LATE SYN-INTRUSIVE CLASTIC DIKES AT THE BASE OF THE PALISADES INTRUSIVE SHEET, FORT LEE, NJ, IMPLY A SHALLOW (~3 to 4 KM) DEPTH OF INTRUSION

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INTRODUCTION

Our investigations of the basal contact of the Palisades intrusive sheet in Fort Lee, New Jersey have focused on the configuration- and effects of deformation of the basal contact zone below the olivine zone. An unusual feature of this contact zone is a series of late syn-intrusive "clastic dikes and irregular apophyses" that have crosscut the igneous/sediment interface at a high angle. Although now contact metamorphosed and indurated near the contact, the clay-rich- and sandy strata of the basal Newark Supergroup are chaotic. Apparently, during- and immediately following initial cooling of the marginal chilled zone of the Palisades magma, but before they had been significantly lithified, they were mobilized as fluidized, cohesionless sediments.

In addition to the clastic dikes, vesicles, pipe amygdales, and brecciated chilled-margin facies of the Palisades suggest that the mafic magma was intruded at relatively shallow depths (roughly 3 to 4 km) where the overburden to which the Lockatong sediments were being subjected had not yet become great enough to cause them to be dewatered and totally lithified. As such, we envision that during intrusion of the mafic magma, at the base of the Palisades intrusive sheet, "wet- and wild" conditions prevailed. In this paper, we outline the field- and petrographic data on which our inference that the Palisades sheet was intruded at a shallow depth of burial is based.

REGIONAL GEOLOGIC RELATIONSHIPS

The Newark Basin of New York and New Jersey is bounded on the NW by the Ramapo fault zone and on the SE by the Hudson River, which occupies the curving basal-Newark strike valley (Lovegreen, 1974 ms.). The Hudson covers the contact between the Mesozoic Newark basin-filling strata and the nonconformably underlying Paleozoic crystalline rocks that are exposed to the east in New York City and vicinity (Figure 1). The thickness of the Newark Supergroup (Upper Triassic to Lower Jurassic) filling of the Newark Basin exceeds 8 km. The Newark strata, entirely of nonmarine origin, consist of sedimentary rocks and interbedded sheets of mafic volcanic rocks. Regional strike is N30øE and the prevailing regional dip is 10° to 15° NW toward the basin- marginal Ramapo fault.

About 300 m stratigraphically above the gently west-dipping basal nonconformity between the Newark Supergroup and the Cambro-Ordovician crystalline rocks of the Manhattan

Prong is the Palisades intrusive sheet, roughly 325 m thick. Today, the tilted- and eroded edge of this formerly buried- and initially horizontal sheet of resistant mafic igneous rock forms a conspicuous ridge that extends for roughly 65 km along the west side of the Hudson River. 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. More recently, however, evidence has mounted that the Palisades sheet is composite and formed as a result of several injections of already differentiated magma [Walker (1969), Shirley (1987), Puffer (1987, 1988), and Husch (1990)]. According to recent U/Pb data from Dunning and Hodych (1990), the Palisades mafic sheet was intruded near the base of the Newark Supergroup during the Sinemurian age of the Early Jurassic epoch (roughly 201 +/-1 Ma). Contact relationships in Fort Lee, Bergen, and King's Bluff, New Jersey, indicate that internal flow of the Palisades magma was directed northeastward, perhaps away from a feeder area near Graniteville, Staten Island (Merguerian and Sanders, 1992; 1994a, b).

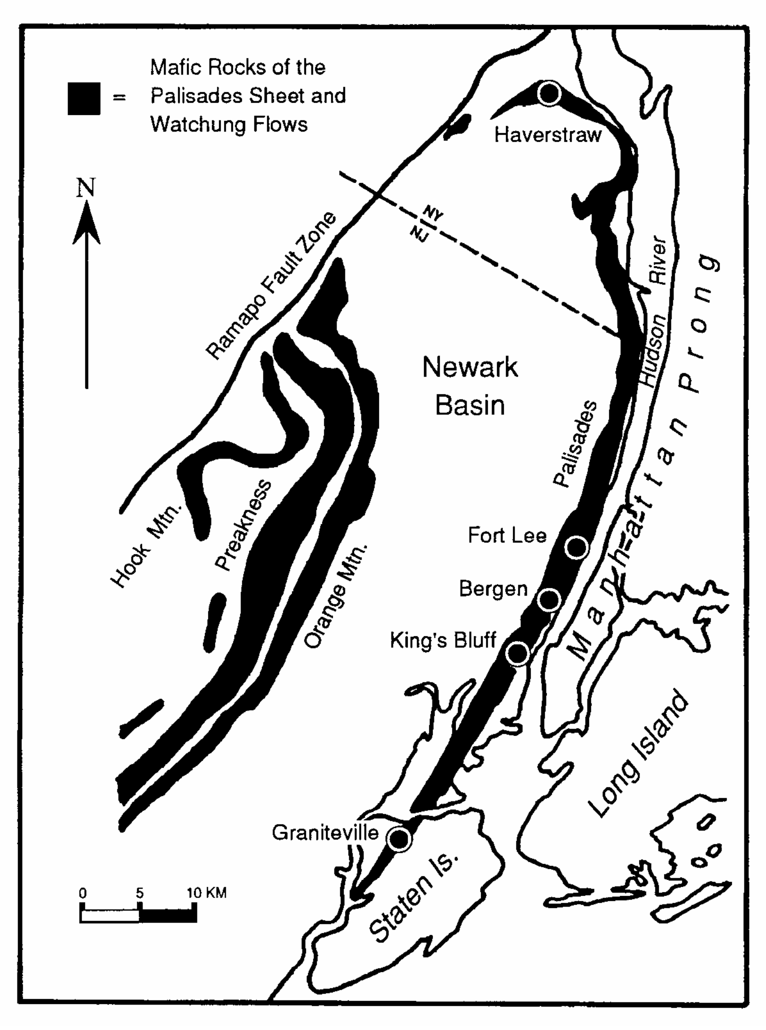

Figure 1 - Index map showing the northern half of the Newark-Delaware Basin, the Palisades intrusive sheet, Watchung basalts, and place-names mentioned in the text. Index map modified from Walker (1969; Figure 1, p. 6.).

Our efforts, which have focused on the basal contact relationships of the Palisades intrusive, place constraints not only on the paleoflow direction of the magma but also upon the state of lithification of the bounding sediments. (See also our allied contribution in this volume.) Using evidence about the latter, we have made a new estimate on the depth of intrusion of the Palisades magma(s).

PALISADES INTERSTATE PARK AT FORT LEE, NEW JERSEY

Exposures along the Palisades Interstate Park access road beneath the George Washington Bridge [Central Park quadrangle; UTM Coordinates: 587.58E/4522.67N] feature the lower contact of the Palisades intrusive sheet above sedimentary rocks of the Lockatong Formation, former lake deposits in the lower part of the Newark Supergroup [Van Houten (1969), Olsen (1980a), and Puffer (1987)]. The fact that the olivine zone is located above the roadbed makes us suspect that the base of the Palisades is exposed at the level of the access road and that the most of the exposed Lockatong is essentially in place, although a few xenoliths and screens are present locally. Our investigations indicate that the sedimentary strata have been contact metamorphosed and that many parts of the contact with the Palisades intrusive are discordant. The strata also display evidence of ductile folding, the probable result of mechanical contrasts between the higher-density magmatic fluid and the contact-heated sediments.

In the contact zone, the effects of contact metamorphism and disrupted Lockatong bedding are well expressed. As noted previously by Van Houten (1969), Miller and Puffer (1972), and Puffer (1987), the pelitic layers have been converted into a black hornfels consisting of biotite and albite with minor analcime, diopside, calcite, pinite and tourmaline or to a green hornfels consisting of diopside, grossularite, chlorite, and calcite, with subordinate biotite, feldspar, amphibole, and prehnite. Columnar joints are prominantly displayed in the Palisades igneous rock; the joints crosscut not only the igneous rocks but also the clastic dikes and other places where sediment has been injected into the basalt.

FIELD RELATIONSHIPS

Elsewhere (Merguerian and Sanders, 1992, 1994a, and this volume) we have documented the discordant top-to-the-northeast contact ramping and northeast-vergent subhorizontal folding of sedimentary strata and xenoliths that have allowed us to interpret a NE paleoflow direction for the Palisades magma in the vicinity of King's Bluff, Bergen, and Fort Lee, New Jersey. Here we focus on the field evidence that during intrusion, the Newarkian sediments had not yet become lithified. We describe late syn-tectonic clastic dikes, and suggest an approximate depth of intrusion.

Palisades Chilled-Margin Facies

The basal contact of the Palisades intrusive in Fort Lee shows a concentration of olivine above a chilled zone of aphanitic to glassy basalt. The basal igneous rocks display gradations and mixtures among microvesiculated to hypocrystalline basalt to aphanitic basalt (near the contact) to dolerite (a few meters above the contact). The microvesicles and a 15 cm long pipe amygdale (See Figure 3 of our previous paper, this volume.) extending upward from the Lockatong into glassy basalt 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.

"Sedimentary Apophyses" and Clastic Dikes

In Fort Lee, the Lockatong contains many sandy interbeds of light-colored feldspathic sandstones of typical "Stockton"-type lithology. Although the sandy layers have been less obviously affected by contact metamorphism than have the argillites, near the contact the sands are chaotic. They have been "intruded" upward to crosscut baked Lockatong as wispy irregular "sedimentary apophyses" up to 20 cm long (Figure 2). Elsewhere, an irregular "stock-like" mass of feldspathic sediment more than 0.5 m thick, which encloses angular, brecciated chunks of chilled basalt, exhibits several elongated drusy cavities that resemble miarolitic cavities of igneous rocks.

More commonly, thin light-colored clastic dikes with sharp contacts project into the Palisades chilled zone (Figure 3). We have found more than a dozen examples of the thin, continuous light-colored "dikes" of clastic sandy sedimentary material crosscutting the chilled contact rocks, in some cases extending upward for more than a meter. In marked contrast to their parent sedimentary sources, they are totally nondeformed. Their thicknesses vary from 0.5 cm to a few cms, and their lengths, from a few cm to more than a meter. These field relationships suggest that the clastic dikes, consisting of formerly fluidized bodies of sand, were intruded upward after the marginal magma had experienced an initial phase of chilling during diminished magmatic flow. The drusy cavities, together with the basalt microvesicles and pipe amygdales noted earlier, support the view that the clastic-dike materials included a vapor phase. We surmise that the bounding sediments still contained pore water before the cooling Palisades magma heated them. Thus, we envision that the sandy injections and dikes represent tongues of hot, fluidized cohesionless sand that were driven by pore waters in the Lockatong and its sandy interlayers that had been vaporized by magmatic heat.

Aphanitic Basaltic Sills and Dikes

Locally, the clastic dikes have intruded across a minor offset (~1 cm) of a basalt-Lockatong contact but in this instance the basalt is a 0.5 m sill found intruding the Lockatong. Although a rare feature, commingled within the zone of clastic dike formation, a 40-cm-thick basaltic offshoot has been found to intrude a xenolith of partly fused Lockatong. We are not sure whether this offshoot, which can be traced back into the chilled zone, is a primary Palisades chilled-margin phase or the result of a younger Palisades intrusive phase. Thus, in the contact zone, late-stage basaltic dikes have crosscut some clastic dikes; therefore some igneous activity postdates the clastic dikes which themselves were mobilized by magmatic heat.

Figure 2 - Photograph illustrating a feldspathic sand "apophyse" intruded upward, beyond level of hammer, from contact- metamorphosed Lockatong into chilled Palisades basalt. The hammer handle is 38 cm in length and rests on the basal contact of the Palisades chilled-margin basalt. (CM photograph.)

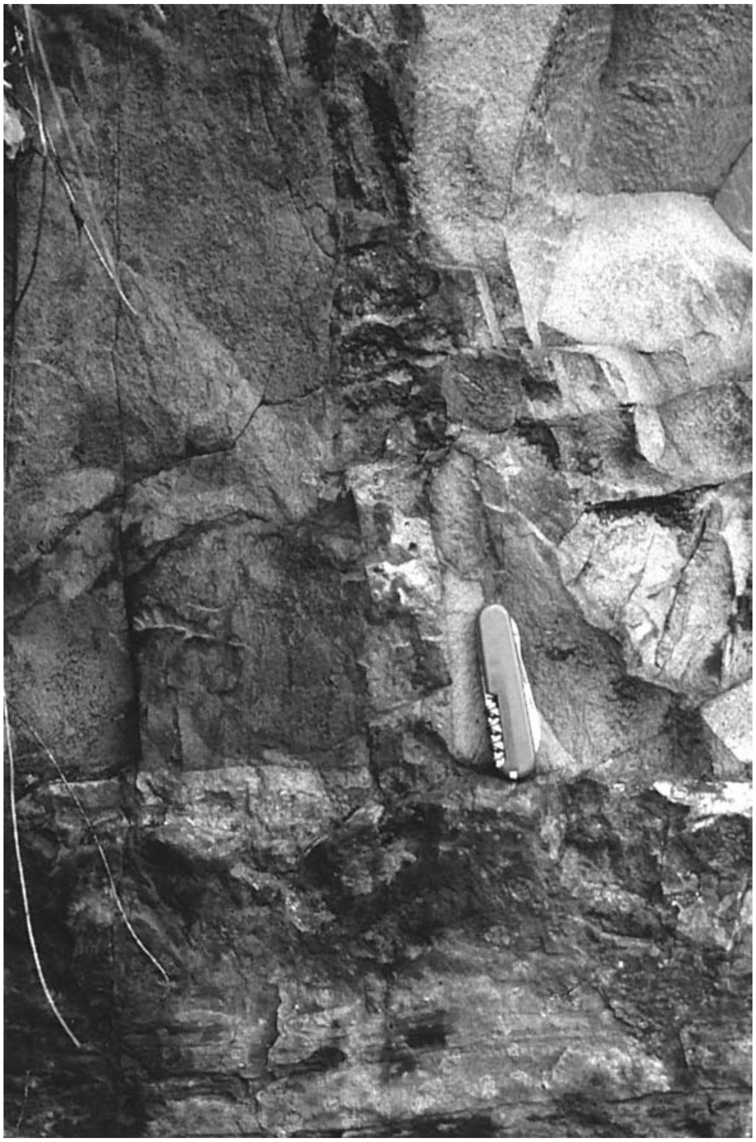

Figure 3 - Photograph showing a 3-cm-thick feldspathic "clastic dike" intruded into the Palisades chilled margin. Knife (scale) is 9 cm in length. (CM photograph.)

PETROGRAPHY OF CLASTIC DIKES

Microscopic study of thin sections of representative samples indicates that the light-colored dikes are composed of thermally altered detrital sediments consisting predominantly of subangular feldspathic sand-size particles. Use of the microscope discloses [Sample PAL-5] altered, contact-metamorphosed remnant clastic textures within the "clastic dikes" with subrounded K-feldspar, plagioclase, and quartz exhibiting pronounced monomineralic overgrowths. The feldspars are clouded and show dominantly granoblastic boundaries, which together with the overall felsic mineral components, may have convinced Walker (1969) to suggest that the light-colored dikes ["rheomorphic veins" of his usage] were of igneous origin. Microscopically, the feldspar particles are clastic; some contain subrounded cores and others preserve rounded boundary edges. As such, we suggest that the granoblastic textures are the result of contact-metamorphic- induced recrystallization. Additional detrital components in the clastic dikes include basalt fragments and other lithic fragments including argillite and chert (?).

Another thin section of a clastic dike [Sample PAL-2] shows that near the contact with basalt, sizes of detrital particles increase and also that elongate quartz, K-feldspar, plagioclase, and lithic fragments have been aligned parallel to the margin. In the interior of the dike, many well-rounded quartz- and relatively fresh feldpar particles are present. We interpret that the aligned fabric of elongate particles parallel to the dike margins resulted from a dynamic flow orientation similar to that found in clastic dikes in the sedimentary realm. At the dike contact, the basalt displays a bleached zone. We interpret the coarser texture at the dike contact with basalt as being the result of localized recrystallization and metasomatism; the chilled basalt margin may have still been hot.

DISCUSSION AND COOLING MODEL

The presence of clastic dikes and vesiculated features in the base of the Palisades suggests that, in the vicinity of New York City, Palisades magma was intruded into Lockatong sediments that had not been buried deep enough so that they had become totally dewatering and lithified. Rather, we suspect that upon being heated by the magma in the chilled margin of the Palisades sheet, the water-bearing sediments became vapor-charged, fluidized bodies of cohesionless sand. The fact that columnar joints penetrate the Palisades intrusive, the clastic dikes, and Lockatong xenoliths, indicates that the clastic dikes were injected quite early in the solidification history of the Palisades igneous rock.

An analogous situation, from a quarry in West Rock in New Haven, CT, in the Hartford Basin, was reported by Walton and O'Sullivan (1950). There, a layer of conglomeratic arkose produced a branching, irregular clastic dike exhibiting sharp contacts which was intruded upward more than 10 m into the dolerite sill. The dike consists of detrital material derived from the underlying conglomerate including several large pebbles, one of which was transported 0.6 m above the base of the sill. According to Walton and O'Sullivan, the clastic dikes were intruded at a temperature of roughly 400øC and a pressure of 0.4 Kb. We suggest similar conditions for our observed features and would argue, based on a simple stratigraphic calculation (below), that the depth of intrusion for the Palisades was in the range of 3 to 4 km.

A recurrent subject of interest among igneous geologists has been proof of consanguinity between the Watchung extrusives and phases of the Palisades intrusive. An important point to be established about the Palisades intrusive is the timing of the intrusion relative to extrusion of one or more of the Watchung extrusive sheets. According to petrographic studies and modal calculations of Sichko (1970 ms.) and geochemical studies of Puffer (1988) and Husch (1990), a likely correlation is between the high-Ti magma that solidified to form the Palisades and the various lavas that cooled to form the multiple flows of the Orange Mountain Formation (First Watchung Basalt). Husch (1990) also correlated a low-Ti magma component of the Palisades with the upper low-Ti flow unit of the Preakness Formation (Second Watchung Basalt).

Based on their interpretation of the duration of deposition under the influence of climate cycles in the associated sedimentary strata, Olsen and Fedosh (1988) calculated that approximately 2.5 Ma elapsed between the time of extrusion of the Orange Mountain Formation and that of the Preakness Formation. This means that if igneous activity within the Palisades took place at the same time as that of the extrusion of these two ancient lava flows, then more than 2.5 Ma were available for the composite Palisades intrusive sheet to cool. The general absence of chilled zones within the main mass of the Palisades intrusive implies that all pulses of magmatic activity took place in a short time interval, before the mafic intrusive had cooled.

The synchroneity of intrusion of the Palisades with one or more of the Watchung flows also settles a further point, the depth of intrusion. Depth of intrusion then is the stratigraphic thickness of Newark strata between the base of the oldest Watchung flow and the base of the Palisades sheet. Using an outcrop-belt map distance of 18 km between the base of the Palisades and the base of the Orange Mountain Basalt and an average dip of 12.5°, the stratigraphic thickness would equate to [Sine 12.5° (.2164) X 18 km = 3.89 km]. A 10°-dip assumption would decrease the estimate to 3.12 km. A 15°-dip assumption would increase the estimate to 4.65 km.

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