

Palisades sill: Origin of the olivine zone by separate magmatic injection rather than gravity settling

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ABSTRACT

The still widely cited view of the Palisades sill, northeastern United States, being differentiated largely by vertically directed, olivine-dominated fractionation is not supported by available structural, petrographic, and geochemical data. Rather, the sill can be viewed as a sheetlike composite intrusion, possibly made up of multiple magma types common to the Mesozoic eastern North America magmatic province. The famous olivine zone of the Palisades sill may have resulted from a separate late intrusion of olivine-normative magma and not from gravity-controlled, olivine-accumulation processes. Pyroxene-dominated fractionation accounts for much of the vertical and lateral compositional variations in the Palisades sill and other related intrusions from the province.

INTRODUCTION

The Early Jurassic Palisades sill, intruded into Triassic continental sedimentary rocks of the Newark basin (Fig. 1), is cited in many introductory geology and igneous petrology texts as the "classic example" of a vertically differentiated sill (see Carmichael et al., 1974; Best, 1982; Hyndman, 1985; Press and Siever, 1985; Atkin and Johnson, 1988; Birkeland and Larson, 1989). This differentiation usually is ascribed to the in situ fractionation of early-formed olivine primocrysts within a quartz-normative tholeiitic basalt magma, associated with either a single magma injection (Walker, 1940) or a second, more fractionated magma (Walker, 1969). A prominent assumption of both hypotheses is that the distinctive "olivine zone," found locally just above the intrusion's lower chill margin, formed

by gravity settling. However, this view is based on several misconceptions, and various lines of evidence, much already published, suggest that it is largely incorrect.

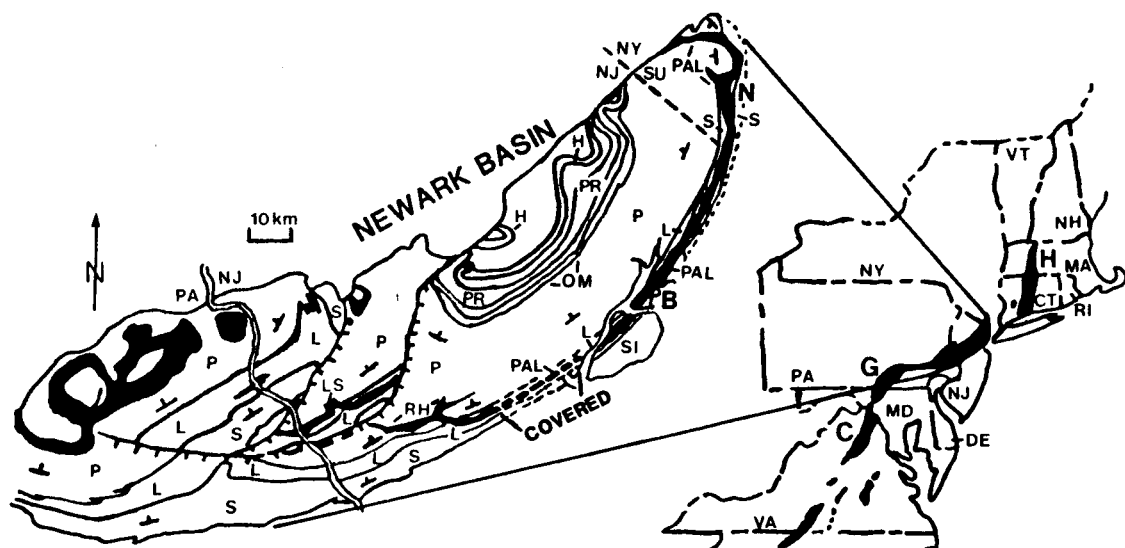
FOUR COMMON MISCONCEPTIONS

The first misconception is that the Palisades sill extends only from Staten Island to near Suffern, New York (Fig. 1), and that the intrusion is largely sill-like as viewed along strike. Although the Palisades generally is conformable within the Newark Supergroup in northern New Jersey, it clearly is discordant at its northern end (Fig. 1). In addition, drill-hole and geophysical data show that the Palisades reemerges from beneath Cretaceous sedimentary cover as the Rocky Hill diabase in the central Newark basin (Fig. 1; Lewis, 1907; Sandberg et al., 1990). Postintru-

sion normal faulting again reexposes the Palisades sill farther west as the Lambertville sill (Husch et al., 1988). Both of these diabase bodies are discordant, particularly at their southwestern ends. Thus, the expanded Palisades body, exposed over a strike length of about 150 km (Fig. 1), is not a sill at many localities and would better be described as a sheet.

A second misconception is that the olivine zone of the Palisades sill is typical of other sheetlike intrusions in the Mesozoic eastern North America magmatic province derived from a high-titanium quartz-normative tholeiitic (referred to herein as "high-Ti") magma. In fact, none of the other studied high-Ti sheets are known to contain such a feature (Froelich and Gottfried, 1985). What many of these intru-

Figure 1. Simplified geologic map (after Olsen, 1988) of Newark basin and location of Mesozoic basins in northeastern United States. Other Mesozoic basins are Culpeper (C), Gettysburg (G), and Hartford (H). Black areas in Newark basin represent diabase sheets. Hopewell and Flemington-Furlong-Chalfont fault systems are shown with hachures on hanging-wall or down side. Strike and dip symbols give regional orientation of sedimentary rocks. PAL = Palisades sill; RH = Rocky Hill diabase part of Palisades; LS = Lambertville sill part of Palisades; S = Stockton Formation; L = Lockatong Formation; P = Passaic Formation; OM = Orange Mountain basalt; PR = Preakness basalt; H = Hook Mountain basalt; B = Bayonne, New Jersey; N = Nyack, New York; SI = Staten Island, New York; SU = Suffern, New York.



sions, including the Palisades, do have in common is the presence of zones of pyroxene (both orthopyroxene and clinopyroxene) accumulation, generally toward their bottoms (Froelich and Gottfried, 1985).

A third misconception is that the olivine zone extends as a prominent feature along most of the exposed length of the Palisades and that olivine abundances decrease gradationally both above and below the zone (F. Walker, 1940). Actually, the olivine zone is seen only between Bayonne, New Jersey, and Nyack, New York. For much of this distance the zone is less than 3 m thick; it pinches and swells along strike, and in places it disappears completely (Walker, 1969). In addition, Walker (1969) and Shirley (1987) reported both the upper and lower contacts of the olivine zone to be abrupt; within 1 m, modal olivine (FO_{55-70}) decreases from 15%–25% to nearly complete absence. Finally, other than the small amounts (0–3 modal percent, $\sim FO_{80}$) found in the upper and lower chills of the Palisades and in some highly fractionated granophyres from the interior of the sheet (FO_{5-20}), olivine is absent from the rest of the intrusion. In the central New Jersey part of the body, only a few anhedral, embayed grains of olivine (FO_{80}) have been observed in chill-margin samples (Husch, 1988; Husch et al., 1988).

Given the paucity of olivine, other than in the olivine zone, and its relatively small grain size (Walker, 1969), it is difficult to envision that gravitational settling could remove *all* olivine from the interior of the Palisades and concentrate it entirely within the zone. This contrasts with the abundant olivine found above and below olivine-accumulation zones in the Ha-

waiian lava lakes (Wright and Peck, 1978) and the Garbh Eilean sill (Johnston, 1953). In addition, olivine abundance and forsterite content increase inward from the margins of the olivine zone (Walker, 1969). This situation is more consistent with a flow-differentiation mechanism (Komar, 1972) than with olivine "raining down" from above.

A fourth misconception is that vertical variations across the Palisades sill are far more extensive than any lateral ones found along its length. As discussed by Husch et al. (1988), many vertical sections through the sheet do not appear to be in mass balance with their high-Ti parent, as represented by the chill-margin composition. This lack of local mass balance appears to be a common feature of many eastern North America magmatic province high-Ti intrusions; those with thick and extensive pyroxene-accumulation zones commonly lack significant amounts of complementary residual granophyres, and those intrusions that do have large volumes of granophyric rock lack any significant amounts of pyroxene-rich compositions (Smith et al., 1975; Gottfried et al., 1985; Froelich and Gottfried, 1988). In many instances, lateral variations are greater than vertical ones. However, for that part of the Palisades sill exposed in the central Newark basin, the regional average is in reasonably close agreement with the chill-margin composition (Husch et al., 1988).

The regional mass balance, coupled with the lack of mass balance locally, could have been produced by residual liquids migrating laterally from where pyroxenes were accumulating. Because there is a consistent tendency for the more granophyre-rich sections of the sheet to be intruded at higher levels within the Triassic rocks

than mafic-rich sections (Puffer et al., 1982; Husch et al., 1988; Murphy and Husch, 1990), the residual liquids appear to have migrated up dip as well.

GEOCHEMICAL MISCONCEPTION

A final, most critical misconception is that the whole-rock geochemistry of the Palisades diabase is consistent with the early, in situ accumulation of fractionated olivine to produce the olivine zone. On the contrary, selected major and trace element whole-rock variation trends from the central Newark basin part of the Palisades (Fig. 2) are not compatible with significant olivine fractionation during the differentiation of the sheet (Husch, 1988; Husch et al., 1988). These trends, with very few exceptions, closely resemble those determined by Walker (1969) for the northern New Jersey part of the Palisades sill.

If olivine fractionated to any meaningful degree early in the crystallization of the Palisades, residual-liquid concentrations for SiO_2 and CaO would have increased significantly, and those for Ni would have decreased much more dramatically than Figure 2 indicates. Although it is true that some of the variation trends might be produced by fractionating a SiO_2 - and CaO-rich and Ni-poor phase, such as plagioclase, along with olivine, the early incompatible behavior of Al_2O_3 (Fig. 2B) and the absence of increasingly negative Eu anomalies with decreasing MgO (Shirley, 1987) are not consistent with the early removal of plagioclase.

On the other hand, the early fractionation of high- and low-Ca pyroxenes is consistent with the observed petrography of the analyzed samples and with the more highly compatible be-

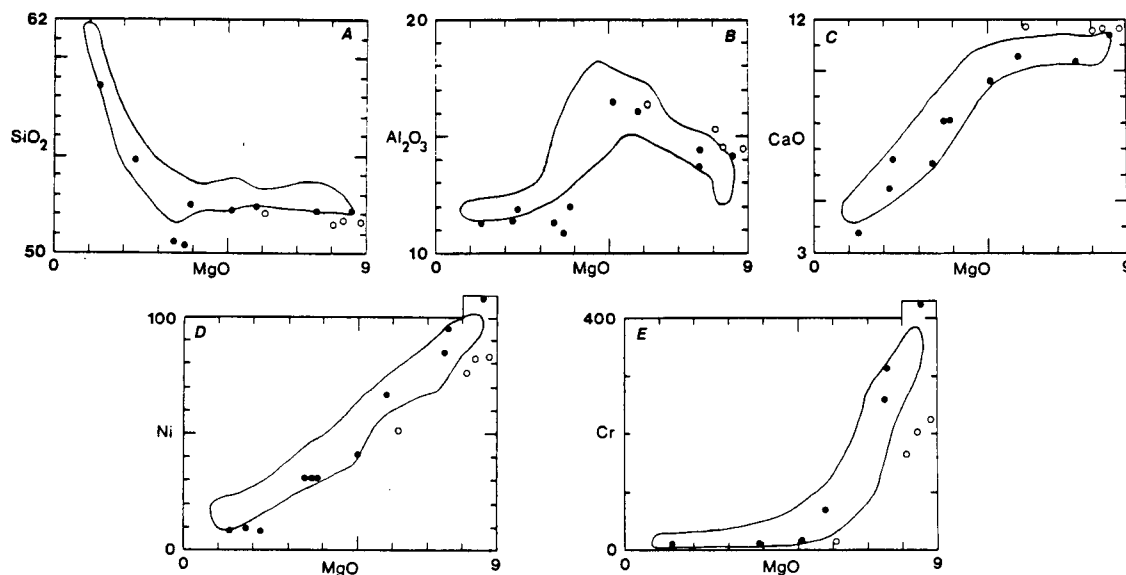


Figure 2. Selected whole-rock oxide and trace element vs. MgO variation trends for Palisades sill. Enclosed fields are for high-Ti magma-related diabase samples from central Newark basin (Husch et al., 1988). For comparison, olivine-free samples from northern New Jersey part of Palisades sill (solid circles; Walker, 1969) and four low-Ti magma-related samples from central Newark basin (open circles; Husch et al., 1988) are shown. Oxide contents are given in weight percent and trace elements are given in parts per million.

havior of Cr (Fig. 2E) compared to Ni (Fig. 2D; Husch, 1988; Husch et al., 1988). Furthermore, the slight early depletion of CaO (and Sc) and the lack of early SiO₂ enrichment agree with the early removal of both pyroxene phases.

The geochemical study of Pearce (1970) also indicated that olivine fractionation did not produce the whole-rock compositions of the olivine-free rocks. A number of his variation trends for the olivine-rich rocks of the Palisades olivine zone are separate and distinct from those for the rest of the sheet; other than in the zone itself, early fractionation was pyroxene controlled.

ALTERNATIVE MECHANISM FOR ORIGIN OF THE OLIVINE ZONE

Given the above considerations and their incompatibility with an origin of the olivine zone by the gravitational settling of olivine, it is logical to consider that the zone may have formed as the result of the intrusion of a separate olivine-normative magma. Such an origin is consistent with available structural, petrographic, and geochemical data. Although olivine-normative magmas, such as the high-lithophile element olivine-normative (Ragland and Whittington, 1983) or Quarryville types (Smith et al., 1975), are common farther south in the eastern North America magmatic province, any proposed parental magma of the Palisades olivine zone appears to have to be dissimilar to them. For example, Pd/Pt ratios for olivine zone rocks are consistently lower than for the Quarryville type (Gottfried, personal commun.). However, as discussed by Shirley (1987), on the basis of the similar slopes for the distribution patterns of the rare earth elements (REE) and the constant Th/Hf values throughout the entire sheet, the olivine zone could represent the intrusion of a magma related to the typical high-Ti type found at the chills of the Palisades sill by either crystal fractionation or a common parental source. Given the difficulty of producing an olivine zone magma from a high-Ti parent with an almost identical REE content, a common-source relation appears more probable. Such a relation has been proposed for olivine-rich basalts inter-layered with typical eastern North America magmatic province high-Ti flows in South Carolina (Gottfried et al., 1983).

DISCUSSION

The Palisades sill has been documented previously by Walker (1969), Puffer et al. (1982), Shirley (1987), Husch and Roth (1988), Husch et al. (1988), and Steiner et al. (1989) as being a composite body produced by the injection of multiple magma batches; the formation of the olivine zone is associated with one of these (Walker, 1969; Shirley, 1987). However, the magmas involved usually have been assumed to

be of a single high-Ti type (Walker, 1969; Puffer et al., 1982; Froelich and Gottfried, 1985; Shirley, 1987). Whole-rock geochemical data from Palisades exposures in the central Newark basin (Fig. 2; Husch et al., 1988; Husch and Roth, 1988) suggest that a second eastern North America magma type, the low-titanium quartz-normative tholeiite (referred to herein as "low-Ti"; Weigand and Ragland, 1970), was injected locally. Therefore, it is not unreasonable to suggest that a third magma type also is present within the composite Palisades; three eastern North America magma types are found in the southwestern end of the Newark basin and the adjoining Gettysburg basin (Smith et al., 1975). Given the internal location of the olivine zone and the apparently low-Ti magma-derived rocks, their parental magma pulses must have been injected after the initial pulse(s) of high-Ti magma found at all chill margins (Fig. 3).

The absolute timing of all pulses is not known. However, only a few internal chills have been observed (Walker, 1969; Steiner et al., 1989), and none are present unambiguously at the margins of the olivine zone, suggesting that the time between most pulses was short. It is tempting to correlate the injection of the high-Ti magma pulses to the multiple flows of the Orange Mountain basalt (Puffer, 1988). The single low-Ti magma pulse hypothesized for the central Newark basin part of the Palisades might correlate with the upper low-Ti flow unit of the younger Preakness basalt (Puffer, 1988). How-

ever, this correlation would require that the Palisades remain largely liquid for about 2.50 ka, on the basis of the lake-cycle sequence of Olsen and Fedosh (1988), an interval not consistent with the few thousands of years needed to cool the 300-m-thick sheet through its liquidus by conduction (Carmichael et al., 1974).

The limitation of the olivine zone to the central part of the Palisades corresponds to where the sheet intrudes near the bottom of the Triassic sedimentary section (Fig. 3). This may be more than coincidental. An olivine-rich magma (~2.8 g/cm³) would be negatively buoyant compared to the sedimentary rocks (~2.6 g/cm³). As a result, the olivine zone magma would encounter a density barrier upon reaching the base of the Triassic section and would tend to spread laterally at about that level. Thus, the density contrast would have hindered intrusion of the olivine zone magma to parts of the Palisades at higher structural levels. This also might explain the apparent absence of an olivine-rich basalt in the nearby Jurassic flows.

A localized, relatively late, separate injection of olivine-rich magma into a crystallizing high-Ti magma-derived Palisades sill also might better explain the lateral variations in thickness of the olivine zone along strike. Sills can spread laterally as fingerlike projections protruding from the perimeter of the main body (Pollard et al., 1975). An exposed section oriented across the projections near where they coalesce would give an along-strike pinch-and-swell form to the

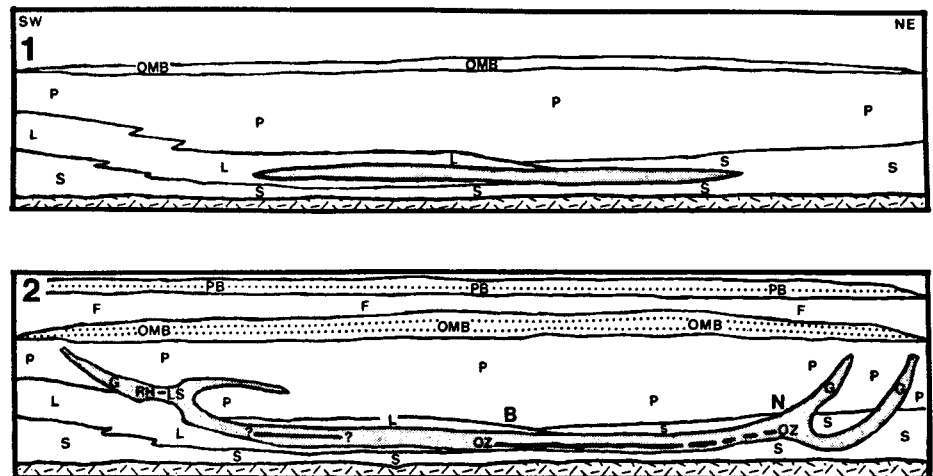


Figure 3. Sketch cross section (not to scale) along strike of Palisades sill. 1: Initial intrusion of high-Ti magmas forms Palisades sill (shaded), and contemporaneous extrusion of same magma type forms Orange Mountain basalt (OMB). 2: Later pulses of high-Ti, low-Ti, and olivine-normative magmas have extended Palisades laterally and up section. Granophyre-rich zones (G) are located where sheet cuts up into Passaic Formation (P). Intrusion of olivine-normative magma between Bayonne, New Jersey (B), and Nyack, New York (N), where sheet is low in Triassic section, has produced olivine zone (OZ). Separate low-Ti magma pulse of uncertain extent has intruded Palisades in Rocky Hill diabase (RH) and Lambertville sill (LS) parts of sheet and perhaps has extruded to form Preakness basalt (PB). Dotted lines: multiple flow units of Orange Mountain and Preakness basalts. F = Feltville Formation; other abbreviations as in Figure 1. Random-dash pattern indicates pre-Triassic basement.

body, with the intrusion being absent between more widely spaced fingers. The present exposure of the olivine zone may be just such a section.

A possible mechanism for driving the lateral and upward migration of residual liquids, producing the observed lateral compositional variations, may have been the multiple injections of various eastern North America magmas. As a new pulse intruded, space would be made for it by displacing the relatively low density residual liquids (Morse, 1988) of an earlier pulse to structurally higher and more distal (to the feeder dike) parts of the sheet (Fig. 3). The areal extent of the Palisades may have been increasing with time as multiple magma injection and lateral differentiation continued (Fig. 3). The cumulate compaction process discussed by Shirley (1987) also may have contributed to the displacement of low-density residual liquids.

SUMMARY AND CONCLUSIONS

The Palisades sill is the only well-documented high-Ti magma-derived sheet intrusion in the Mesozoic eastern North America magmatic province known to contain relatively large amounts of olivine. In addition, whole-rock variation trends for olivine-poor parts of the Palisades are very similar to variation trends for parts of the sheet where the olivine zone is found. These trends, however, are consistent with the early fractionation of pyroxene. Pyroxene-rich zones are found near the bottom of many high-Ti eastern North America sheetlike intrusions, including the Palisades; no extensive in situ olivine fractionation is needed to produce the observed residual whole-rock compositions.

Given the available geochemical data, the restricted lateral extent of the olivine zone and its abrupt upper and lower boundaries, and the paucity of olivine elsewhere in the sill, it seems more likely that the genesis of the zone was related to the intrusion of a magma distinct from the Palisades high-Ti parent. The olivine zone may represent the late intrusion of an olivine-normative eastern North America magma that underwent olivine accumulation prior to its emplacement within the Palisades. The Palisades sill is a composite intrusion, and the multiple injection of various magma batches led to large lateral displacements of residual granophyric liquids with mafic and felsic complements often separated over large distances.

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