# NE-, NOT SE-, DIRECTED PALEOFLOW OF THE PALISADES MAGMA NORTH OF STATEN ISLAND, NEW YORK: NEW EVIDENCE FROM XENOLITHS AND CONTACT RELATIONSHIPS

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## INTRODUCTION

The world-renowned mafic Palisades intrusive sheet is continuously exposed along the east edge of the Newark Basin from west of Haverstraw, New York southwestward to Staten Island, New York City where it passes beneath an intertidal salt marsh. The sheet continues southward, although with limited exposure, into New Jersey and Pennsylvania within the Delaware Subbasin. For the northern Newark segment, many investigators have suggested that the Palisades magma flowed outward from buried fractures paralleling the NE-SW-trending Ramapo fault zone. To reach Fort Lee, New Jersey and vicinity, magma from such fractures would have to have flowed from NW to SE. In Fort Lee, beneath the George Washington Bridge, xenoliths, screens, and in-situ laminated lacustrine Lockatong sedimentary strata (black argillite and interlayered buff-colored feldspathic sandstone) have been contact metamorphosed and deformed. Here, the basal contact of the Palisades sheet cuts across the bedding in a ramp-like fashion toward the north. Folded xenoliths and folds of Lockatong sedimentary strata at the igneous contacts invariably are products of subhorizontal shear. Their steep- to overturned axial surfaces trend E-W and are vertical or dip southward. Together, these marginal relationships suggest the general paleoflow of the magma was from S to N. Similar contact relationships for the Palisades are exposed near Bergen and at King's Bluff, both farther south in New Jersey.

Our proposal for magmatic paleoflow toward the NE is consistent with evidence from the Graniteville quarry, Staten Island, where a vertical, partially fused, curved Lockatong xenolith is surrounded by annular cooling(?) fractures. The quarry is near the stratigraphically lowest part of the Newark Supergroup and in the geographical center of the total outcrop belt of the Palisades intrusive sheet. By contrast, the orientations of most xenoliths elsewhere in the Palisades are parallel to the gently dipping base of the intrusive sheet. We interpret this unusual vertical xenolith to imply upward flow of the magma and thus proximity to a steeply oriented feeder channel. If this interpretation is correct, then from Staten Island to Fort Lee, the lateral paleoflow pattern would have been from the SW toward the NE, not from the NW toward the SE as previous investigators have postulated.

We propose several tests of our "feeder-at-Staten-Island" model. (1) Look for SW-directed paleoflow indicators in the Delaware Subbasin; (2) carry out local microgravity surveys to look for any anomaly that would be associated with a subsurface dike; (3) drill holes several hundred meters deep to see if any subsurface feeder dike is present.

## REGIONAL GEOLOGIC RELATIONSHIPS

The Newark Basin of New York and New Jersey is bounded by the Ramapo fault zone on the NW and by the Hudson River valley on the SW (Figure 1). From Haverstraw, NY to Hoboken, NJ, the modern Hudson flows in the curving strike valley at the base of the Mesozoic Newark basin-filling strata (Lovegreen, 1974 ms.)

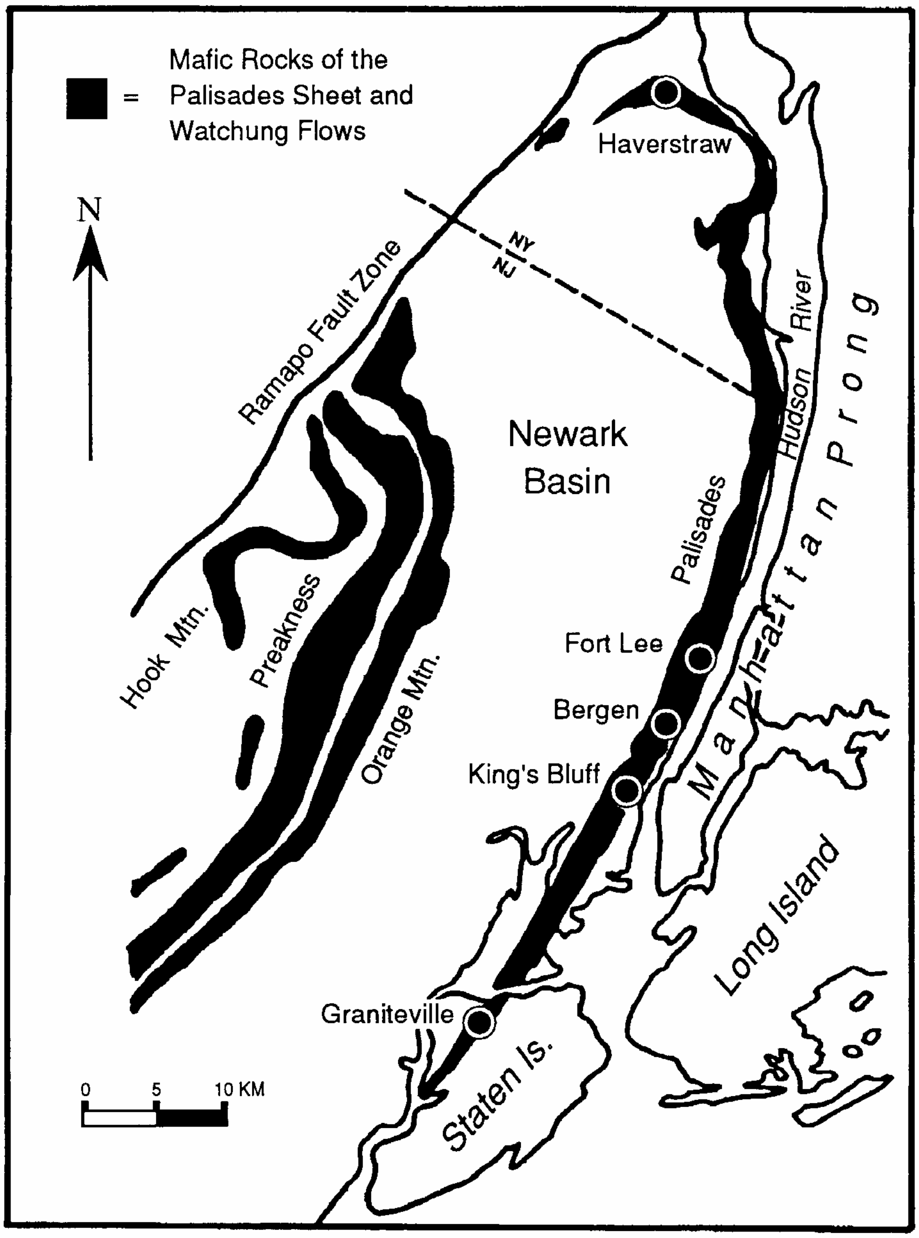


**Figure 1** - Index map showing the northern half of the Newark-Delaware Basin, the Palisades intrusive sheet, Watchung basalts, and place-names mentioned in the text. Index map was modified from Walker (1969; Figure 1, p. 6.).

The river forms a boundary between Newark strata and the Paleozoic crystalline rocks exposed to the east in New York City and vicinity. About 350 m above the basal unconformity between the Newark Supergroup and the Cambro-Ordovician crystalline rocks of the Manhattan Prong is the 325 m thick Palisades intrusive sheet. Today, the tilted, eroded edge of this formerly buried and subhorizontal sheet of resistant mafic igneous rocks forms a conspicuous ridge that extends for 65 km along the west side of the Hudson River. Because this sheet of mafic igneous rocks is not concordant along its strike length (Figure 2), we have abandoned the formerly used term Palisades "sill." Rather, from Staten Island northward to Haverstraw, the sheet climbs discordantly upward through the strata from the Lockatong formation (New York City area) to the Passaic Formation (Haverstraw area). Extensions of the Palisades to the SW, (the Lambertville Sill and Rocky Hill intrusive of the Delaware Subbasin) mirror the stratigraphic discordance displayed in the Newark Basin (Figure 2). As such, the longitudinal profile of the Palisades indicates a lopolithic intrusive [following the definition of Grout (1918)]. However, at the NE end, post-intrusive deformation along the transverse Danbury anticline has created much of the hook-like map pattern (Merguerian and Sanders, 1994c, d; See Figure 1.)

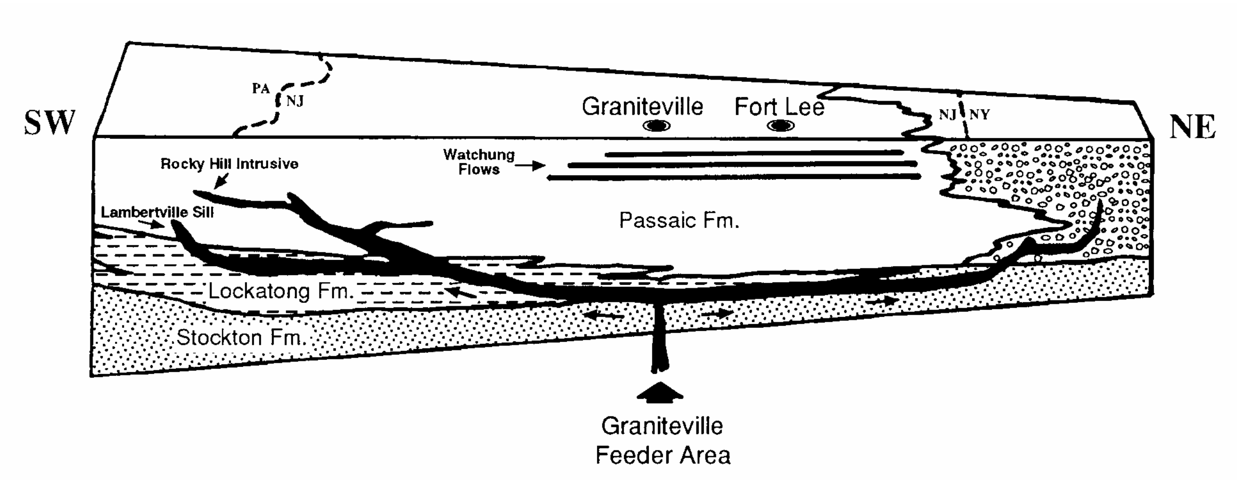


**Figure 2** - Block diagram showing SW- to NE-trending longitudinal profile (not to scale) of the Palisades intrusive sheet of the Newark Basin and its extension southward into the Delaware Subbasin showing, with arrows, our interpreted paleoflow patterns. Note the overall lopolithic form to the intrusive sheet as viewed in this orientation and the low stratigraphic position of the central part of the sheet including our conjectured feeder area at Graniteville, Staten Island. The positions of Fort Lee, NJ and Graniteville, NY are shown on the top (map view) of the block diagram. Diagram adapted from Van Houten (1969; Figure 1, p. 315).

The thickness of the Newark Supergroup strata of the Newark Basin fill exceeds 8 km. The strata consist of Upper Triassic- to Lower Jurassic nonmarine sedimentary rocks and interlayered sheets of mafic volcanic rocks. Regionally, these strata strike N30°E and dip gently (10° to 15°) NW toward the basin-marginal Ramapo fault. Table 1 shows the names of the formations of the Newark Supergroup and their estimated thicknesses in the Watchung syncline.

As noted above, the Newark mafic igneous rocks include both intrusives (the Palisades sheet) and extrusives (forming the three "Watchung" basalt sheets in the Watchung syncline and several scattered areas along the Ramapo fault and elsewhere). The Palisades mafic sheet was intruded into the base of the Newark Supergroup during the Sinemurian age of the Early Jurassic (roughly 201 +/-1 Ma) according to recent U/Pb data on Palisades zircon and baddeleyite by Dunning and Hodych (1990). These data conform with Sutter's (1988) 40Ar/39Ar dating, which has yielded a 202.2 +/- 1.3 Ma age for a xenolith of Stockton arkose within the Palisades.

**Table 1 - Names of formations of the Newark Supergroup with thicknesses in the Watchung syncline (Olsen 1980a).**

| Formation Name / Thickness (m) |
|---|
| Boonton (sedimentary strata; top eroded) / 500+ |
| Hook Mountain Basalt (two flow units) / 110 |
| Towaco Formation (sedimentary strata) / 340 |
| Preakness Basalt (2, possibly 3 flow units) / 300 |
| Feltville Formation (sedimentary strata) / 170 |
| Orange Mountain Basalt (at least 2 flow units, one of them pillowed) / 150 |
| Passaic Formation / 6,000 |
| Lockatong Formation / 150 |
| Stockton Formation / 350 |
| **Total (Watchung syncline) / 8,070** |

Historically, the Palisades has been viewed as a concordant sill-like body, the product of a single charge of magma that differentiated in situ by gravity settling [Darton (1889, 1890), Kummel (1899a, b), Lewis (1908a, b), Walker (1940), Hess (1956), Lowe (1959), and Thompson (1959)]. More recently, however, evidence has mounted that the Palisades sheet is composite. It is inferred to have formed as a result of several injections of already differentiated magma [Walker (1969), Puffer, Geiger, and Camanno (1982), Shirley (1987), Puffer (1987, 1988), Husch (1990), Puffer, Husch, and Benimoff (1992)]. Today, the major unanswered questions center on the consanguinity of the intrusive pulses of the Palisades magma charges and their possible synchroneity with extrusion of one or more of the "Watchung" (Orange Mountain, Preakness, and Hook Mountain) basalt flows.

Our efforts have sidestepped this continuing inquiry into the possibilities of comagmatic ancestry. In search of a better understanding of the environmental conditions that prevailed during injection of the Palisades magma(s), we have focused on the basal contact relationships. Thus far, our studies have placed constraints on the paleoflow direction of the magma and on the state of lithification of the bounding sediments (this extended abstract), and have enabled us to estimate that the Palisades magma(s) intruded at a depth of 3 to 4 km. (See our allied contribution in this volume.)

## CONTACT RELATIONSHIPS AT THE BASE OF THE PALISADES INTRUSIVE SHEET

### Fort Lee, Bergen, and King's Bluff, New Jersey

The lower contact of the Palisades intrusive sheet (Figure 3) with presumably in-situ sedimentary rocks of the Lockatong Formation is spectacularly exposed on the Palisades Interstate Park access road beneath the George Washington Bridge [Central Park quadrangle; UTM Coordinates: 587.58E/4522.67N]. The rocks at this locality have been studied by many geologists, including Van Houten (1969), Olsen (1980b), and Puffer (1987). The fact that the olivine zone lurks above the roadbed allows us to infer that most of the Lockatong here has not been detached although some Lockatong screens and xenoliths are present. Within the larger xenoliths, it is possible to see the cyclic successions of strata (Van Houten cycles) that are inferred to have been deposited as the ancient lake level fluctuated (Olsen, 1980a). These sedimentary strata have been contact metamorphosed; the contact with the Palisades intrusive locally is discordant. Present also are folds as well as numerous nondeformed clastic "dikes", which crosscut the primary igneous-sedimentary contact. Contact-zone breccias include those with angular pieces of basalt in a "matrix" of light-colored feldspathic sand.

**Figure 3** - Outcrop view of the general contact relationships at the base of the Palisades intrusive sheet in Fort Lee, New Jersey. Note the pipe amygdale extending up from the contact-metamorphosed Lockatong at the right side of the view (black arrow). Field of view is roughly 2 m (knife for scale is in shadow). (Photo by Richard Stytzer.)

The columnar-jointed basal part of the Palisades intrusive in New Jersey is interrupted at the level where olivine has been concentrated. The olivine zone lies above a chilled zone of aphanitic- to glassy basalt. The sizes of the crystals in the igneous rock here change profoundly with distance above the contact. At the contact, the texture is aphanitic to glassy. With increasing distance from the contact, the texture becomes gradually coarser. As a result, many gradations and discrete mixtures can be found, from microvesiculated- to hypocrystalline basalt to aphanitic basalt (near the contact), to dolerite (a few meters above the contact), to gabbro (a few tens of meters above the contact). Local microvesicles in glassy basalt and a pipe amygdale (See Figure 3.) in the base of the Palisades sheet, together imply that the mafic magma was chilled extremely rapidly and that Newarkian pore water, formerly present in the sediment, was transformed into a vapor phase, thus enabling the sediments to become fluidized.

The contact zone displays excellent products of contact metamorphism and disrupted Lockatong bedding. As noted previously by Van Houten (1969), the layers of original argillite have been converted into a black hornfels consisting of biotite and albite with minor analcime, diopside, and calcite, or to green hornfels consisting of diopside, grossularite, chlorite, and calcite, with subordinate biotite, feldspar, amphibole, and prehnite. Miller and Puffer (1972) and Puffer (1987) have noted pinite after cordierite and tourmaline as porphyroblasts in the hornfels. Our studies indicate that although contact metamorphism has changed them to a lesser degree than the argillites, near the contact, the sandy Lockatong interlayers are chaotic. They have been "intruded" upward into the chilled zone where they form irregular "sedimentary apophyses" up to 20 cm long. (See Figure 2 in our allied paper.)

We have found more than a dozen examples of thin (a few cm thick), continuous "dikes" of light-colored, clastic sandy sedimentary material, exhibiting sharp margins, that crosscut the chilled contact rocks and extend upward for more than a meter. Microscopic study of thin sections indicates that these light-colored dikelets [termed "rheomorphic veins" by Walker (1969) and interpreted by him and others as products of partial melting] are, in fact, composed of thermally altered detrital sediments. The microscope discloses altered, contact-metamorphosed remnant clastic textures within these "clastic dikes". Present are diagnostic subrounded feldspars, quartz particles displaying pronounced overgrowths, and other lithic fragments. In the same area within the igneous contact zone, a basaltic offshoot 40 cm thick has been found to intrude a xenolith of partly fused Lockatong; chilled basalt has been fractured and intruded by a "clastic dike" 0.5 m thick composed of feldspathic- and quartzose sand. Such relationships may have been produced during cooling of the chilled margin as hot tongues of fluidized, formerly cohesionless sand in the contact zone was "intruded" across the igneous/sediment interface (Merguerian and Sanders 1992, 1994a).

When one focuses on the contact patterns of the igneous- and sedimentary rocks (Figure 4), one cannot help being struck by the discordance exhibited by the top-to-the-north ramp-like contact. In almost every case [including exposures near Bergen (Central Park quadrangle; UTM Coordinates: 584.78E/4516.75N) and at King's Bluff (Weehauken quadrangle; UTM Coordinates: 582.65E/4513.00N)], the basal contact of the Palisades ramps upsection toward the NE. The Palisades contact typically migrates gently upsection to the N; it truncates the bedding in the bounding sedimentary rocks at low angles for distances of a few meters to tens of meters. (See Figure 4.) At the northern end of a ramp, the igneous contact drops abruptly. It truncates the bedding at a high angle, thus creating a broad, saw-tooth outcrop pattern. Locally, at the leading edges of the Palisades northward-directed ramps, the Lockatong shows broad E-W-trending arches (Figure 5).

**Figure 4** - Outcrop view of the megascopic saw-tooth pattern produced by north-directed low-angle ramping of the basal contact of the Palisades intrusive sheet along its contact with sedimentary rocks of the Lockatong Formation in Fort Lee, New Jersey. Hammer handle is 38 cm in length and rests immediately below chilled Palisades basalt. (CM photograph).

The megascopic discordance of the ramp-like contact is obvious, as are localized folds in the bounding sedimentary strata. In one case, about 200 m north of the GWB, a chevron fold with a wavelength of 30 cm, lies immediately below a northward-ramped contact between the base of the Palisades and the Lockatong (Figure 6). The chevron fold plunges ~10° into N75°W with an axial surface oriented N75°W, 90°. After the regional-dip component of the Newark Supergroup has been removed this structure reorients into a horizontally plunging fold. Elsewhere, folded NE-vergent xenoliths exhibit subhorizontal plunges and steep SW-dipping axial surfaces. The pronounced northward-ramping effect of the basal Palisades contact and the structural evidence together suggest that within the contact zone, top-to-the-north shearing prevailed. We can best explain the orientations- and vergences of folds and the discordant northward ramping of the basal Palisades contact by a ductile boundary response to subhorizontal intrusion of a cooling, perhaps gelatinous, high-density mafic magma whose paleoflow pattern was from the SW toward the NE.

**Figure 5** - Photograph showing a broad E-W-trending arch of the underlying Lockatong in discordant contact with the leading edge of a north-directed ramp. Hammer handle is 38 cm in length and rests immediately above chilled Palisades basalt contact with the Lockatong. (CM photograph).

## POSSIBLE FEEDER, GRANITEVILLE QUARRY, STATEN ISLAND, NEW YORK

Examination of the orientations- and marginal relationships of xenoliths in the Palisades of New York and New Jersey has helped to identify a possible feeder area for the intrusive sheet. At Graniteville, Staten Island [Elizabeth quadrangle boundary; UTM coordinates: 571.60E/4497.72N], a curved, partially fused, Lockatong xenolith is vertical and largely surrounded by concentrically oriented annular joints. Studies here by Benimoff and Sclar (1984, 1988), offer proof that a xenolith of the Lockatong Formation (formerly considered to be a small dike intruding the dolerite) was not only internally altered by the heat from the surrounding mafic magma, but that some of the Lockatong actually melted in situ to produce a trondhjemitic magma. We have suggested (Merguerian and Sanders, 1994b) that such intense melting may have been caused by a continuous heat source, perhaps emanating from an area of active magmatic flow. Furthermore, we suggest that the annular joint pattern may mimic paleoisothermal cooling surfaces.

By contrast, most xenoliths reported from the New York City area dip gently and are oriented parallel to the regional dip of the Palisades intrusive sheet. At Graniteville, a fused vertical xenolith and the annular cooling(?) joints imply that the magma here flowed upward and thus is close to a steeply inclined feeder channel. Geological relationships described above from

Fort Lee, Bergen, and King's Bluff, New Jersey suggest that internal flow of the magma in those areas (See Figure 1.) was directed northeastward, perhaps away from Graniteville. If this is correct, then from Staten Island to Fort Lee, the lateral paleoflow pattern would have been from SW to NE. In support of this model we note that the Palisades intrusive is thickest and at its lowest stratigraphic position in the vicinity of New York City and that the body progressively thins as it migrates up section to the northeast (toward Haverstraw) and to the southwest (into the Delaware Subbasin). (See Figure 2.)

**Figure 6** - Photograph showing an upright chevron fold gently plunging into N75°W in contact-metamorphosed strata of the Lockatong Formation. The black arrow, which was drawn immediately above the Palisades-Lockatong contact, shows the interpreted flow direction of the Palisades magma. The exposure is immediately north of the George Washington Bridge on the Palisades Interstate Park access road in Fort Lee, New Jersey. Knife (scale) is 9 cm in length. (CM photograph).

## CONCLUSIONS

Examination of contact relationships- and xenoliths at the base of the Palisades intrusive sheet of New York and New Jersey suggests that one of the feeder areas for the intrusive sheet may have been in the vicinity of Graniteville, Staten Island. Geological relationships in Fort Lee, Bergen, and King's Bluff, New Jersey, indicate that internal flow of the magma was directed toward the NE (not to the SE), perhaps away from a possible feeder area in Graniteville.

The existence of vesicles, a pipe amygdale, and "clastic dikes" intruding into the basal Palisades chilled margin and intrusion of basaltic offshoots into contact-metamorphosed sediments suggest that, in the vicinity of New York City, the Palisades magma intruded Lockatong sediments that had not been buried deep enough to cause them to be totally compacted and dewatered. We estimate that this paleodepth of burial was ~3 to 4 km. As such, we envision that at the base of the Palisades intrusive sheet, chilled- and partly cooled magma was chaotically and synintrusively commingled with heated, wet, fluidized sediments. The structural deformation of the bounding sedimentary strata and xenoliths may have resulted from contrasts between the higher-density NE-directed magmatic fluid and the underlying sediments. Ultimately, the flow of magma away from the vicinity of Staten Island resulted in a lopolithic intrusive (as viewed in longitudinal profile section). Accordingly, we propose that the Palisades sheet no longer be assigned to the category of "sill." Instead, we recommend the term "lopolith" or "lopolithic intrusive sheet" be applied.

Our "Staten-Island-feeder" model implies that in the Lambertville Sill and Rocky Hill intrusive of the Delaware Subbasin, NE- to SW-directed paleoflow indicators should be present. Although exposures of basal contacts in the Delaware Subbasin are limited, we suggest that they be carefully examined. Other possible tests of our model include microgravity surveys and drilling.

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