to 10%. In the section at 70 m: plagioclase varies from 45 to 60%; augite from 35 to 50%; and opaques from 3 to 10%. Layers defined by variations in the more abundant phases (plagioclase and pyroxene) do not correlate with layers defined by the less abundant phases (olivine and opaques).

The well known olivine horizon of the Palisades sill is a layer of olivine-rich dolerite ranging from 1 to 10 m in thickness. It is located 10 to 13 m above the basal contact of the sill and is traceable for over 40 km along strike (Walker, 1969). The origin of this unit has been debated for almost 100 years, and was cited by Bowen (1928, p.71) as a classic example of crystal settling. Recent

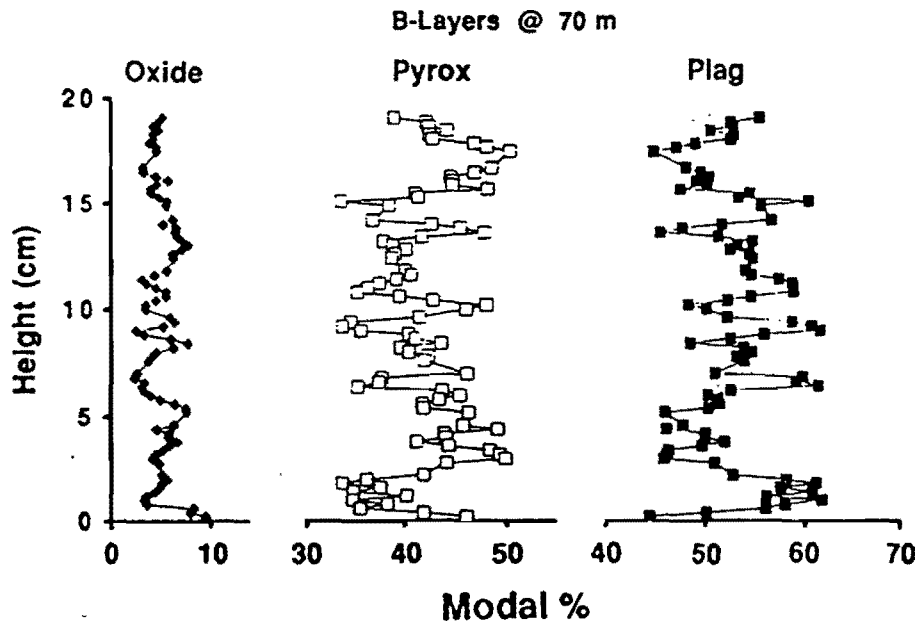
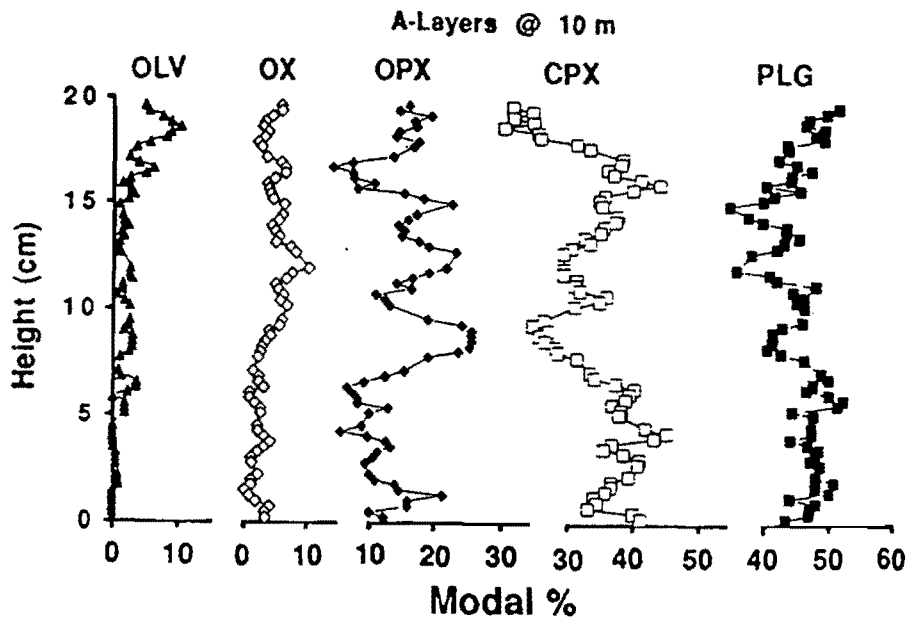


Fig. 7 Modal variation in layered sequences at the 10 m (A layers) and 70 m (B layers) stratigraphic levels.

interpretations, however, argue against gravity settling, suggesting instead that the olivine horizon is the result of either a separate pulse of olivine-rich magma (Husch, 1990) or an initially inhomogeneous magma (Gorring and Naslund, 1995). Both interpretations suggest that olivine was concentrated in the olivine-rich zone by flow segregation. Irregular cm- to m-scale layering within the olivine horizon appears to be the result of minor variations in the degree of flow segregation. Geochemical evidence from the lower part of the Palisades Sill indicates that, although plagioclase/augite and augite/orthopyroxene ratios are relatively constant, olivine/(plagioclase+pyroxene) in the olivine horizon is quite varied, suggesting that the olivine has been mechanically sorted (Gorring and Naslund, 1995). In figure 5, where olivine, plagioclase, and augite cause similar fractionation trends, samples from the olivine horizon plot along with samples from the main part of the sill. In figure 6, where the effects of olivine fractionation are separated from the effects of plagioclase and augite fractionation, samples from the olivine horizon plot as a wide scatter above the trend from the main part of the sill, indicating that the olivine horizon contains variable amounts of accumulated olivine.

Coats (1936) was probably the first to point out that crystals of differing sizes and densities tend to sort themselves in crude layers as they consolidate under the force of gravity. The forces responsible for this sorting are not well understood, but seem to be related to a self-organization of particles according to their drag coefficients in a viscous fluid. At a number of horizons within the lower part of the sill, weak, irregular, sub-horizontal layers are present. These layers appear to be similar to those postulated by Coats.

In the roof sequence of the sill, numerous pods and stringers of coarser-grained diabase form irregular grain-size layers. These are probably the result of auto injection of differentiated melts into the roof sequence.

The first 50 % solidification: A number of geochemical modeling techniques have been developed to explain the compositional variations observed in igneous rock suites. Five of these techniques have been used to model the first 50% solidification of the Palisades sill: (1) Rayleigh fractionation of excluded elements (Henderson, 1975); (2) incremental subtraction of the observed rock sequence from an initial magma composition (Morse, 1979,

1981; Naslund, 1989); (3) a least-squares-fit mass-balance calculation (Bryan, Finger & Chayes, 1969; Wright & Doherty, 1970; Bryan, 1986); (4) Pearce element ratio analysis (Pearce, 1968, 1990; Nichols & Russell, 1990); and (5) a liquid-line-of-descent calculation (the CHAOS program, Nielsen, 1985, 1988). Each of these methods requires assumptions about the differentiation process, and provides a set of relationships compatible with those assumptions.

Two methods were used to calculate the average "trapped" liquid content for the first 50% solidification of the Palisades sill. The two methods, however, are not entirely independent, in that both are based on the average content of excluded elements in the Palisades diabase, and both are dependent upon the choice of an initial liquid composition. The estimated average "trapped" liquid by these two methods ranges from 68% to 77%. The two preferred estimates are very similar; mass balance calculations, based on the average variation for ten major elements, yielded an average "trapped" liquid content of 75.6 %; a value of 76.7% was calculated from Rayleigh fractionation of TiO_2 . Rayleigh fractionation of P_2O_5 and K_2O suggest slightly lower trapped liquid contents (~68%).

Geochemical modeling by Shirley (1987) estimated 40 to 50% "trapped" liquid. This estimate, however, was based on a Palisades bulk composition in the Fort Lee section that was richer in excluded trace elements than the chilled margin by a factor of 1.5x. The Palisades bulk composition in the Fort Lee section calculated by averaging analyzed samples over uniform thickness intervals is also richer in TiO_2 , K_2O , Na_2O , and Fe_2O_3 (total iron) than the chilled margin, and is unlike any other magmas in the Eastern North America Mesozoic magma province (Whittington, 1988; Puffer & Philpotts, 1988; Puffer, 1992) (Table 1). It is likely that the sandwich horizon in the Fort Lee section is thicker than the intrusion-wide average (Figure 8). Mass balance calculations suggest that the bulk composition in the Fort Lee section can be obtained from a mixture of 73% chilled margin and 27% sandwich horizon. Shirley's (1987) estimate of 40-50% "trapped" liquid would be 60-75% if the excluded element content of the chilled margin was used for the initial magma in his calculations instead of the bulk composition calculated by summation.

Three relatively independent methods were used to determine the trend of magma differentiation and the fractionated mineral assemblage represented by

Table - 1

Estimated initial Palisades magmas and selected ENA magmas

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	CM f	CM r	BU*	BU	HTiQT	HFeQT	LTiQT	HFO	LFO	OMB	P-1	P-2	P-3	HMB
SiO ₂	52.5	52.8	53.3	53.5	51.5	52.2	51.4	47.5	49.2	51.5	52.7	51.7	50.9	49.8
TiO ₂	1.137	1.026	1.633	1.671	1.128	1.130	0.756	0.585	0.600	1.163	1.114	1.065	0.816	1.444
Al ₂ O ₃	14.2	14.3	13.8	13.9	14.3	14.1	14.9	14.4	16.9	14.4	14.1	14.4	15.6	13.5
Fe ₂ O ₃ t	11.1	11.0	12.5	12.5	11.7	13.7	11.7	12.6	10.3	11.0	12.5	13.2	11.5	16.0
MnO	0.177	0.163	0.178	0.178	0.191	0.218	0.199	0.188	0.170	0.162	0.213	0.195	0.184	0.252
MgO	7.47	7.28	6.19	5.78	7.47	5.48	7.40	12.19	8.94	7.84	5.92	6.13	7.72	5.67
CaO	10.25	10.39	8.85	8.86	10.74	9.78	10.75	10.47	11.27	10.80	9.72	7.12	10.18	10.39
Na ₂ O	2.07	2.07	2.36	2.41	2.14	2.49	2.22	1.79	2.11	2.46	2.97	5.10	2.70	2.30
K ₂ O	0.865	0.674	1.034	1.057	0.665	0.634	0.478	0.258	0.390	0.486	0.648	0.942	0.357	0.404
P ₂ O ₅	0.142	0.202	0.202	0.207	NR	NR	NR	0.089	0.140	0.142	0.132	0.143	0.092	0.192
sum	100.0	100.0	100.0	100.0	99.8	99.8	99.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Mg#	57.0	56.6	49.6	47.9	55.9	44.1	55.6	65.7	63.1	58.5	48.5	47.8	57.0	41.2

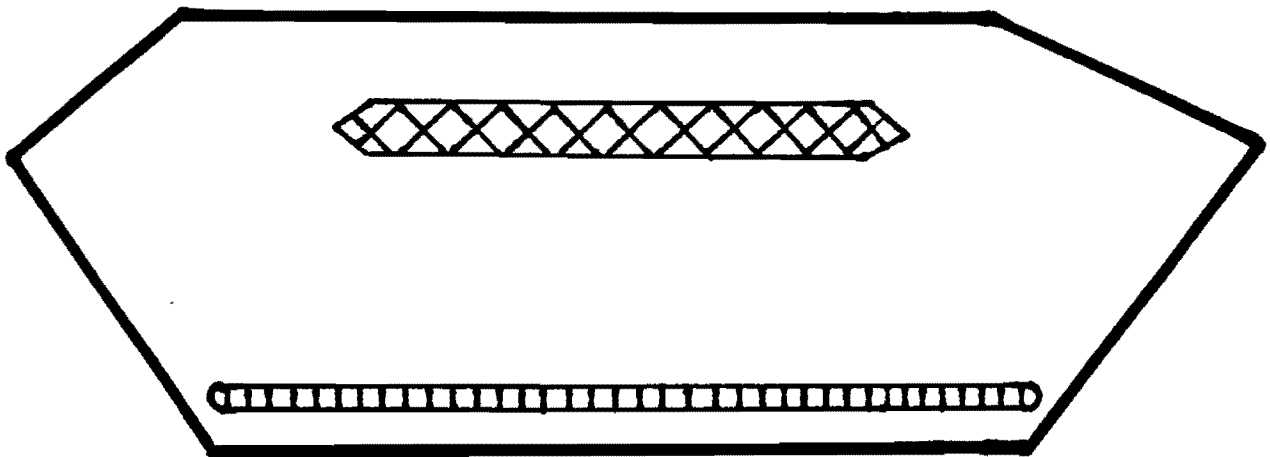
1 - 4 Estimated Palisades magmas: floor chilled margin, roof chilled margin, bulk composition, bulk composition without olivine horizon.

5 - 7 ENA magma types: high-Ti quartz tholeiite, high-Fe quartz tholeiite, low-Ti quartz tholeiite (Puffer and Philpotts, 1988)

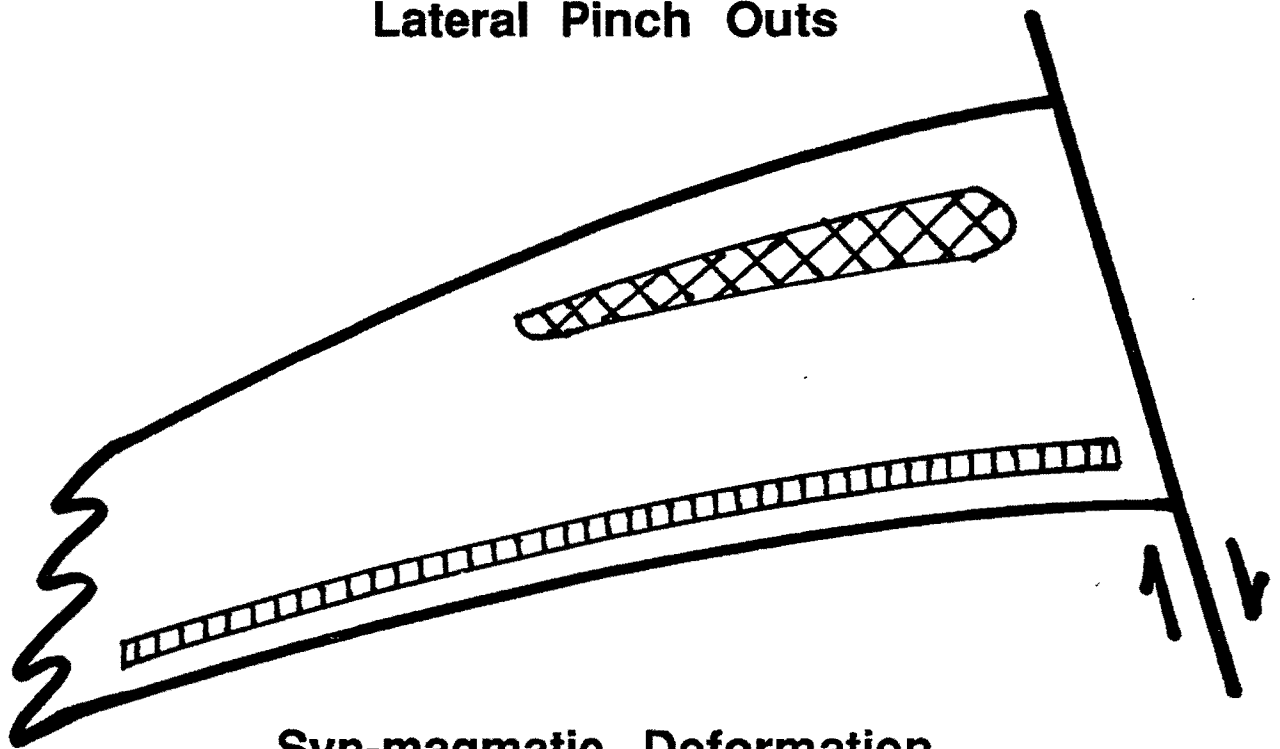
8 - 9 ENA magma types: low-Fe olivine tholeiite, high-Fe olivine tholeiite (Whittington, 1988)

10-14 Whatchung basalts: Orange Mountain, Preakness 1, Preakness 2, Preakness 3, Hook Mountain (Puffer, 1992)

Fe₂O₃ t = Fe₂O₃ + 1.11*FeO; Mg# = Mg/[Mg+Fe] in cation %; NR = not reported



Lateral Pinch Outs



Syn-magmatic Deformation

Figure 8 - Two possibilities that could explain why the Fort Lee section of the Palisades sill is more iron-rich than the chilled margin. Cross hatched pattern = iron-rich Sandwich horizon; vertical ruled = olivine horizon.

the initial 50% solidification of the Palisades sill. All three methods indicate that the composition of the Palisades magma was enriched in TiO_2 , K_2O , P_2O_5 , Fe_2O_3 (total iron), and MnO , and depleted in MgO as differentiation proceeded. SiO_2 remained relatively constant (<1% change) over the first 50% solidification of the sill in all three models. These models suggest that the Palisades sill fractionated a crystal assemblage dominated by plagioclase (43-58%), augite (24-30%), and orthopyroxene (19-27%), with the percentage of plagioclase and the ratio augite/orthopyroxene increasing as differentiation proceeded over the first 50% solidification. Similar results were obtained by Steiner *et al.* (1992) for the section in Upper Nyack, NY, where their cumulus-transport-deposition model calculated 46.1% plagioclase, 36.8% augite, and 17.1% olivine or orthopyroxene fractionation for the first 49% crystallization, with similar increases in plagioclase and augite / (olivine or orthopyroxene) with increasing crystallization.

Although, the magmas at the roof and floor appear to have fractionated similar mineral assemblages, the compositional differences between the roof and floor sequences suggests that the roof sequence has lost early formed minerals while the floor sequence has gained them. The floor sequence diabbases fit reasonably well a model in which the fractionated mineral assemblage and the percent "trapped" liquid change as crystallization proceeds in accord with the proportions calculated by mass balance. The roof sequence, however, has much lower Mg#s and fits best a model in which the roof sequence diabbases represent approximately 95% "trapped" liquid, but in which the liquid has undergone approximately 50% differentiation (i.e. crystals have settled out of the magma at the roof into the lower part of the chamber).

Implications for the crystallization of magma chambers:

Geochemical models for the Palisades sill suggest that the initial solidification of the sill was accompanied by approximately 25% fractionation of a crystal assemblage dominated by plagioclase, augite, and orthopyroxene. Compositional variations within the roof and floor sequences appear to be related to similar fractionation assemblages, but between 66 and 90% of the differentiation recorded in the roof sequence, as indicated by excluded element enrichment and Mg# depletion, is the result of crystal accumulation at the floor.

Although heat loss through the roof of the intrusion presumably exceeded heat loss through the floor, the floor sequence is approximately 5 times thicker than the roof sequence. These results require a mechanism for transferring crystals from the roof to the floor, and/or heat and differentiated magma from the floor to the roof.

A number of recent papers have discussed the dynamics of heat transfer during cooling in sheet-like magma chambers; some have concluded that convection is vigorous (Sparks, Huppert & Turner, 1984; Brandeis & Jaupart, 1986; Martin, Griffiths & Campbell, 1987; Sparks, 1990; Huppert & Turner, 1991; Worster, Huppert & Sparks, 1993), some have concluded that convection is weak or absent (Helz, 1987; Marsh, 1988, 1989a, 1989b, 1990, 1991; Gibb & Henderson, 1992), and some have concluded that heat (or heat loss) is transferred by plumes (Brandeis & Jaupart, 1986; Helz, 1987; Marsh, 1988, 1989a, 1989b). The Palisades sill is important in this debate because, with a thickness of 300 m, it is thicker than most of the sheet like bodies with D- or S-shaped profiles that show little evidence for the settling of crystals formed in-situ, or any evidence for post emplacement convection (Gibb & Henderson, 1992), but is smaller than most gabbroic intrusions that have clearly differentiated in-situ, and therefore, must have undergone convection or some other form of internal heat and mass transfer.

The Palisades data fit best a model in which heat loss at the roof results in crystallization adjacent to the upper solidification front, with plumes of cool, crystal-rich magma continuously detaching from the roof zone and settling to the floor where they remain and eventually solidify. Owing to the fact that pyroxene is richer in MgO than magma with which it is in equilibrium, crystallization at the roof results in a situation where both the fractionated crystal assemblage and the residual magma are denser than the underlying, unfractionated magma. This will result in the development of a "convection half-cell" in which there is steady downward flow of cool, crystal-rich magma from the roof zone, but no return upward flow. As plumes detach from the upper crystallization front, some of the interstitial liquid in the crystal-liquid mush is extracted from the plume to fill the void behind the plume. This is a process similar to that proposed by Marsh (1996) for liquid extraction from detached solidification fronts at a later stage of crystallization (55 to 60% crystals). Such a model allows the roof

sequence magma to evolve as though it was fractionating 30 to 50% early formed crystals, while the roof sequence diabases appear to represent 90 to 95% "trapped" liquid, and allows the floor zone to accumulate at five times the rate at which the roof zone accumulates, even though the majority of the heat loss occurs at the roof and the floor zone diabases contain only about 25% accumulated crystals. It is probably more than a coincidence that the percent of crystals added to the floor sequence is the same as the percent of entrained crystals proposed by Marsh (1989a) for the limit between a crystal suspension and a crystal mush. Plumes that arrive at the floor with less than approximately 25% entrained crystals are likely to be displaced upward by the later arrival of denser plumes. Plumes with 25% or more entrained crystals, however, once attached to the floor, are unlikely to move regardless of where the majority of the heat loss in the intrusion is occurring, or how the density of the overlying magma changes. Indeed, the presence of a thick floor sequence with approximately 25% accumulated crystals, may provide a indication of plume driven cooling in other sills (Fig 9).

The final 50 % solidification: Studies of lava lakes have suggested that compositional and thermal transfer can occur in magma bodies through vapor migration, and diapiric melt transfer (Helz, 1987). McBirney (1980) suggested that plumes of buoyant melt generated at crystallization fronts can rise through a magma and collect under the chamber roof to produce zoned magmas. In thick section of the Holyoke flood basalt differentiated liquid separated from the partially crystallized basalt after ~33% crystallization and migrated upward to form segregation sheets of coarser grained diabase (Philpotts, *et al.*, 1996). Similar pods and sheets of coarse-grained diabase are common in the Palisades sill in the crystallization interval from 50% to 100% solidified. Preliminary examination of this part of the sill suggests that during the later stages of crystallization of the Palisades sill, this may have been the dominant differentiation process.

Irvine (1980) suggested that heat and chemical components can be transferred though cumulate rocks by the upward migration of interstitial liquids through the porous crystal-liquid mush. Such a process results in extensive mineral-melt reequilibration, or "infiltration metasomatism". The segregation of

Model For Palisades Crystallization:

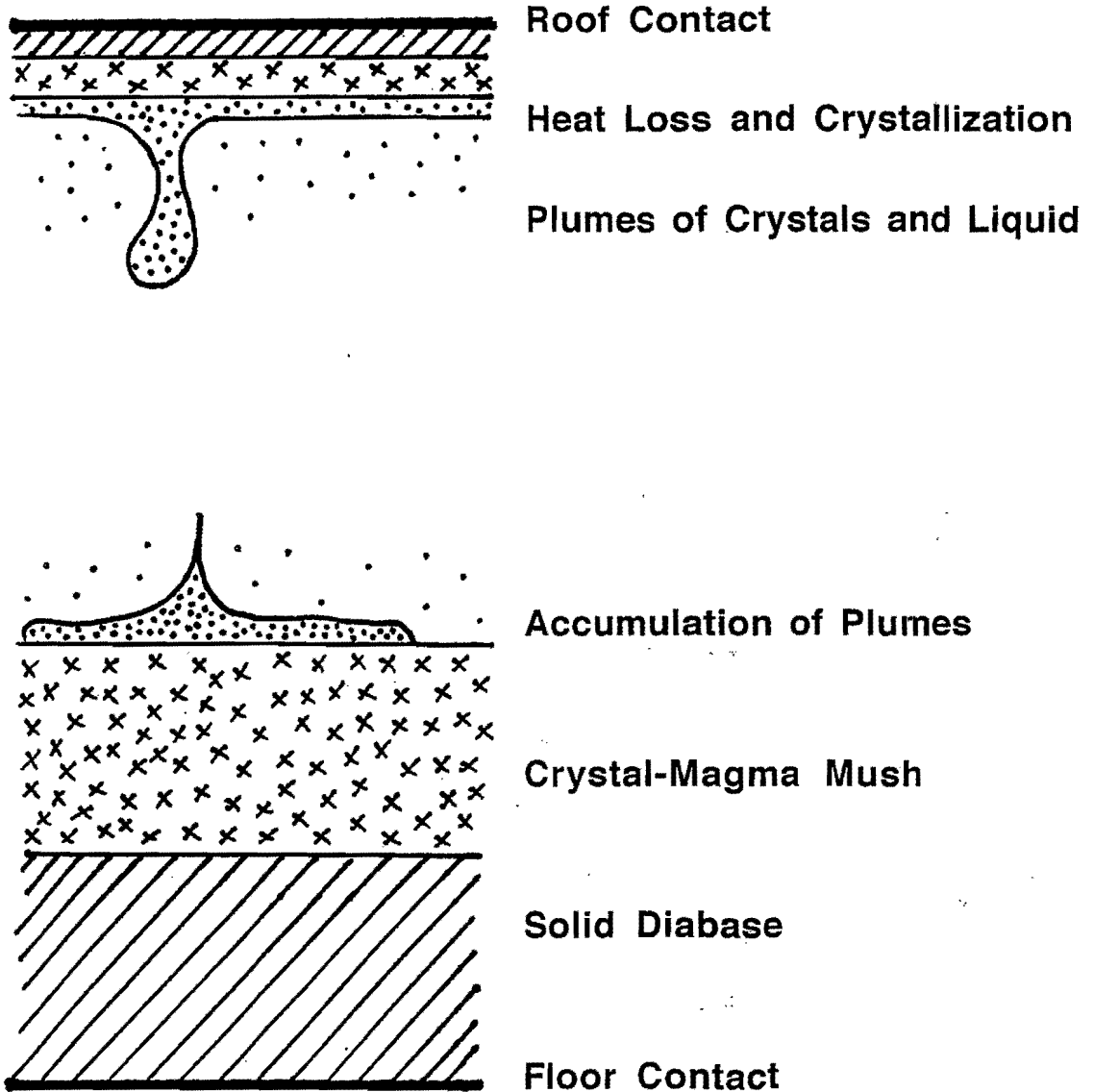


Figure 9 - Crystallization Model for the Palisades sill.

coarse grained diabase pods and lenses in the Palisades sill may have occurred through such a process of interstitial melt migration. This process has been modeled for the Palisades sill by Shirley (1987) who demonstrated that the process could qualitatively explain some of the features of the general Palisades differentiation trend. His study, however, lacked the detailed sampling necessary to confirm the model.

In the Skaergaard intrusion the roof-zone sequence is enriched in SiO₂, TiO₂, K₂O, P₂O₅, and Zr relative to the floor sequence (Naslund, 1984) suggesting that the magma at the roof of the Skaergaard chamber was compositionally zoned relative to that at the floor, or that components were added to the roof sequence by upward migration through the crystal-liquid mush. In the Palisades sill, the roof-zone sequence is enriched in Na₂O, K₂O, Al₂O₃, TiO₂, FeO, Zn, Ba, and Zr relative to the floor-sequence. In both intrusions, plagioclase in the roof-sequence has lower K₂O contents than plagioclase in the floor-sequence, in spite of the fact that, the host rocks at the roof are richer in K₂O (Naslund, 1984 and unpublished data). This relationship suggests a concentration of volatiles and increased P_{H₂O} in the roof-zones of these intrusions. An additional similarity between the Palisades and the Skaergaard is that both have significantly coarser grain-sizes in their roof sequences relative to their respective floor sequences. This is probably a reflection of a slower advance of the crystallization front at the roofs of the chambers, but might also be influenced by an increased volatile content at the roof.

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A4 - Roadlog

Mileage is broken up into three parts: (1) Binghamton to the Palisade Interstate Park Headquarters; (2) From the Park Headquarters to Fort Lee NJ (3) From Fort Lee to Binghamton, New York.

Binghamton, New York to the Palisades Interstate Park Headquarters:

- 0.0 Leave from the Parking lot at Binghamton University, turn right and proceed out the main campus entrance.
- 0.4 Turn Right on Vestal Parkway, Rt. 434
- 3.4 Follow the road as it turns left over the Susquehanna River and get into the right lane.
- 3.6 Turn right onto Rt. 363 following signs for Interstate 81.
- 5.3 Turn right onto Interstate 81 south. Watch the merge lane onto 81 South, traffic enters from the left.
- 9.3 Get in the left hand lane and take route 17 east.
- 138 Take exit to route 6 through Harriman Park.
- 144 Take the Palisades Parkway south.
- 169 Take exit 2 off of the Palisades Parkway. Turn left and then left again passing under the Parkway. Follow signs to the Palisades Interstate Park Headquarters.

From the Park Headquarters to Fort Lee, New Jersey:

- 0.0 **Stop 1** - Park in the parking lot at the headquarters building and walk down the road (away from the parkway, towards the river) about 0.1 miles to the second set of outcrops on the left. This is about the 70m stratigraphic level in the sill. The rock here is a two pyroxene diabase with weak modal layering. Plagioclase abundances vary from 45% to 60 % and pyroxene varies from 35% to 50 % from layer to layer. The Palisades diabase is, in general, a rather featureless rock. This horizon is one of two in the sill that has poorly developed rhythmic layering.

Along the length of the central part of the sill similar layering is found at the 70 m level near the top of the cliff face. At stop 6 we will see another example of this layering.

Return to cars at Park headquarters and drive down the road to the river past the stop 1 outcrop. Go slowly and watch for bikers.

- 0.6 **Stop 2** - Leave flashers on and stay on the right side of the road to avoid traffic. Remind students to stay out of the roadway. Well developed rhythmic layering is present below the olivine horizon at the 10m stratigraphic level. The main layering "signal" is in the orthopyroxene which varies from 10% to 25%. Texturally the orthopyroxene is ophitic to poikilitic at this level.

Proceed down the road and turn right at the circle to drive south along the river. If the road is closed return to the Palisades parkway heading south and get off at exit 1 (Hudson Terrace). Turn left at the stop sign and proceed down to the river to rejoin the roadlog at the base of the cliff (mileage 5.6) and proceed south along the river. As you drive along the river you are at a level below the Palisades sill in arkoses of the Stockton formation.

- 7.4 The circle above Ross landing boat dock. Note the crude columnar jointing in the diabase above the circle. If you desire an additional stop: above the steps under the roadway at the circle, in the second buttress of outcrops to the north, flow banding is present within the olivine horizon. Watch for poison ivy !!! Continue south from the circle along the river.

- 7.6 **Stop 3** - Chilled margin (if the road is blocked you can see similar contact relations by walking south from the circle). Note the minor stair steps in the lower contact and the contact metamorphism of the arkose below the sill. The sill here has a uniform composition for 3 m in from the very fine grained chilled margin. Note that in places it is hard to tell the difference in hand specimen between hornfels sediments below the sill and the Palisades fine-grained chilled margin.

Proceed south under the George Washington Bridge. A phytosaur

(Clepsysaurus Rutiodon) was found in the Stockton arkose below the bridge.

- 8.2 **Stop 4** - Just before the park entrance there is a classic undercut outcrop of the olivine horizon. Although it looks really rotten you can see fresh olivine in it.

Proceed south to the entrance on Bergen County route 505. Turn right (north) and proceed up the hill.

- 8.6 **Stop 5** - The entrance to Fort Lee Historic Park. Drive in or park on the street and walk in. The first outcrops inside the park along the entrance road have sub-horizontal, irregular, plagioclase-rich layers. These appear to be layers of the type theorized by Coats (1936) to have formed by settling and compaction of a crystal mush within a viscous fluid.

From the park entrance turn right on Bergen county route 505. Mileages assume you parked on the street and did not drive in which would add ~0.2.

- 8.8 Just after you pass under the interstate turn left on Merkel past the Toll Gate Motel (hourly rates available). After 1 block Merkel runs into N. Central. Turn left and circle around onto Bridge Plaza North. After two blocks turn right on Hudson St. and park.

- 9.0 **Stop 6.** - Outcrop with the best rhythmic layering in the Sill is located around the corner you just passed on Bridge Plaza North. This is again at the 70 m level in the sill. This layering is very regular suggesting a mechanism involving changing conditions of crystallization at the crystal/magma interface rather than layering due to compaction processes.

Continue west on Bridge Plaza North to mileage 9.5, take the middle of three lanes. Turn left on Fletcher, stay in the right hand lane and after crossing over the interstate bear slightly to the right down the hill on Edwin.

- 9.8 **Stop 7** - Park in front of the NJ dept. of transportation lot. Outcrops of coarse, iron-rich "sandwich horizon" are exposed to the left of the cemetery entrance.

Proceed on Edwin to the stoplight, turn left and then left again on Fletcher. As you pass back over the interstate stay in the right lane and take the first right onto 80/95 west/south. Stay in the right hand lane and watch for traffic entering from the right.

- 11.2 **Stop 8** - Just after you pass under an impressive high bridge pull over on the shoulder. Park with your flashers on and **stay off of the roadway. Be careful, if the police come, be polite and they will probably ask you to leave.** Cross over the guard rail and look at the upper contact of the sill. Lots of interesting vein minerals and some grain-size layering. The roof rocks below this level (back before the bridge you just passed under) contain segregations of coarse-grained gabbro injected as dikes and sills.

From Fort Lee, New Jersey to Binghamton, New York:

- 0 Proceed west on I-80 through the Delaware Water Gap.
- 93 Proceed north on I-380.
- 121 Proceed north on I-81.
- 180 Stay in left lane on Route 17 west.
- 184 Turn right onto 201 south.
- 185 Take first right at circle and cross the Susquehanna River. Follow signs to route 434 east and SUNY.
- 186 Turn right into SUNY campus.