TRIP B6: LATE AND POST-IGNEOUS MINERALIZATION OF THE ORANGE MOUNTAIN BASALT AND THE CO-MAGMATIC PALISADES SILL

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ABSTRACT

The three Orange Mountain basalt flows are typical in most respects to other occurrences of HTQ-type CAMP basalt. However, some unusual to rare mineralization and structures are associated with the flows. Unusually high quality zeolite mineralization is associated with an Orange Mountain pillowed flow while high quality prehnite is found associated with highly vesiculated subaerial structures and historically important copper mineralization is associated with metasomatism at the base of the first flow. A distinct and uniform 4 m thick black layer at the base of the first flow contains up to 35 volume percent fine grained disseminated calcite and is overlain by a 4 m thick white albite enriched micro-vesicular layer that has locally thickened into diapir shaped structures containing vesicles up to a meter across. We propose that these mineral and structure associations are the result of a complex sequence of high temperature hydrothermal activity heated by the underlying intrusion of co-magmatic Palisades diabase magma and by subsequent low temperature hydrothermal activity associated with later pulses of Palisades magma and by post igneous burial dewatering.

INTRODUCTION

Safety considerations

The field trip accompanying this chapter will include rock quarry sites. Therefore, for your protection, hard hats, steel-toe boots, long pants, and eye-goggles, must be worn while visiting these sites. Stay a safe distance away from quarry or road-cut walls where loose rock may fall, and be sure to wear goggles when trimming rock samples. Be aware that using a steel hammer as a chisel can cause steel splinters to fly off.

Geological Setting

Extrusives

The Orange Mountain Basalt together with the overlying Preakness and Hook Mountain flows are part of the Central Atlantic Magmatic Province (CAMP) that is distributed across eastern North America, northeastern South America, northwestern Africa, and southern Europe (Marzoli et al., 2011). High precision age dating (Blackburn et al., 2013) indicates that the Orange Mountain basalt extruded 201.56 Ma and defines the end of Triassic extinction at the Triassic-Jurassic boundary. Recent isotopic evidence (Merle et al., 2014) and trace element evidence (Whalen et al., 2015) indicates that the Orange Mountain Basalt originated from a subduction-enriched mantle source as originally proposed by Puffer (2003).

The trap-rock quarries of Lower and Upper New Street expose Orange Mountain basalt consisting of three flows (OMB1, OMB2, and OMB3) from the base to the top of the formation. The first flow is a 60 to 70 m thick subaerial flow, the second flow is about 40 m thick unit that near Paterson is alternately pahoehoe and pillowed. The third flow is subaerial and about 30 m thick. The three flows are locally discontinuous throughout parts their entire geographic distribution but wherever drill cores through the flows have been logged three flows have been reported. The three flows are separated by scoraceous flow tops and thin discontinuous beds of intertrappen red-bed sediment.

Intrusives

In addition to the Palisades Sill which is exposed roughly parallel to the Hudson River from Staten Island to Rockland County, the Palisades Intrusive System includes several small co-magmatic shallow sills such as the Arlington Sill, and dikes such as Laurel Hill and several larger co-magmatic intrusion located in west-central NJ such as the Byram diabase, Stockton diabase, Lambertville Sill, Belle Mountain diabase, Pennington Mountain diabase, and Baldpate Mountain diabase. The central portion of the Palisades sill is about 300 m thick and dips to the west at about 10 to 15 degrees. Puffer et al. (2009) present evidence that the lower half of the central Palisades geochemically resembles the Orange Mountain Basalt while the upper half more closely resembles the Preakness Basalt. They proposed that the Palisades intruded as a series of pulses that broke through to the surface and extruded as basalt flows. Block et al. (2015) present supporting evidence for the multiple pulse model and show that with each successive pulse additional fractionated residual melt was carried north where thick layers of iron enriched granophyre accumulated. The Haverstraw Quarry that we will visit is located near the north end of the Palisades and is, therefore, enriched in fractionated rocks.

The late igneous history of the first magma pulse of the lower Palisades contrasts with the late igneous history of late pulses. The principal difference is the development of common granophyre layers in the upper Palisades and thick pegmatoid layers in the co-magmatic Preakness basalt that are absent in the lower Palisades and co-magmatic Orange Mountain basalt (Block et ., 2015). To date no pegmatoids have been found in the Orange Mountain basalt, although we encourage all field trip participants to continue the search.

Objective

The purpose of this chapter and field trip is to examine the late and post-igneous mineralization of the Orange Mountain Basalt and co-magmatic lower Palisades Sill. In particular we will describe our recent and ongoing research activity pertaining to the precipitation of zeolites, prehnite, carbonates, and albite in the Orange Mountain Basalt. We will focus on events and processes that began immediately after the Palisades diabase sill was intruded and secondary events that began after the Orange Mountain basalt was extruded. Our presentation will, therefore, include 1. The highly localized fusion of sediments at the igneous contacts of the Palisades sill and Orange Mountain basalt. 2. The development of historic commercial copper concentrations at the lower contact of the Orange Mountain basalt. 3. The effects of high-temperature hydrothermal activity on the Orange Mountain basalt, particularly the development of a highly unusual and highly altered “white layer” associated with volcanic diapirs that invaded the still mushy lava core and the development of a basal layer within a meter of the lower contact that has been infused with up to 35 % very fine grained calcite. 4 The effects of medium to low-temperature hydrothermal activity associated with the precipitation of coarse grained sulfates, particularly anhydrite, and glauberite, in vesicles and the alteration of pillow rinds. 5. The precipitation of a secondary population of fine grained albite near the base of the Orange Mountain basalt and 6. The effects of burial metamorphism including the recrystallization of hydrothermal mineral assemblages to form coarse grained zeolite facies minerals, calcite and prehnite.

1. SEDIMENT FUSION

In addition to the development of a thick hornfels in the Lockatong Formation below the Palisades sill and a thin hornfels at the base of the Orange Mountain basalt, there are well documented occurrences of fusion at the base of the Palisades sill and at the base of the Orange Mountain basalt. The fusion occurrences are not continuous and were presumably localized by concentrations of salts capable of fluxing the sediments within a meter or less from the Palisades intrusion and rarely the Orange Mountain extrusion.

The base of the Palisades intrusive system

Fusion products at the base of the Palisades include granitic and syenitic components of some migmatites, and a network of leucocratic trondhjemite dikes that occupy parallel cooling joints in the Jurassic diabase intrusions. Detailed field descriptions of these occurrences including precise locations of samples analyzed for Table 1 are found in Benimoff and Puffer (2000). These fusion products are exposed at several sites along the margins of Jurassic intrusions throughout the northeastern New Jersey and Staten Island, New York. Four of the most carefully studied field occurrences include:

1. Migmatites at the base of the Palisades Sill at Ross Dock, Palisades Park near the George Washington Bridge.

Flow of the diabase through Lockatong argillite has excavated a few channel-like cuts several meters across that truncate underlying Lockatong bedding planes. In addition, anticlinal dome-like structures that rise a few meters into overlying diabase have been observed. It is at these dome-like structures where most fusion has taken place.

Three clearly exposed domes occur within 2 km of Ross Dock near the George Washington Bridge where partial fusion has occurred resulting in migmatites consisting of granitic rock veined with black laminated rock. The major element compositions of the granitic rock and the surrounding dark rocks appear in Table 1. The bedding at these domed structures is disrupted and may have involved movement of volatiles derived from brackish groundwater within the lacustrine Lockatong sediments. The host rock of the migmatite is dark gray laminated meta-siltstone. The chemical composition of the meta-siltstone host rock is consistently intermediate between the black biotite enriched refractory portion of the migmatite and the granitic component (Table 1).

2. Trondhjemite dikes exposed along an I-95 road cut through the Palisades Sill, at Fort Lee, New Jersey.

A group of three parallel and vertical trondhjemite dikes are exposed within the upper 70 meters of the Palisades Sill along a major road-cut along Interstate 95 (Figure 1). Several thin calcite veins up to 12 cm thick have precipitated into joints approximately parallel to the trondhjemites. The trondhjemite dikes are near vertical and strike N 27° E parallel to a major joint set of cooling cracks in the sill. Five samples across the width of the 4.5 m thick dike were selected for chemical analysis (Table 1). Some of the calcite veins contain about 10 percent sulfides and probably precipitated out of hydrothermal vapors injected into cooling shrinkage joints in the Palisades from a Lockatong sedimentary source.

The trondhjemite dikes are leucocratic holocrystalline microphanerites composed almost exclusively of quartz and albite. The rock is porous and most of the pores are miarolitic cavities. The microtexture observed in thin section is unusual because it consists of a granophyric intergrowth of quartz and albite. Polished thin sections reveal an intergrowth of clear grains of quartz in a turbid matrix of albite; ilmenite, hematite and skeletal sphene grains are also present. Most quartz grains are in approximately parallel optical continuity. This texture is interpreted as resulting from simultaneous crystallization of quartz and albite from a eutectic melt. The total iron is very low (<1.8%) and the silica is very high (77 - 80% , 34 - 41.5% normative quartz). Na_2O (6.5-7%; 54-60% normative albite) is exceptionally high and K_2O is extremely low (0.04%). In addition, CaO and MgO are each less than 1%. The trondhjemite dikes are interpreted by Benimoff and Puffer (2000; 2005) as the fusion products of previously metasomatised Lockatong hornfels.

Figure 1. Photograph of 4.5 m thick trondhjemite dikes at I-95 roadcut through the Palisades Sill, Fort Lee, New Jersey.

3. Migmatites near the upper contact of the Stockton diabase intrusion exposed along a stream cut at Brookville, New Jersey.

Migmatite composed of pink syenite and a refractory residue composed of black biotite, chlorite, and calcite is exposed along the banks of a stream that flows along the upper contact of the early Jurassic

Stockton Diabase sill (a Palisades correlative) with the Lockatong Formation. The Stockton Diabase is approximately 500 m thick and is truncated by a southeast-dipping normal fault near the migmatite occurrence.

The syenite component of the migmatite is a holocrystalline phanerite containing 15 modal percent black euhedral amphibole prisms in a matrix of mottled pink and white feldspar. Electron microscopy reveals that the amphibole is zoned with an Mg -rich core and an Fe- rich rim. The Mg -rich core is a sodic kaersutite and the Fe rich rim is a sodic magnesium hastingsite. Around the amphibole is an extremely fine intergrowth of oligoclase surrounded by K-feldspar that shows reverse rapakivi texture.

The Lockatong meta-argillite hornfels at Brookville is composed principally of sodic plagioclase and biotite with minor but variable pyroxene, amphibole, chlorite, calcite and muscovite. Quartz is conspicuously absent. Van Houten (1965; 1971) has studied the hornfels above the sill near Brookville and describes it as "metamorphosed calcareous feldspathic argillite", a variely of detrital cycle meta-argillite. It is similar to the detrital cycle hornfels exposed under the Palisades sill at Fort Lee although it contains less pyroxene and more sodium. Olsen (1980) describes the detrital cycle hornfels as dark gray laminated meta-siltstone. Chemical analyses of this dark gray hornfels appear in Table 1.

Fusion of the hornfels produced syenite and a black biotite and chlorite refractory residue exposed within 3 meters of the Stockton sill. MgO and Fe_2O_{3T} were highly partitioned into the refractory residue reaching concentrations of 11 and 15 percent respectively (Table 1). Most other elements in the syenite and hornfels host rock maintain approximately consistent levels indicating high degrees of partial fusion.

4. Fusion at the base of the Orange Mountain basalt

Puffer et al. (1993) have presented evidence of fusion of sediment under the OMB1 flow at the discontinued Tilcon (UBC) Quarry at Paterson. They described a thin (up to 1 m) layer of sediment fluxed by salt that was melted at the base of the 70 m thick OMB1 extrusion. During fusion K_2O was strongly partitioned into residual sediment while Na_2O was partitioned into the melt phase resulting in a gray vesicular aphanitic rock composed of microphenocrysts and microlites of albite set in an optically irresolvable reddish-brown groundmass containing vesicles filled with calcite and pumpellyite. The rock is characterized by 8.0 percent Na_2O, 0.03 percent K_2O, and 73 percent normative albite. The composition of the fused sediment closely resembles the composition of a network of 0.5 to 2 m thick trondhjemite dikes that have penetrated the Palisades sill at Fort Lee, New Jersey that have also been interpreted as the product of sediment fusion (Benimoff and Puffer 2000; 2005). In the case of the Tilcon (UBC) Quarry occurrence, salt enriched Passaic siltstone containing 1.5 percent K_2O and 3.3 percent Na_2O was entrained and fused, based on analyzed samples collected 10 m below the base of OMB1. In the case of the Fort Lee occurrence Lockatong argillite containing 4.0-6.4 percent Na_2O and 3.3 to 5.2 percent K_2O (Van Houten 1965) was fused. In both cases the composition of the trondhjemitic melt plots very close to the binary eutectic of the Qtz-Ab phase diagram as described by Benimoff and Puffer (2005).

The sediment fusion layer at the base of OMB1 is absent at most lower contact exposures but is about 0.25 m thick along the east wall of the UBC quarry. Elsewhere at the UBC quarry a thin layer of travertine is exposed along the base of OMB1.

<u>Petrologic controls on fusion</u>

Figure 2 is a Quartz-Nepheline-Kalsilite phase diagram at 1 kilobar illustrating the petrologic control on the composition of fusion products. The composition of the trondhjemite dikes and the fusion zone at the base of the Orange Mountain basalt in particular plots almost exactly at the binary quartz-albite eutectic point. It is also true that the composition of Lockatong hornfels sampled at Graniteville, New York also plot close to the eutectic but the hornfels have undergone considerable metasomatic alteration from their previous sedimentary composition, chiefly a major decrease in virtually all potassium content. Details of these relationships are found in Benimoff and Puffer (2005).

Fusion of the hornfels at Brookville has generated a syenite that is also depicted in Fig. 2. The hornfels is compositionally intermediate between the black biotite enriched refractory residual portion of the migmatite and the igneous syenite portion. The same relationship is also seen at Ross Dock where again the hornfels is compositionally intermediate between the black biotite enriched refractory residual portion of the migmatite and the granite portion (Table 1). It is noteworthy that the composition of the Ross Dock granite plots very close to the ternary minimum of the Quartz-Albite-Orthoclase phase diagram (Table 1).

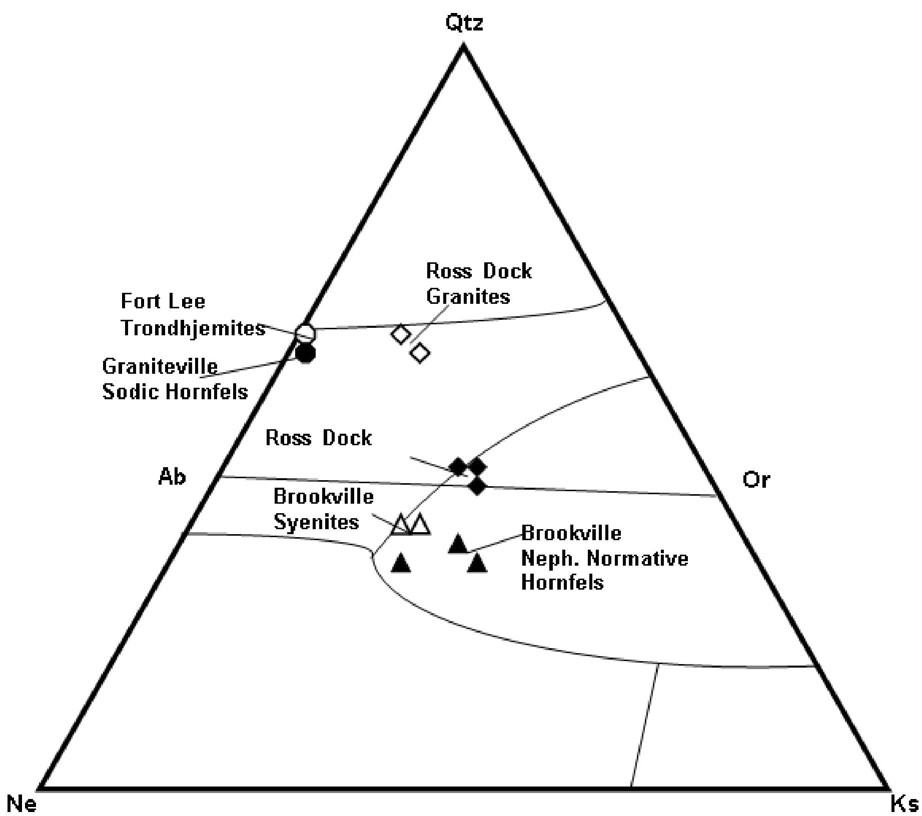

Figure 2. after Benimoff and Puffer (2005). Quartz-Nepheline-Kalsilite phase diagram at 1 kilobar with trondhjemite, granite, syenite compositions together with their respective hornfels sources. Trondhjemites from Fort Lee (open circles) plot close to the eutectic point along the Ab-Qtz boundary. Granite from the George Washington Bridge site plot close to the thermal valley of the Quartz-Albite-Orthoclase system and syenites from Brookville plot close to the Albite-Orthoclase-Nepheline-Kalsilite minimum.

Table 1. Chemical composition of trimodal fusion prodcts and their host rocks at three sites, New Jersey and New York

Location	Stockton Sill at Brookville NJ			Palisades Sill at Ross Dock			Palisades at Fort Lee
Structure	Migmatite			Migmatite			trondhjemite dikes
Rock Type	Syenite	Residue	Int-hornfels	Granite	Residue	K-hornfels	
Sample #	av. 5	B11c	B-10	G2E-L	G12D1	G2BD	av. 5
Color	pink-gray	black	dark gray	pink	black	dark gray	white
SiO_2	55.64	38.4	51.33	76.17	53.52	55.4	78.42
TiO_2	0.84	0.83	0.81	0.22	0.93	0.91	0.57
Al_2O_3	18.13	14.14	17.2	12.77	17.63	17.6	11.67
Fe_2O_{3t}	5.16	14.84	9.88	0.62	8.87	8.4	1.54
MnO	0.06	0.17	0.06	0.01	0.13	0.08	0.01
MgO	1.87	10.98	5.24	0.62	6.92	4.59	0.16
CaO	3.34	5.3	2.65	0.29	0.53	0.65	0.68
Na_2O	7.32	0.54	7.29	5.04	2.78	4.68	6.85
K_2O	4.34	5.22	4.81	3.05	7.35	5.4	0.04
P_2O_5	0.27	0.61	0.31	0.09	0.16	0.15	0.14
LOI	0.98	8.45	1.52	1.34	2.31	1.38	0.53
Total	97.95	99.48	101.1	100.22	101.13	99.24	100.61
ppm:							
Rb	97	68	63	64	99	73	7
Sr	569	239	297	392	1180	1120	39
Y				0.23	0.57	0.41	37
Zr	165	149	157	151	119	116	466

2. COPPER MINERALIZATION

The copper ores of the Newark Basin have been described by Weed (1902, 1903, 1911), Lewis (1906, 1907), Woodward (1944), Puffer (1984; 1987a; b), Robinson (1987), Robinson and Woodriff 1987), Robinson and Sears 1987), Puffer and Proctor (1992, 1994), Sclar and Moses (1995), Cattafi et al., 1998), and Puffer and Graham (2005). Genetic interpretations by these authors are wide ranging but in most (but not all) cases have addressed the close association of the copper mineralization with the Orange Mountain Basalt.

All of the 29 Mesozoic Cu mines of New Jersey described by Lewis (1906, 1907) are found along the upper or lower contact of the Orange Mountain Basalt or near thin early Jurassic dikes and sills that intrude the Passaic Formation. Copper ore is most commonly found in: 1) Passaic hornfels within 1 m below the base of the Orange Mountain Basalt; 2) Passaic hornfels within 1 m above or below thin shallow dikes and sills of Orange Mountain composition and; 3) in Orange Mountain Basalt within 2 m above the base of the first flow (Figure 3) or within 1 m below flow tops. A few very minor copper occurrences are found in unmetamorphosed red-beds of the Passaic Formation.

Figure 3. Sheet of native copper in basalt joint sampled at the Chimney Rock trap-rock quarry, New Jersey

Each of these mine locations have been visited by the principal author of this report (except for Glen Ridge and Newtown). In most cases there is very little that remains of the former workings except for occasional samples of discarded ore and host-rock. However, the underground workings at the Schuyler mine at North Arlington were examined on several occasions throughout 1970-1980 by the principal author and good exposures of ore and country rock are also still accessible at the mines near Somerville N.J., particularly the American Mine.

Chalcocite, native copper, and chrysocolla are found in most ore samples together with minor malachite, and cuprite. Pyrite is a common gangue mineral in samples of hornfels and trace amounts of chalcopyrite is found in most samples of massive basalt. Chrysocolla is easily observed at most mine exposures, and flakes and sheets of native copper are readily observed in high grade samples. However, observation of disseminated chalcocite and native copper typically requires microscopic observation of polished sections.

<u>Proposed Origin</u> - The diversity of the Mesozoic copper deposits of New Jersey make it impossible to categorize all of them into any one USGS (Cox and Singer, 1986) or Canadian Geological Survey (Eckstrand el al., 1995) genetic model. However with few minor exceptions the best fit is the USGS "Basaltic Cu" model which is approximately equivalent to the CGS "Volcanic redbed copper" model. Characteristics of "Basaltic Cu" deposits that apply to most of the Mesozoic Cu deposits of New Jersey include:

1.) Host rock is subaerial to shallow marine (brackish water) basalt and interbedded red-beds.
2.) Ore textures include precipitation in basalt amygduloids and in adjacent sediments with high original porosity.
3.) Association of ore with copper-rich basalt (90-405 ppm) and interbedded red-beds.
4.) An intercontinental rift tectonic setting.

5.) A native copper – chalcocite ore
6.) A gangue of hematite, quartz, chlorite, and zeolites.

A few New Jersey copper deposits comply in all respects to the "Basaltic Cu" model, particularly the deposits located within the amygduloidal flow-top of the Orange Mountain basalt including the Pluckamin (Hoffman) mine. In agreement with the "Basaltic Cu" model a close association of copper mineralization with subaerial basalt or comagmatic intrusives is a characteristic of all the larger deposits of New Jersey. However, copper in the mines at the base of the Orange Mountain basalt was probably precipitated in surface muds, probably boiling "mud-pots", in the solfateria that with little doubt characterized the Newark Basin immediately preceding the extrusion of the Orange Mountain basalt (Figure 4). The underlying Palisades Sill and shallow off-shoots fed these copper rich flows as it intruded beneath wet Passaic redbed sediment.

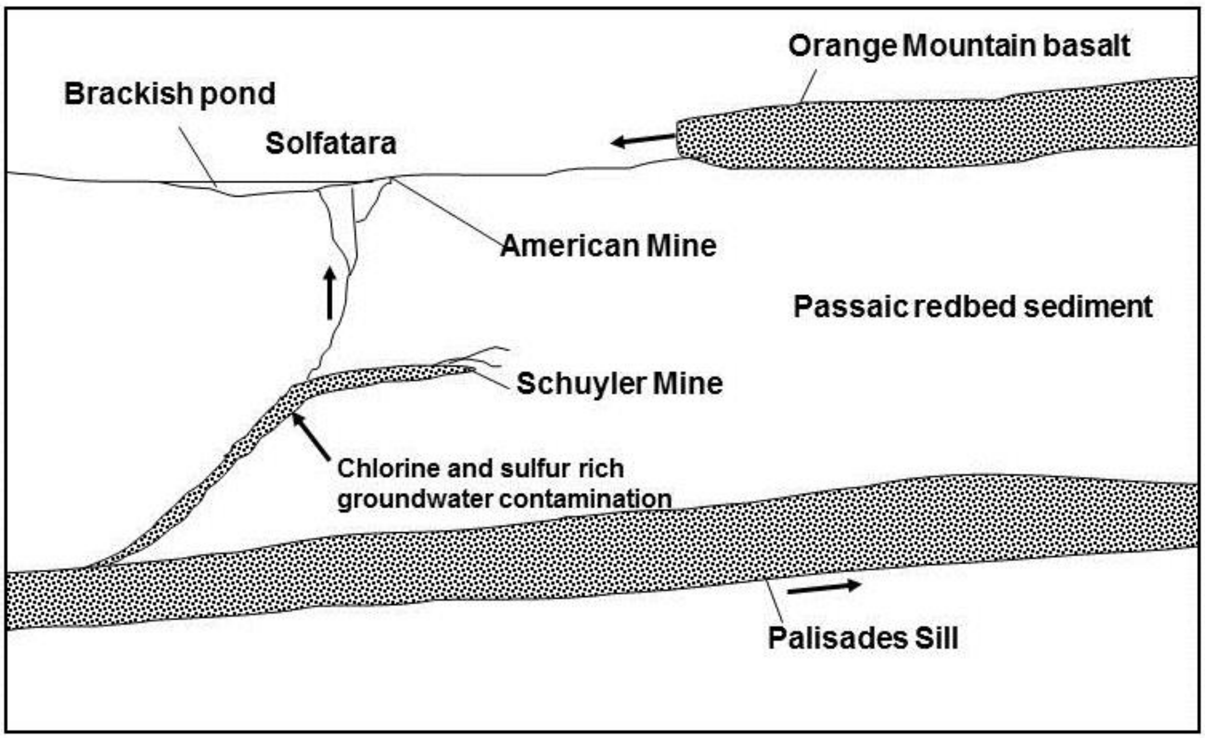

Figure 4. Idealized cross section through Passaic redbeds illustrating the leaching of copper from diabase into epithermal brines followed by movement to solfatara vents at the surface. Copper precipitation in explosion breccia occurred wherever thin diabase offshoots encountered wet sedimentary horizons as at the Schuyler Mine.

Hydrothermal water circulation through the intrusive system of diabase could have leached considerable copper during the entire cooling history of the sill as first proposed by Lewis (1906). Copper leached from the intrusive system would have been driven toward the surface as complex ions in hydrothermal solutions. Some copper was probably concentrated in the muds of solfatara or may have formed small Besshi-type hot-spring precipitates at the bottom of any water bodies. Where shallow diabase sills encountered wet muds, hot-spring-type explosion breccias would have formed, such as those of the Schuyler mine (Figure 5) together with a network of thin veins.

Figure 5. Explosion breccia sampled at the Schuyler mine consisting of diabase clasts in sandstone.

Several additional examples of Basaltic Cu deposits are listed by Cox and Singer (1986) and Eckstrand et al (1995) including the Keweenaw and Denali deposits, in the US, the Redstone, Sustut, and White River deposits in Canada and the Manto and Buena Esperanza deposits of Chile.

3. HIGH-TEMPERATURE HYDROTHERMAL ACTIVITY

3a. Development of the "white layer" and the "diapirs" of the Orange Mountain Basalt

Extrusion of the OMB1 flow onto a very active geyser field would have resulted in the injection of alkali vapors into the flow. However, deep upward penetration into or through the flow would not occur if the lava was rapidly flowing. Instead, any vapor plume encountering a rapidly advancing flow would have been dragged downstream to form a vesicular layer such as the layer we describe as the White Layer (Figs. 6 and 7a,b). An initially thick OMB1 flow may have blocked or sealed off a geyser field. However, it is likely that the full 70 m thickness of the OMB1 flow was not reached during first encounter with any such vents and reached full thickness only after subsequent inflation between the overlying vesicular lava crust and the vesicular (white) layer. This interpretation of the origin of the white layer is a departure from the less dynamic origin previously proposed by Puffer and Laskowich (2012) but best fits all the evidence.

The white layer is about 4 m thick throughout the greater Paterson area and is characterized by its white to light gray color due to albite and calcite content and its microvesicular texture. High-temperature reactions between the alkali vapors of the proto-white layer and basalt lava occurred before solidification of the OMB1 flow. The pressure of the overlying 50 m portion of the OMB1 flow kept most vesicles from expanding. However, once forward flow subsided some vesicles locally coalesced into large mega-vesicles that carried some white layer up into the still unsolidified core zone to form diapir shaped bodies (Fig. 7b) that are typically 7 m across and penetrate 4 m to 30 m above the top of the white layer.

The vesicules of the diapirs are typically 2 to 100 cm across and in many cases have collapsed to form lenses of breccia up to 4 m across. The chemical composition of the white layer is about the same as the core zone except for considerable sodium enrichment (4.5 vs 2.1 % Na_2O) and calcium depletion (6.5 vs 10.5% CaO). It is suspected that at least some of the sodium enrichment is the result of high-temperature hydrothermal reactions.

The unusually high temperatures that drove the circulation of hydrothermal activity including geysers and hot springs during the extrusion of the lower Orange Mountain flow was due to the co-magmatic intrusion of the underlying Palisades sill and associated shallow sill offshoots.

Figure 6. White layer (4 m thick) exposed near the base of OMB1 at the Prospect Park Quarry.

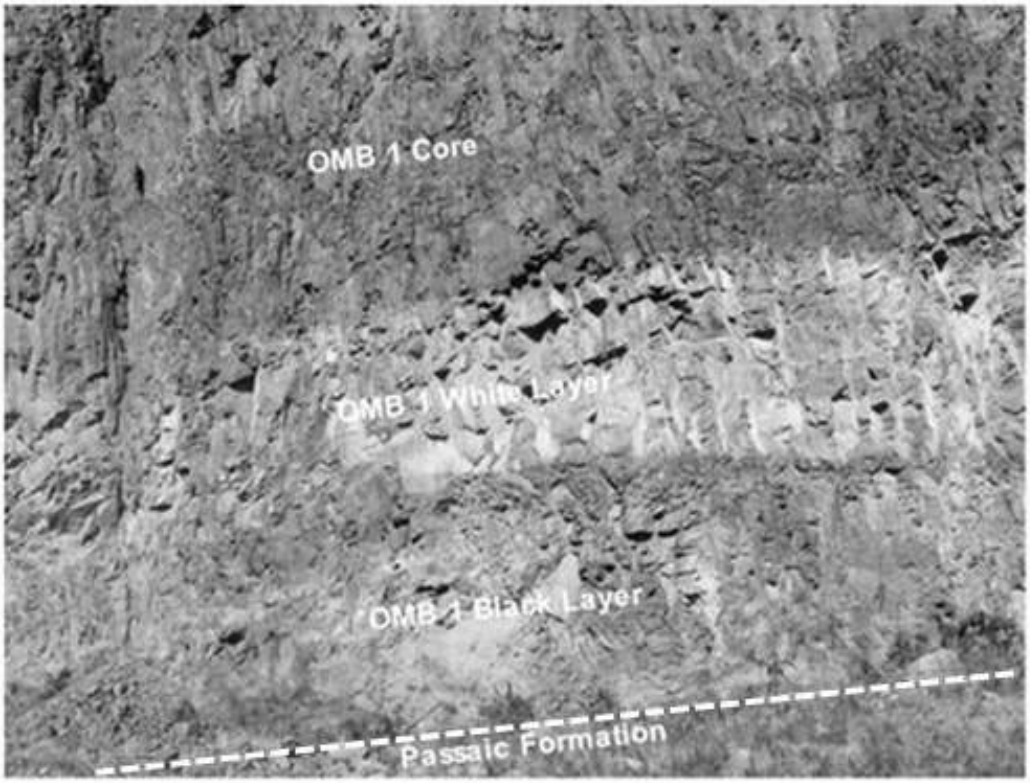

Figure 7a. Close up photograph of Black, White, and Core layers at UBC Quarry. White layer is about 4 m thick; black layer is 5 m thick.

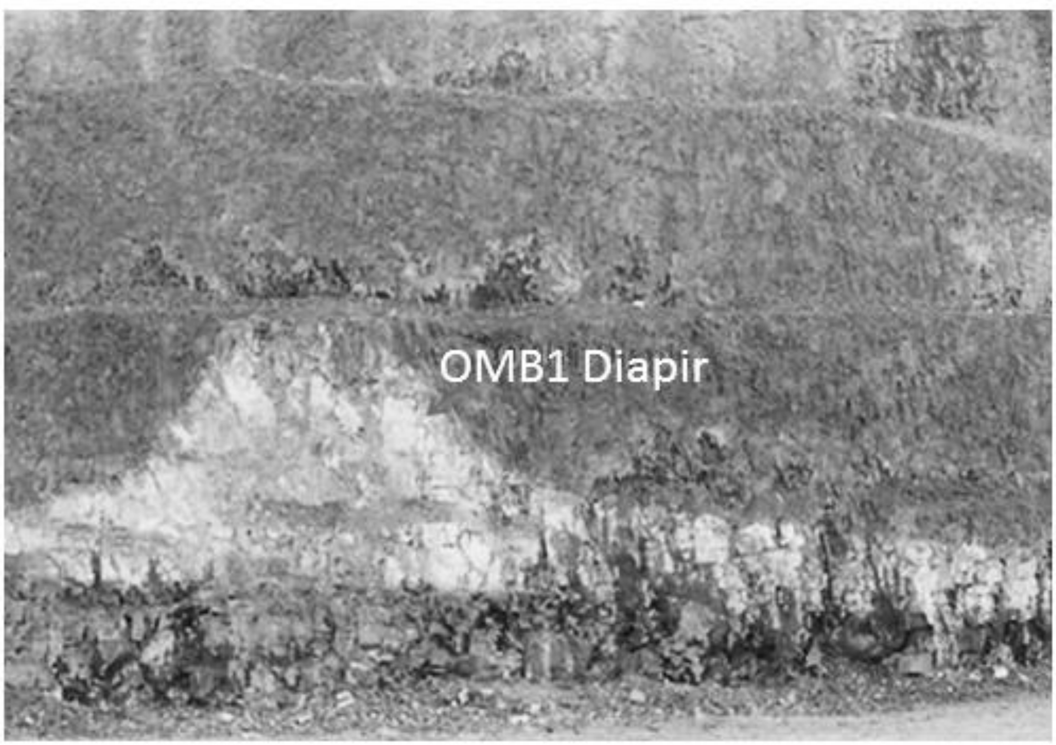

Figure 7b. Diapiric intrusion of white layer into the overlying still molten flow interior at Prospect Park Quarry.

3b. The “Black Layer” and fine grained calcite precipitation

The lowermost 3 to 5 m thick layer of the Orange Mountain basalt exposed throughout the Paterson area is characterized by its black color and absence of a vertical joint pattern. In outcrop and in hand specimen none of the layer appears to be altered. However, the lower 2/3 of the layer and the lowest 1.5 m thickness of the layer in particular is extremely altered and has been replaced by up to 35 % calcite. The calcite is very fine grained, resembling a quench phase in distinct contrast with the white veins and encrustations of coarse-grained sparry calcite found in vugs within the white layer or in vesicular flow tops. The melting point of aragonite is only 825 C and if fluxed with brine would melt at still lower temperatures. The thin layers of banded yellow travertine that are commonly found at the base of several Paterson area exposures of Orange Mountain basalt, however, do not appear to have melted.

Steinen et al. (1987) describe hot springs that penetrated through the entire thickness of the Talcott basalt (a co-magmatic correlative of the Orange Mountain found in Connecticut) and locally resulted in total replacement of basalt with carbonates. Therefore, it is more likely that superheated vapors supersaturated with carbonates at the base of the flow diffused into the lava flow as described by Steinen et al. (1987).

4. MEDIUM TO LOW-TEMPERATURE HYDROTHERMAL ACTIVITY

As the superheated vapor that formed under and within the basalt flow began to cool a variety of medium to low-temperature hydrothermal reactions occurred.

4a. Clay-palagonite alteration

Berger et al (1987) has shown experimentally that not much happens to basalt lava when it reacts with seawater except for some clay alteration of thin glass rinds. Mg, Al, Fe, and K increase in the glass while Si, Ca, Na decrease in the glass. None of these alteration effects have occurred in the White Layer or in the pillow basalts of OMB2. In addition, Rosenbauer et al (1983) have shown that reaction of Na-Cl solutions or seawater with basalt does not produce spilitic alteration. However, Bischoff and Seyfried (1978) have experimentally shown that more sustained exposure to warm seawater (or presumably basin brine) at 70 C^o at 1 bar results in an increase of Mg, Na, and K in the basalt and loss of Ca and Si to solution, similar to what has occurred in the basalt of the White Layer and in the pillow basalts of OMB2.

4b. Anhydrite-Glauberite precipitation

Another result of the initial cooling of basin brine contained within the white layer is the precipitation of abundant anhydrite in vesicles. Hajash and Chandler (1981) have experimentally reacted seawater with basalt in a 200 to 500 C^o range at pressures up to 1000 bars and found that anhydrite precipitates at high temperatures in response to decreased pressures. Bischoff and Dickson (1975) experimentally examined basalt-seawater reactions at 200 C and found that originally slightly basic solutions of seawater become acid as Ca and SO_2 are diminished during anhydrite precipitation and that K^+ is quickly leached into the aqueous phase. They found that the composition of the resulting acid solution is similar to those of the Icelandic geothermal fields. This is also the stage in the sequence when most SO_2 and then finally HCl emissions would have occurred.

5. FINE GRAINED ALBITE PRECIPITATION

Albitization of basalt is difficult to accomplish using seawater or Na-Cl solutions, generally producing insignificant amounts of albite compared to natural spilites (Rosenbauer et al 1988) or the albitized basalt of the White Layer and pillow basalts. However, increased confining pressures under overlying volcanic flows and accumulating sediments eventually reached the special environmental and geochemical conditions proposed by Rosenbauer et al., (1988) as most conducive to the albitization of basalt. They have experimentally demonstrated that albitization of basalt is maximized at pressures of 400 bars, 350 C, 3.4 m NaCl, excess silica, an absence of strong acidity and therefore minimal dissolved Mg. The porous and permeable portions of OMB1 were presumably saturated with basin brine during burial and the base of the OMB1 flow was also presumably subjected to the flow of heated brine. Reaction with silicate wall rock would eventually neutralize the brine and saturate it with silica. Reoccurring volcanism and intrusive activity associated with the extrusion of the Hook Mt Basalt could have generated temperatures of about 350 C. Reaction of basalt with deep circulation of neutral Mg-depleted basin-brine in this environment would result in sodium metasomatism (spilitization or albitization) that is a characteristic of the white layer and the pillow basalts of the OMB2 flow. Re-precipitation of Ca released by Na substitution in plagioclase resulted in the abundant calcite found in the vesicles and breccia of the white layer and in the interstices of the pillow basalt of OMB2. Similar calcite found in the vesicles of a basalt pillow from the co-magmatic Talcott Formation has been described by Greenberger et al., (2015) together with considerable albitization.

6. BURIAL METAMORPHIC ACTIVITY / POST IGNEOUS HEATING EVENT

Alt et al. (1986) described hydrothermal alteration throughout a 1 km section of MORB. They described zeolites, coarse grained calcite, and prehnite precipitating in sheeted dikes at 100-250 C at a depth of 1075.5 m. As burial sequentially loaded the Palisades sill, the OMB, the Preakness, and the Hook Mountain basalts zeolites and prehnite were progressively precipitated. The fact that zeolites and prehnite are common among the Hook Mountain basalt indicates that at least 1000 m of sediment must have been deposited over them. Stratigraphic evidence (Olsen et al., 1996) indicates that 3000 m of sediment was indeed deposited over the Hook Mt basalts.

Most of the zeolite and prehnite mineralization did not require metasomatism; instead the authigenic minerals including clays were simply recrystallized isochemically. Where excess calcium was present, as in the case of the white layer and diapirs, abundant prehnite precipitated. Where excess sodium was present, as in the case of the pillow basalts of OMB2, abundant zeolites precipitated. Abundant calcite precipitated wherever the porosity of the basalt permitted transmission of CO_2. A similar study of zeolite and prehnite mineralization of the basalts of Greenland (Neuhoff et al., 1997) has shown that zeolite precipitation occurred rapidly during and just after volcanism. Prehnite precipitation occurred at 3000 m.

FIELD GUIDE AND ROAD LOG

Meeting Point: Double Tree Inn, Nanuet, New York

Meeting Point Coordinates: (41.0922914, 73.996757)

Meeting Time: 8:30 AM

Distance in miles

Cumu-lative	Point to Point	Route Description
0.0	0.0	Assemble in the parking lot of Double Tree Inn.
0.23	0.23	Start out going east on NY- 59.
0.5	0.27	Turn slight right onto ramp.
1.31	0.81	Merge onto PIP N/Palisades Interstate Pkwy.
3.85	2.54	Merge onto I-87 W/I-287/New York State Trwy via EXIT 9W toward Albany.
4.73	0.88	Take EXIT 14A.
6.86	2.13	Merge onto Garden State Parkway Connector (Portions toll).
18.94	12.08	Garden State Parkway Connector becomes GSP S/Garden State Pkwy (toll) (Crossing into New Jersey).
19.33	0.39	Take EXIT 159.
19.41	0.08	Keep left at the fork in the ramp.
19.59	0.18	Keep right at the fork in the ramp.
22.78	3.19	Merge onto I-80 W toward Paterson.
23.29	0.31	Take EXIT 57C.
23.29	0.02	Turn left onto CR 509/Main St.
23.85	0.56	Turn left onto (638)/Grand St.
24.27	0.42	Turn left onto (633)/New St. Proceed 0.42 miles south on New Street then turn left into PNC Bank parking lot across from Hugo Street. Follow path into Lower New Street Quarry.

<u>STOP 1: Lower New Street Quarry, Woodland Park, NJ.</u>

Location Coordinates: (40.9044069, 74.1913619)

The Lower New Street Quarry (Fig. 8) is located in a wooded lot at 100 New Street, Paterson, New Jersey adjacent to Route 80 east, in Passaic County, and is mapped within the Paterson Quadrangle. It is one of several trap-rock quarries cut into the Orange Mountain basalt of New Jersey. High quality specimens of prehnite (Fig. 9), analcime, chabazite, datolite, heulandite, pectolite, natrolite, stilbite, and amethyst have been found in at Lower New Street and in the adjacent Upper New Street quarry located on the east side of New Street. This secondary mineral assemblage in the context of Paterson area trap-rock quarries has been described by Fenner (1910), Schaller (1932), Drake, (1943), Mason (1960), Sassen (1978), Peters et al. (1980), Peters (1984), Cummings (1985, 1987), Kent and Butkowski (2000), Imbriacco (2009, 2010) Sinkankas, J. (1964), Puffer and Student (1992), Puffer and Laskowich (2012), and Laskowich and Puffer (in press).

Subaqueous pillowed OMB2 at base of quarry

At the base of the Lower New Street quarry, in a trench along the south end of the quarry wall, excellent exposures of pillow basalt provide evidence of subaqueous extrusion. Pillows are an important characteristic of the OMB2 flow wherever it has been described. Most of the pillows are large (about one meter across) and are coated with a dark green palagonite rind. Subtle differences in shape and distribution have enabled Manspeizer (1980) to distinguish between pillows, flow lobe pillows, and bedded pillow buds although some of the distinctions among sub-types are based on observation made at other quarries including the Upper New Street quarry that was cut into the OMB2 flow.

Subaerial pahoehoe OMB2 (OMB3?) on quarry wall

Flat pahoehoe surfaces, pahoehoe toes, collapsed and open lava tubes, large lower flow vesicles, and massive to columnar joint systems are exposed along the quarry wall of the Lower New Street quarry. In contrast to the pillows observed in the trench at the base of the quarry the elongate ellipsoidal structures exposed on the quarry wall are here interpreted as subaerial pahoehoe toes. The criteria for distinction between pillows and pahoehoe toes was presented by Manspeizer (1980) as first established by Macdonald (1953):

Pahoehoe toes

Major axis of the ellipsoid 3 or 4 times the cross sectional axis.
Concentric structures in cross section.
Moderately to highly vesicular or amygdaloidal.
Vesicles elongate tangentially to edge or not at all.
Lava tubes are common, resulting in central cavities.
Radial joints are poorly developed or absent.

Pillows

Major axis of ellipsoid less than 3 or 4 times the cross sectional axis.
Radial structures well developed.
Moderately to poorly vesicular or amygdaloidal.
Vesicles elongate radially, especially near the edge.
Lava tubes are rare.
Radial joints are well-developed and conspicuous in cross section.

These criteria continue to be generally accepted among volcanologists. Although not all of the ellipsoid dimensions of the pahoehoe toes exposed on the quarry wall appear to be more than 3 times the cross section axis, the criteria is based on the maximum dimension of the cross section axis which is not typically exposed in outcrop. It is, however, apparent that lava tubes are common across the quarry face. Each of these tubes have been lined to varying degrees with prehnite. Most of these tubes have collapsed or partially collapsed under the weight of late OMB3 flow inflation resulting in horizontal layers of breccia cemented with prehnite.

At a central location on the south-west quarry wall a smooth flat surface dipping northward about 15 degrees is interpreted as a subaerial pahoehoe surface. Similar surfaces are not commonly found throughout the OMB1 and OMB3 flows despite their generally recognized acceptance as subaerial flood basalt flows. The pahoehoe surface exposed here marks the transition of a subaerial flow lobe before it was buried by a thick layer of massive tholeiitic basalt. Some columnar cooling joints are apparent in the upper quarry wall together with large vesicles that are a characteristic of OMB1, again, generally accepted as subaerial.

Secondary Mineralization

In general, the most of the prehnite (Fig. 8) that we have found among Orange Mountain basalt exposures throughout New Jersey is contained within subaerial structures including diapirs, large partially filled vesicles, half-moon vesicles, and vesicular flow-tops (Puffer and Laskowich, 2012). In contrast, the most productive zeolite collecting is largely confined to the pillows of the OMB2 flow with some notable exceptions. The prehnite to zeolites abundance ratio throughout the Lower New Street quarry above the pillow layer is typical of Orange Mountain subaerial exposures elsewhere and is quite high. There is no definitive explanation for this. However, the zeolites found in the Orange Mountain basalt are much more highly hydrated than prehnite and in most cases are sodic in contrast to prehnite which contains calcium as the only significant octahedral cation. Perhaps preferential salt water contamination of the pillowed layers during extrusion is a controlling factor. Geochemical evidence (Puffer and Student, 1992; Tollo and Gottfried, 1992) indicates that the zeolite enriched pillowed portions of OMB2 contain up to 5.34 percent Na_2O compared to a typical OMB concentration of 2.4 %.

Figure 8. Prehnite from Lower New Street Quarry, Paterson New Jersey.

Distance in miles

Cumu-lative	Point to Point	Route Description
24.69	0.42	Start out going northeast on (633)/New St toward Hugo Ave.
24.56	0.98	Turn right onto (638)/Grand St.
25.03	0.47	Turn left onto CR 509/Main St.
25.26	0.23	Turn slight left onto CR 509/West Broadway.
25.36	0.10	Turn left onto Ryle Ave.
25.44	0.08	Turn left onto Ryle Rd. The cliff face exposes the black and white layers at the base of the Orange Mountain basalt.

STOP 2: Very Strange White and Black Layers at base of first Orange Mt basalt flow, Woodland Park, NJ

Location Coordinates: (40.9212118, 74.1771544)

At Stop 2 we will sample the White and Black layers of OMB1 exposed along Ryle Road at the Paterson Animal Shelter near the north end of Totowa Road (Fig. 9). Large slabs of basalt fallen to the base of the cut allow close inspection of pipe vesicles at the base of the black layer. Note the microvesicular texture of the White Layer and the black spherical shaped structures 1 to 3 mm across that comprise about 80% of the Black Layer. They are best observed with a hand lens. These spherical structures were interpreted by Puffer and Laskowich (2012) as collapsed bubbles that formed too early in the cooling history of the basalt to prevent closure of lava behind them.

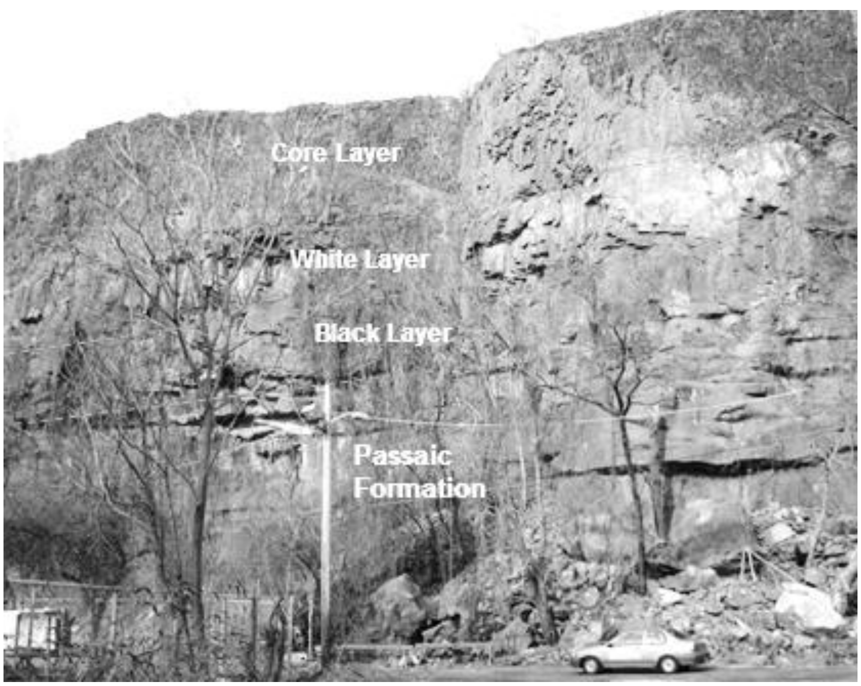

Figure 9. OMB1 Core, White, and Black layers exposed along Ryle Road.

Distance in miles Cumu-lative	Point to Point	Route Description
25.52	0.08	Start out going north on Ryle Rd toward Ryle Ave.
25.62	0.19	Turn right onto Ryle Ave.
25.85	0.23	Turn right onto CR 509/West Broadway.
26.04	0.19	Turn slight right onto CR 509/Main St.
26.41	0.37	Turn right onto CR 648/Market St.
26.49	0.08	Turn right onto (639)/Spruce St.
26.57	0.08	(639)/Spruce St becomes CR 639/McBride Ave. Lunch stop at Libby's Lunch (optional).

STOP 3: Orange Mountain Basalt at Great Falls, Paterson, NJ

Location Coordinates: (40.9141809, 74.1841325)

We plan to stop across from the Libby's Lunch Restaurant within a three minute walk from the edge of the cliff overlooking Great Falls. Simply walk toward the US flag at the falls (Fig. 10). The upper-middle 70 % of the OMB1 flow is exposed. An abandoned hydroelectric power plant can be seen on the bank of the Passaic River. Common half-moon vesicles are exposed along upper surfaces of basalt.

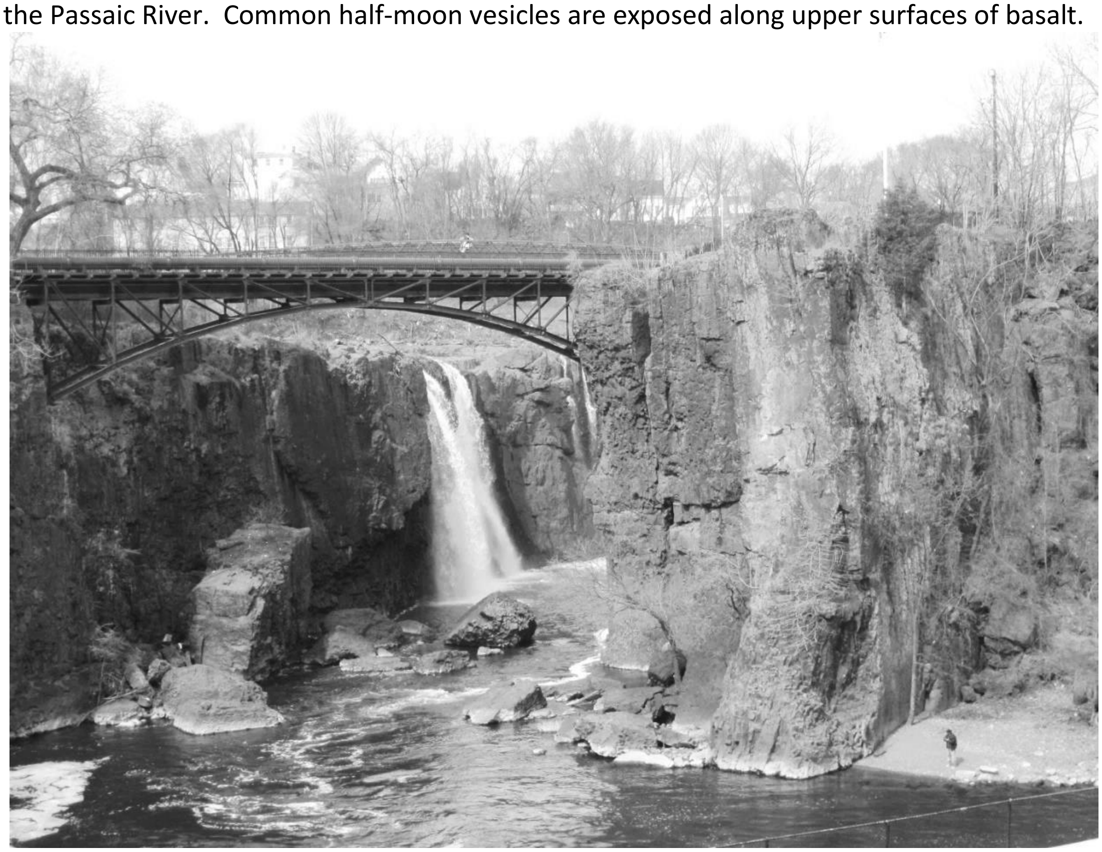

Figure 10. Great Falls, Paterson, New Jersey.

Distance in miles

Cumu-lative	Point to Point	Route Description
26.65	0.08	Start out going east on CR 639/McBride Ave toward (639)/Spruce St.
26.85	0.20	Stay straight to go onto (639)/Spruce St.
26.96	0.11	Turn left onto Oliver St.
27.23	0.27	Stay straight to go onto NJ-19 S.
31.15	3.92	Merge onto I-80 E.
31.59	0.44	Take EXIT 62A-B.
32.16	0.57	Take EXIT 62A.
32.28	0.12	Keep left at the fork in the ramp.
32.35	0.07	Keep left at the fork in the ramp.
44.35	12.00	Merge onto GSP N/Garden State Pkwy (Portions toll) (Crossing into New York).
46.14	1.79	Garden State Pkwy becomes Garden State Parkway Connector.
47.51	1.37	Merge onto I-87 E/I-287/New York State Trwy.
49.25	1.74	Merge onto NY-59 via EXIT 14.
50.24	0.99	Merge onto NY-304 N.
51.56	1.32	NY-304 N becomes State Hwy 304.
56.10	4.54	State Hwy 304 becomes NY-304.
56.28	0.18	Turn left onto Berts Rd.
56.33	0.05	Turn left onto Long Clove Rd. Park vehicles at the Tilcon Quarry parking lot.

STOP 4: Tilcon Haverstraw Quarry in Palisades SIll, Haverstraw, NY.

Location Coordinates: (41.173221, 73.953693)

The trap-rock quarry at Haverstraw (Fig. 11) is owned and operated by Tilcon Corp. and is located on the west bank of the Hudson River. We will exit our bus at the mine office located at 66 Scratchup Road.

Tilcon N.Y., part of the Oldcastle Materials group, operates a crushed stone quarry in Haverstraw, New York. The quarry first began mine operations in 1927 and has since expanded to cover 112 acres. The majority of stone crushed in the northern Rockland County quarry ships out on barges down the Hudson River to terminals in New York City and Long Island where it will be used for construction projects including asphalt and concrete.

The quarry produces crushed diabase, known as “trap rock” in the construction industry. The stone is first blasted from the quarry’s rock faces before being crushed by the primary crusher, which is visible from the entrance of the mine. From the primary crusher, stone is sent through a tunnel under Route 9W to the secondary plant where it is crushed and screened to ensure proper size for construction usage/applications. Once the stone passes a quality test, it is transported to customers via trucks or barges.

The quarry sits on the Northern extent of the Palisades sill. The top of the quarry by the radio antenna is 580ft above sea level. The current quarry floor is -220ft. Cores drilled down from this level show another 160ft of diabase before intersecting the lower contact with the Newark group sedimentary sequence (Moore 2015). The diabase is columnar jointed in the south west corner of the quarry and dips sharply in the north east. This sharp dip causes the northeast faces to appear less defined and there is more rubble on the benches. The eastern face also shows evidence of faulting with no displacement. There is evidence of slickensides on some of the rock mined. Inside some of these faults and also in some joints mineralization of primarily calcite occurs (Delcos 2003).

The quarry has exposed both upper and lower contacts between the palisades sill and the surrounding sedimentary rocks of the Newark basin. The lower contact was intersected while constructing a conveyor tunnel under 9W (Delcos 2003). Unfortunately, the contact was covered by concrete upon completion of the tunnel. The upper contact is exposed on one of the uppermost benches on the North West face. This contact has only been recently exposed by mining operations. The upper contact zone is not clearly defined in the quarry. This is evident in The Western side of the mine where overburden is being stripped to expose more diabase. This stripped area has a horst and graben structure making it difficult to find the contact.

The Haverstraw Quarry is one of only two Quarries actively mining the Palisades sill diabase, the other is Tilcon's West Nyack Quarry.

Probably the first thing that most visitors to the Haverstraw Quarry notice is the impressive depth of the open pit. Thirteen 50 foot benches have been cut into the Palisades Sill that have exposed the lower few meters of the overlying Lockatong Formation (a non-marine meta-siltstone/argillite) and about 700 feet (about 230 m) of the Palisades Sill. Drilling into the base of the quarry has penetrated another 200 feet (65 m) of Palisades; therefore about 78% of the total thickness of the Palisades sill is visible along the quarry walls. The upper contact is rarely exposed; however at Haverstraw a distinctly red hornfels is exposed. Some of the Lockatong hornfels has dropped down along normal faults to form a graben at the southern quarry wall. The northern end of the sill becomes increasingly dike-like and at Haverstraw dips to the south at about 15 degrees.

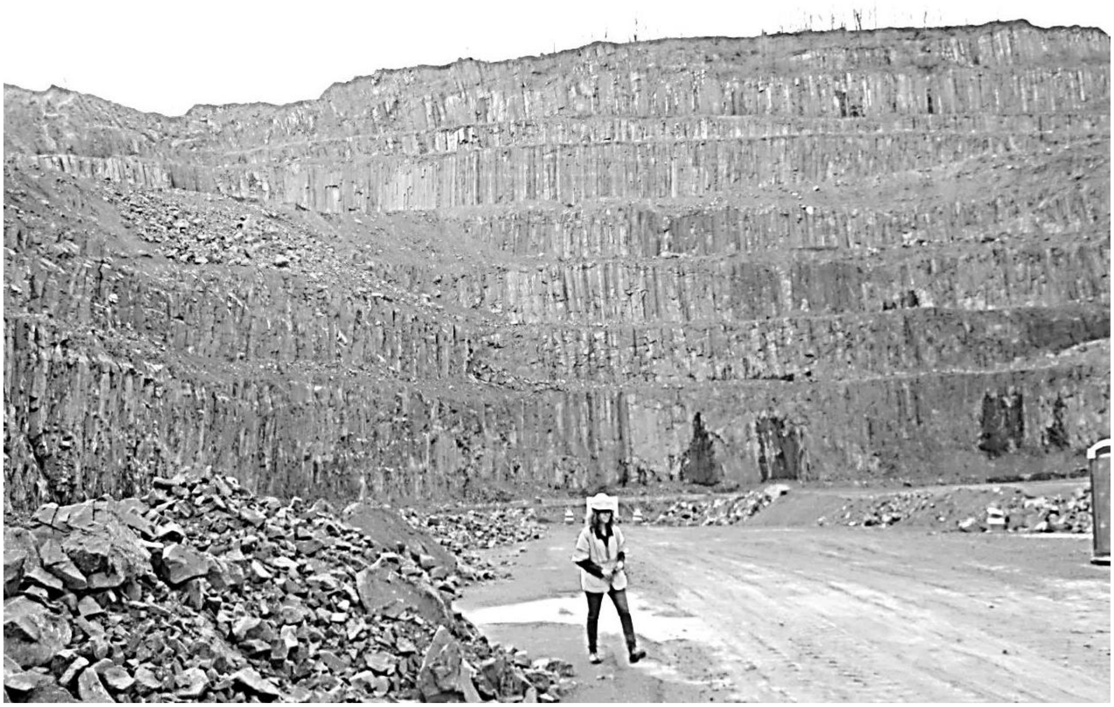

Figure 11. Quarry walls of the Haverstraw Quarry. Note the well-developed columnar jointing.

Some of the late to post-magmatic structures and textures that are exposed in the walls of the quarry include granophyres and pegmatoids. However, it is important to point out that these structures are confined to the upper Palisades. The geochemistry of the upper Palisades does not resemble the Orange Mountain basalt which is the principal objective of this chapter. The exception is the thin layer of upper chill zone that represents the upper portion of the first pulse of Palisades magma. All late pulses have intruded between the initial upper and lower chill zones. However, we have not yet analyzed samples of diabase from the upper chill zone at Haverstraw and it is possible that some late pulses intruded parallel to and above the initial chill zone, although evidence of hornfels layers or chill zone contained within the sill have not yet been found.

Granophyres

Ferrogranophyres are defined as rocks primarily composed of residual liquid with > 55% SiO2 and > 14% FeOT. In Fort Lee, NJ these constitute the sandwich horizon where the upper and lower crystallization fronts meet. The granophyre assemblages at this location exhibit significant deuteric alteration exemplified by pyroxenes almost entirely replaced by amphibole, sericitized plagioclase, and abundant myrmekite.

Gabbroids/Pegmatoids

In Upper Nyack, ferrogranophyres adopt a gabbroid/pegmatoid texture and occur from ~ 200 m to ~ 300 m. At 84 m where FeO_T reaches a maximum of 18%, the texture corresponds to a coarse ferrodiorite with abundant skeletal opaques, large euhedral plagioclase, and interstitial pyroxene. Higher in the section, (124 m to180 m) the ferrodiabase exhibits a similar texture to that observed at 84 m. Hornblende often replaces pyroxene along the rims and is accompanied by alteration products of plagioclase (sericite). From 168 m to 250 m the most evolved differentiates are ferrogranophyres containing abundant interstitial myrmekite and opaques, and exhibiting evidence of hydrothermal

alteration. There is evidence of sheared fabrics possibly caused by transport of residual liquid northward, and resulting in changes in the mineral assemblages near the solidus temperature.
At the Haverstraw quarry, smeared lenses of light-colored granophyric pegmatoid are apparent near the upper contact (Fig. 12). These lenses have been previously interpreted as products of segregation of liquid expelled from crystal mush accumulated on the floor of the magma chamber (Ragland and Arthur, 1985) and has been dubbed a 'pocket pegmatite' (Steiner et al. 1992). In places where pocket pegmatites occur, large crystals grow against the facies boundaries as a result of rapid crystal growth likely due to saturation with an deuteric fluids.

Zeolite veins
Most of the mineralized veins exposed in the wall of the Haverstraw occupy thin (0.25 to 2 cm) joints that cut through the diabase at an angle to the columnar joint system. These joints are commonly mineralized with calcite, stilbite, prehnite, chabizite, and other zeolites as mono-mineralic veins or mixtures. Where there has been displacement along joints the slickensides are typically coated with chlorite or amphiboles.

Figure 12. Fine to medium grained chill-zone diabase near the upper contact of Palisades Sill exposed at the Haverstraw Quarry. From top to bottom are red-bed sediments and slightly metamorphosed hornfels of the Lockatong Formation overlying a red v-shaped notch containing possibly fused sediment. Light gray lenses of pegmatoid oriented parallel to the upper contact have been described in detail by Steiner et al., 1992 and interpreted as pockets of residual liquid that accumulated after expulsion from a crystal mush.

Distance in miles

Cumu-lative	Point to Point	Route Description

56.38	0.05	To return to the Double Tree Inn start out going east on Long Clove Rd toward Berts Rd.
56.56	0.18	Turn right onto Berts Rd.
62.38	5.82	Turn right onto NY-304/State Hwy 304. Continue to follow NY-304.
62.74	0.36	NY-304 becomes State Hwy 304.
63.12	0.38	State Hwy 304 becomes NY-304 S.
63.23	0.11	Take the exit.
63.33	0.10	Turn right onto Smith St.
63.61	0.28	Turn right onto NY-59 and exit vehicles at the Double Tree Inn parking lot.

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