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Sedimentary Exhalative Origin for Magnetite Deposits of the New Jersey Highlands

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ABSTRACT

The New Jersey Highlands and contiguous Hudson (New York) Highlands host hundreds of small, worked-out magnetite mines, and the major zinc-oxide deposits of Franklin and Sterling Hill. The origin of the magnetite ore remains controversial. Two temporally distinct genetic models have been proposed for magnetite: 1) a pre-Ottawan, sedimentary exhalative model in which ores were deposited on the sea floor as precipitates from iron-enriched hydrothermal fluids; 2) a late Ottawan, fluid alteration model in which the current mineral composition of ores was derived from Fe-rich, alkaline fluids, associated with late episodes of granitic plutonism (Low-Ti Kiruna-type deposits), or in which deposits derived from metamorphogenic fluids circulating in a regional shear zone leached metals from host rocks and precipitated them in veins and faults. Detailed mapping of ore deposits and host rocks near Wanaque, NJ, Ringwood, NJ and Warwick, NY reveal that ore bodies are hosted by supracrustal rocks deposited in a back-arc basin. At Wanaque and Warwick, ores are strataform and stratabound. Discordant ore bodies at Ringwood are associated with a feeder zone, presumed to have intersected the paleosurface at a steep angle. Sharply-layered quartz-diopside gneiss is spatially associated with ore at Wanaque and Warwick, and massive diopsidite is spatially associated with ore at all three locations. Diopsidite in these rocks is non-aluminous, iron-enriched and shares these characteristics with modern metalliferous sediments. Massive diopsidite and quartz-diopside gneiss are interpreted to be metamorphosed carbonate facies iron formation, and associated magnetite to be metamorphosed oxide-facies iron formation.

27

28 **Introduction**

29 Magnetite deposits are common in the New Jersey Highlands and contiguous
30 Hudson Highlands of New York, Appalachian inliers of the Grenville Province (Fig. 1).
31 They are also abundant in the Adirondack Highlands, the southeastern extremity of the
32 contiguous Grenville Province (Fig. 1). Over 400 deposits have been documented in
33 New Jersey (Peck 2009), including the relatively large past-producing Edison, Andover,
34 and Dover mines (Fig. 2). However, given the diversity of age and composition of host
35 rocks, the genesis of this group of ore deposits has remained controversial. Numerous
36 genetic models have been proposed for the formation of magnetite deposits regionally,
37 but two models that are distinct in terms of process and relative timing during the
38 Grenville Orogenic Cycle (McLelland 1996) are predominant: 1) late to post-orogenic
39 magmatic or metamorphogenic; and 2) early orogenic, syn-depositional exhalative.

40 The late- to post-orogenic model was developed, in part, based on deposits from
41 the magnetite mining district of the eastern Adirondack Highlands (McLelland et al.
42 2001; McLelland et al. 2002; Valley et al. 2011). Many mines in this area are hosted by
43 the Lyon Mountain granite, a rock which lacks widespread penetrative deformation. On
44 this basis, its crystallization age of 1060-1050 Ma is understood to coincide with the end
45 of the Ottawa orogeny in the Adirondack Highlands (Valley et al. 2011). Subsequent to
46 formation of these deposits, and presumably coincident with intrusion of the granite, the
47 ores were pervasively altered by two or three pulses of alkali-rich hydrothermal fluid
48 (Valley et al. 2011). Associated hydrothermal zircons have permitted dating of Na-
49 alteration at 20-60 Ma after granite crystallization (Valley et al. 2011). Oxygen isotope

studies of quartz-magnetite pairs from multiple locations suggest that these minerals equilibrated with hydrothermal fluids between 565 and 675° C (McLelland et al. 2001; McLelland et al. 2002). Although formulated based on Adirondack deposits, this model has been applied to the interpretation of iron ores of New Jersey (Foose 1995)

Magnetite mineralization at the Hogencamp, Pine Swamp and other nearby mines in the Hudson Highlands also has been interpreted to have occurred late in the Grenville Orogenic Cycle (Kalczynski and Gates 2014). In this area, two 3-5 km long veins of massive magnetite occur within a regional shear zone. Alteration zones separate the mineralized veins from unaltered rocks. Geochemical analysis of the veins and surrounding rocks led the authors to conclude that acidic, iron-rich metamorphic fluids introduced into shear zones caused exchange reactions with country rocks and precipitated magnetite in the centres of the veins (Kalczynski and Gates 2014). Although timing of this event is not well-constrained, Gates (1995) inferred a post-Ottawan age based on the retrograde parageneses associated with mylonitic fabric and brittle failure of rocks within the shear zone (Garrels and McKenzie 1971; Gates 1995).

In contrast, an early-orogenic, sedimentary exhalative (sedex) model has been proposed for carbonate-hosted zinc and magnetite deposits in the New Jersey Highlands (Johnson et al. 1990; Johnson and Skinner 2003; Peck 2009). Johnson et al. (1990) found that calcite within mineralized layers of the host Franklin Marble has lower $\delta^{18}\text{O}$ than calcite in unmineralized layers, leading to the conclusion that isotopic character was controlled by whole rock mineral modes. Their isotopic measurements were successfully replicated by models using assumed mineral protoliths with values adjusted for metamorphic devolatilization. The models indicated equilibrium between

protolith minerals and hydrous fluid at $150^{\circ}\text{C} \pm 50^{\circ}\text{C}$. This fluid must have been principally seawater to account for the unusually oxidative character of the Sterling Hill and Franklin Furnace zinc deposits.

Later work on the Franklin Furnace magnetite deposit and spatially associated magnetite deposits along strike further support a seafloor, or sub-seafloor, hydrothermal origin. Isotopic measurements of O and C in calcite and O in magnetite remained consistent with the earlier modeling, confirming the presumed equilibration with hydrothermal fluid at $\sim 150^{\circ}\text{C}$ (Johnson and Skinner 2003). The authors noted that measured values of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ at the Franklin Furnace deposit are within the range reported for Superior-type banded iron formations.

Peck et al. (2009) studied the isotopic and petrologic character of 15 other carbonate or skarn-hosted magnetite deposits in the New Jersey Highlands, as well as new samples from Franklin Furnace. Their isotopic measurements supported a model for fluid-rock equilibration at temperatures between 125 and 175°C . Peck et al. (2009) presented additional evidence for the presence of a hydrothermal/volcanic centre in the western NJ Highlands during the Mesoproterozoic. This evidence includes the occurrence of a high-Mg, orthoamphibole gneiss (metamorphosed alteration zone) between the Sterling Hill and Andover mining districts (Fig. 2) and a trend of increasing alteration in bimodal metavolcanic rocks with proximity to magnetite deposits (Peck 2009).

Timing of the deposition of these carbonate-hosted orebodies of the western NJ Highlands is constrained to the period 1.3-1.25 Ga, based on U-Pb dating of zircons from meta-rhyolite intercalated with the Franklin Marble (Volkert et al. 2010). This time

period broadly coincides with the Elzevirian orogeny of the Grenville Orogenic Cycle (McLelland 1996), and an associated episode of back-arc extension (Chiarenzelli et al. 2011).

The distinctly different models of ore genesis described above have influenced the interpretation of the less-studied, non-carbonate-hosted iron deposits of the New Jersey Highlands. Syngenetic, magmatic, and metamorphogenic models have all been invoked to account for these deposits. Puffer (2001) noted that these orebodies are associated with a diversity of host rocks, and suggested that the lithologic character of the deposit hosts could provide insight into deposit geneses. Based on this, Puffer (2001) proposed that there could be as many as five distinct magnetite mineralization styles/events in the region.

Although the character of the host rock lithologies of New Jersey Highlands magnetite deposits is variable, the modest geographical range and limited variation in ore composition suggests that there may be common processes that formed many of these deposits. Accordingly, this study focuses on three small magnetite deposits, each associated with distinct lithological hosts: 1) stratiform, metasedimentary-associated deposits (Roomy and Blue mines) in Wanaque, NJ; 2) a stratiform, metavolcanic-associated deposit in Warwick, NY (Miles Standish mine); and 3) a non-stratiform basement-hosted deposit in Ringwood, NJ (Hickory Valley and Hickory Mountain deposits) (Fig. 3). The objective was to determine if each of these lithologically distinct deposits was produced by a different mineralizing processes, or whether a common model could account for their genesis.

Bedrock Geology and Geochronology of the New Jersey Highlands

The New Jersey Highlands is a 24-32 km wide by 88 km long belt of Mesoproterozoic metamorphic rocks stretching from the Delaware River near Easton, PA, northeast to the New York state line (Fig. 1). The Highlands are in fault contact with Mesozoic rocks of the Newark basin to the east, and Paleozoic sedimentary rocks of the Appalachian Valley and Ridge province to the west. A Paleozoic graben in the central part of the Highlands separates the region into eastern and western parts.

The Losee Metamorphic Suite, a group of metavolcanic to metaplutonic rocks with a compositional range from mafic to felsic, constitutes the basement of the New Jersey Highlands. Felsic rocks have dacitic to tonalitic protoliths (Puffer and Volkert 1991). Intermediate rocks are locally charnockitic (Volkert and Drake 1999). Volumetrically minor amphibolites in the suite are predominantly calc-alkaline, and have basaltic to basaltic andesitic protoliths (Volkert et al. 2010). Losee Suite rocks range in age from 1366 ± 9 to 1248 ± 12 Ma, a time span during which magmatism may have been continuous or episodic (Volkert et al. 2010). Volkert (2004) considers the Losee Suite to be part of a continental arc that formed at the southeastern edge of Laurentia prior to the assembly of Rodinia.

Supracrustal rocks formed in a back-arc basin inboard of the Losee arc (Volkert and Drake 1999). These rocks are metasedimentary (marble, quartzite, felsic gneisses and calc-silicate gneisses) and metavolcanic (amphibolite and meta-rhyolite). Metapelitic rocks are rare. Volkert and Drake (1999) used a multi-component analysis of major elements to infer that felsic gneisses originated as immature sandstones sourced from an active continental margin, whereas calc-silicate gneisses were derived

from immature island arc sediments. Marble was metamorphosed from shallow marine limestones. Supracrustal amphibolites are meta-basalts with a range of affinities, from MORB-like, to E-MORB-like, to island-arc-like. Meta-rhyolites of arc affinity overlie the Franklin marble in the western Highlands (Volkert et al. 2010). Intermediate metavolanic rocks are lacking among NJ Highlands supracrustals. This variety of lithologies and their inferred protoliths supports the interpretation of a back-arc basin tectonic setting.

Deposition of the Franklin marble and associated zinc ore is constrained to the period ~1295-1300 Ma by SHRIMP zircon ages of intercalated metarhyolites, (Volkert et al. 2010). A metarhyolite from beneath the structurally higher Wildcat marble was dated at 1259 ± 7 Ma. These ages overlap with those of younger members of the Losee basement suite, ~1248-1282 Ma, but are significantly younger than the oldest basement rocks, ~1363-1366 Ma (Volkert et al. 2010). These data suggest that following an initial episode of arc magmatism, new crust of continental arc affinity was created concurrently with deposition of eroded arc products, arc-derived volcanic rocks and chemical sediments.

Monzonitic to leucogranitic rocks of the Vernon Supergroup were emplaced at ~1185 Ma (Volkert et al. 2010). These metaluminous to peraluminous A-type granites are ubiquitous, underlying some 55% of the Highlands (Volkert and Drake 1999).

Weakly foliated to undeformed granitoids of the Mt. Eve suite were emplaced at ~1020 Ma, marking the end of Grenville compressional tectonics (Gorring et al. 2004; Volkert et al. 2010). The spatially restricted outcrop of Mt. Eve rocks suggest that

magmas were generated by depressurization melting due to localized extension associated with post-tectonic transpression (Gorring et al. 2004).

With the exception of Mt. Eve rocks, Highlands rocks were metamorphosed at upper amphibolite to granulite facies. Peak metamorphic conditions of $\sim 760^{\circ}\text{C}$ at 0.41–0.50 GPa occurred by 1030 Ma (Vokert 2010) and were associated with the Ottawa orogeny (Volkert and Drake 1999; Johnson and Skinner 2003; Gorring et al. 2004; Volkert 2004; Peck et al. 2006; Peck 2009). Recent geochronology on Highlands rocks shows a variety of metamorphic ages on zircons with clusters at ~ 1212 – 1252 Ma, ~ 1140 – 1170 Ma, 1010–1030 Ma, and ~ 989 – 997 Ma (Volkert et al, 2010). These data support multi-stage histories of Grenville orogenesis (McLelland 1996; Rivers 1997). The youngest dates indicate some post-Ottawan thermal activity (Volkert et al. 2010).

Analytical Methods

Representative samples of mapped units were collected from each of three map sites. A subset of these were thin-sectioned. After petrographic analysis, a final group of 41 unweathered and non-retrograded samples were analyzed for 32 trace elements on the Perkin Elmer Dynamic Reaction Cell-e Inductively Coupled Mass Spectrometer (ICP-MS) at the Brooklyn College Environmental Sciences Analytical Center (Table 2).

Samples were crushed to sand-size, then powdered in a Retsch PM-100 ball mill fitted with a tungsten carbide container and balls. Powders were digested in 7 ml Teflon vials using a 3:1 solution of trace metal grade HF and 8N HNO_3 . Capped vials were heated overnight at 120°C and allowed to evaporate the following day. Dry residue was twice dissolved in 8N HNO_3 , heated and evaporated. The samples were then diluted

with 2.5 ml deionized water and 2.5 ml 8N HNO₃, capped, heated and checked for clarity. Clear fluids were diluted with 50 ml deionized water for an initial dilution factor of 500x. Further dilutions to 2000x and 10000x were made as required for specific analytes.

To correct for mass-dependent instrument drift, a matrix-matched drift solution was inserted between every 5 samples in each run. This drift solution was made by mixing digested, 1000x diluted mixed samples of a subset of the rocks examined in this study. USGS standard rock powders GSP-2, BHVO-2, QLO-1, AGV-2, BIR-1 and W-2 were analyzed to calibrate instrument output.

Ten samples were analyzed for major oxide concentrations on the Horiba JY Ultima C Optical Emission Spectrometer (ICP-OES) at Montclair State University (Table 1). Powders were prepared for analysis using the flux fusion method per MSU protocols: addition of lithium borate flux, transfer of powders to graphite crucibles and heating to 1050°C in a muffle furnace for 15-20 minutes. Melts were diluted to a factor of 500x in 7% HNO₃, then to 4000x in 2% HNO₃ prior to analysis. An additional six samples were analyzed for major and trace elements at Activation Laboratories in Ancaster, Ontario, Canada, using their analysis package code 4Litho (Tables 1,2).

All samples were analyzed for major oxide concentrations on the Hitachi TM-1000 Scanning Electron Microscope-SEM-EDS at Brooklyn College (Table 1). Powdered samples were compressed and placed in an aluminum stage receptacle. Raster analyses were obtained for a minimum of three 0.5mm² areas, and an average composition was calculated. Machine outputs in element weight percent were

converted to oxide weight percent and calibrated to the values obtained at Montclair State for the same powders.

Approximately 125 SEM-EDS analyses from polished thin sections of 28 samples were performed to characterize the compositional variability of pyroxene, and to a lesser extent, amphibole and biotite.

Descriptions of Mapped Rocks

Brief descriptions of the mapped units (Fig. 4) are provided below. For comprehensive descriptions of the regional bedrock, see Volkert (1999, 2004, 2010, 2011). Mapped rocks are divided into four groups: 1) tonalitic gneiss (basement); 2) felsic gneisses; 3) amphibolites; and 4) high-Fe and Fe-altered rocks. A fifth rock, marble (unmapped because of limited outcrop) is also described. Rock units were classified based on mineral assemblages, field relationships, rock textures and geochemical profiles. Rock names are those used on the maps (Fig. 4). All rare earth element abundances have been normalized to the chondritic values of Boynton (1984). La/Yb and La/Lu are both used as indicators of light/heavy rare earth element abundances because not all rocks referred to herein were analyzed for both Yb and Lu. However where both elements were analyzed, the two ratios are sufficiently similar to be comparable.

Tonalitic Gneiss

This is a massive, tan- to light grey-weathering, medium-grained, mafic-poor rock. Quartz comprises 10-50% of the rock, with the majority of the remaining rock

composed of antiperthite and plagioclase. Magnetite, biotite, augite and apatite are accessory constituents. Two samples show marked enrichments in light rare earth elements (LREE), with La/Yb 5.8-8.9 and a distinct, but small positive Eu anomaly (Fig. 6). The REE abundances of these samples resemble Losee samples analyzed by Volkert (1999).

Metre-scale lenses of amphibolite are common within the tonalitic gneiss. One basement outcrop of amphibolite is significantly larger, with a more massive texture than average. This rock has greater overall REE concentrations and much greater enrichments of LREE, compared to tonalitic gneiss (Fig. 6). However the general shape of its REE curve resembles that of the tonalitic gneiss, suggesting similarity of the magma sources. This suggestion is supported by the close cluster formed by the tonalitic gneiss and basement amphibolite on the discrimination diagram of Winchester and Floyd (Pearce 1996) (Fig.8). The tonalitic gneiss has been mapped by Volkert (2011) as a member of the Losee Metamorphic Suite, the regional basement.

Marble

Unlike the western New Jersey Highlands, marbles are rare in the eastern New Jersey Highland sites described herein. We observed two ~1 m layers of impure marble, too thin to map, in the Wanaque map area. The marble is composed of 50-80% calcite, with humite representing most of the balance. Phlogopite and quartz are minor constituents. Marbles have low overall REE abundances, with high fractionation between the LREE- and middle rare earth elements (MREE) (Fig. 6).

Felsic Gneisses

We distinguished 5 felsic gneisses on the basis of principal mafic minerals, feldspar type and abundance of quartz: Bt-Qz gneiss, Cpx gneiss, Opx gneiss, Cpx-Pl gneiss and Cpx-Kf gneiss.

Biotite-quartz gneiss was mapped at Ringwood and Wanaque. Alternating biotite-rich and quartzofeldspathic layers define foliation in this rock which typically contains the mineral assemblage $\text{Mag-Bt-Kfs-Pl-Qtz} \pm \text{Grt}$. Plagioclase comprises 20-65% of the rock and varies inversely with quartz which locally accounts for up to 75%. Microcline constitutes 10-15% of this unit. Rusty brown garnets, up to 3 mm in diameter, are locally abundant (<20%). Apatite, clinopyroxene, and rutile are common accessories. Bt-Qz gneiss has REE abundances similar to average upper crust, as represented by post-Archean Australian shale (PAAS) (McLennan 1989)(Fig. 6). Garnet-bearing samples show heavy rare earth element (HREE) enrichment, and quartz-rich samples are depleted in all REE, a dilution effect of quartz (McLennan 1989). Most samples plot as wacke on the discrimination diagram of Garrels and McKenzie (1971) (Fig. 5). REE and major element abundances suggest that Bt-Qz gneiss is an immature clastic metasedimentary rock.

Quartz-poor rocks that are rich in clinopyroxene and/or orthopyroxene were mapped as Cpx and Opx gneiss, respectively, at the Ringwood deposit. Cpx gneiss is composed of green, monomineralic, cm-scale bands of Fe-rich diopside and a cream-colored rock whose approximate mineral composition is dominated by plagioclase (~60%), and clinopyroxene (~30%), along with titanite and trace quartz and apatite. Opx gneiss stratigraphically underlies the Cpx gneiss. Opx gneiss has alternating light-colored Opx-rich layers and dark-colored Hbl-rich layers. The combined mineral

278 assemblage is Bt-Kfs-Cpx-Mag-Opx-Hbl-Pl with accessory apatite. Magnetite is
279 particularly abundant in Opx-rich layers, comprising up to ~15% of these layers. Both
280 the Cpx gneiss and Opx gneiss most resemble the garnet-bearing samples of Bt-Qtz
281 gneiss with respect to REE abundances, displaying gullwing-shaped curves with more
282 or less pronounced negative Eu anomalies (Fig. 6), suggesting a predominantly clastic
283 composition of the protoliths (Fig. 6), but with Fe-enrichment.

284 Clinopyroxene-plagioclase gneiss, mapped at Wanaque, is pale gray to pale
285 pink on both fresh and weathered surfaces. It has a distinct lineation defined by grayish-
286 green clinopyroxene. Locally lenses of coarser-grained clinopyroxene or magnetite
287 define a discontinuous foliation. Cpx-Pl gneiss has the mineral assemblage Ap-Ttn-Cpx-
288 Pl and may contain quartz, K-feldspar, orthopyroxene, magnetite, perthite and/or
289 antiperthite. Pyroxenes comprise ~20% of the rock.

290 Cpx-Pl gneiss has moderately enriched, gently sloping REE curves with
291 abundances between those of PAAS and carbonates (Fig. 6), suggesting a mix of
292 clastic and calcareous input in the protolith. The lack of a Eu anomaly in the Cpx-Pl
293 gneiss may be explained by the high modal abundance of plagioclase, as well as the
294 contribution of carbonate. Cpx-Pl gneiss plots as wacke on the discrimination diagram
295 of Garrels and McKenzie (1971) (Fig. 5).

296 Clinopyroxene-K-feldspar gneiss was mapped at Warwick. Cpx-Kf gneiss has
297 two variants, a well-foliated rock with alternating layers rich in either Cpx or Kf in the
298 western part of the map and a massive, mafic-poor rock in the eastern part. Both units
299 are quartz-poor. In the foliated western unit, felsic layers are dominantly microcline,
300 which constitutes up to 90% of the layers. Mafic layers are dominantly Cpx, which

constitutes up to ~80% of the layers. In the massive eastern unit, perthite and microcline make up ~80% of the rock with quartz contributing 15%. Mg, Ap, and Ttn are minor components of both variants of Cpx-Kf gneiss. Plagioclase is generally absent from Cpx-Kf gneiss, except where it grades into amphibolite. Petrographically, the Cpx in the western unit is dark green and pleochroic. It is iron-rich, with molar ratios of $\text{FeO}/(\text{FeO} + \text{MgO})$ between 0.80 and 0.93 .

A thin band of Mc- and perthite-bearing amphibolite separates the two types of Cpx-Kf gneiss. This amphibolite shows several geochemical affinities with the Cpx-Kf gneiss. Both rocks are enriched in REE, with fairly smooth, steeply sloping curves produced by La/Lu ratios of ~39, (Fig. 6). This pattern resembles that of alkaline, continental rift volcanic rocks (Winter 2001). However Smith (1990) found ultra-potassic basaltic rocks with similar REE abundances in the Central Metasedimentary Belt. The Cpx-Kf gneiss and the neighboring amphibolite define a calc-alkaline trend on the AFM diagram (Fig. 7). The Mc-bearing amphibolite plots in the field of basalt and the Cpx-Kf gneiss plots from rhyolite to trachy-andesite on the Zr/Ti vs. Nb/Y modified diagram of Winchester and Floyd, (Pearce, 1996) (Fig. 8). Both rocks plot in the metaigneous field on the Zr/TiO₂ vs. Ni discrimination diagram of Winchester and Floyd (1984) (not shown). Taken together, these geochemical characteristics suggest that both rocks originated as members of a bimodal volcanic suite.

Amphibolites

Amphibolites are spatially associated with Fe deposits at all three areas. Amphibolite is dark gray, or black and white on fresh and weathered surfaces. It is medium-grained, and usually displays mineral lineations defined by $\text{Hbl} \pm \text{Mag}$. Locally,

1-2 mm thick segregations of light- and dark-colored layers create a discontinuous foliation. The characteristic mineral assemblage is $\text{Hbl-Pl}\pm\text{Cpx}\pm\text{Opx}\pm\text{Mag}\pm\text{Bt}$. Plagioclase is the most abundant mineral, comprising 50-75% of the rock. Hornblende comprises 20-50% of the rock, and varies inversely with clinopyroxene and/or orthopyroxene which together constitute 10-30% of the rock. Magnetite is a common accessory to minor mineral. Apatite, titanite, and microcline are accessory to minor minerals in Warwick amphibolite.

Most amphibolites from the Wanaque and Ringwood map areas have gently sloping REE curves with La/Lu ranging from 1.5 to 2.7, some with small negative Eu anomalies (Fig. 6). These REE patterns resemble those of basalts from the Scotia Sea, a modern back-arc basin (Fretzdorff et al. 2002). The most enriched samples have REE abundances similar to basaltic sills and dykes from the western edge of the Elzevir Terrane in the Central Metasedimentary Belt (CMB), identified as a back-arc basin, which opened during the Elzevirian orogeny (Smith and Holm 1990; Dickin 2010). The massive amphibolite that occurs as a tens of metres-scale inclusion in the basement tonalitic gneiss at Ringwood has a distinctly higher LREE/HREE ratio than other amphibolites at Ringwood and Wanaque (Fig. 6). The LREE/HREE ratio of this unit suggests that these mafic dykes are associated with basin volcanics, rather than basement magmatism which yields lower La/Yb ratios (Volkert 1999).

Most amphibolites form a cluster centred on the field of back-arc basin basalt on the tectonic discrimination diagram of Cabanis and Lecolle (1989). The LREE-enriched amphibolite from the basement at Ringwood has a distinct position in the calc-alkali

field, and Kfs-bearing amphibolites from Warwick cluster in the high-La region of the calc-alkali field (Fig. 9).

High-Fe Units and Fe-Alteration

Ore in each of the studied localities has been extracted, and available ore samples were limited to waste piles associated with past mining activity. Accordingly, ore characteristics were not examined systematically in this study.

Stratiform rock units composed of massive clinopyroxene are spatially associated with ore in all three map areas. Massive Cpx rocks are herein referred to as diopsidite, in keeping with local convention. Diopsidite occurs as a monomineralic rock, or as a component of quartz-diopside gneiss, a unit composed of alternating centimetre- to metre-scale layers of light-gray quartz and dark green diopside. Cpx in these rocks generally has $\text{FeO}/(\text{FeO}+\text{MgO})$ values between 0.4 and 0.6. Qtz-Di gneiss occurs at Wanaque and Warwick and is spatially associated with ore. Contacts between layers are very sharp. Diopside layers may contain up to 2% apatite, either as inclusions or interstitial grains. Minor magnetite is disseminated in both layers. Massive diopsidite, Qtz-Di gneiss and ore are enriched in iron and nearly aluminum-free, characteristics shared with modern metalliferous sediments (Spry et al. 2000)(Fig. 10).

At Wanaque, Qtz-Di gneiss includes light-brown weathering, sugary-textured, massive feldspathic layers up to 15 cm thick. Feldspathic layers have the assemblage $\text{Ttn-Cpx-Kfs-Pl}\pm\text{Qtz}\pm\text{Ap}\pm\text{Mag}$. Their REE abundances are similar to those of Cpx-Kf gneiss (Fig. 6), except that they are more enriched in MREE and HREE. Given this similarity, the generally massive appearance of the feldspathic layers, and their sharp

boundaries with quartz and diopside layers, the feldspathic layers are interpreted to have formed from a tuffaceous protolith.

Amphibolite is sometimes altered in proximity to ore deposits or exploration pits. At Wanaque, scapolite and biotite may comprise significant percentages of the whole rock. Scapolite occurs with or without plagioclase and ranges from 15-75% of total mineral abundance. Where scapolite-bearing amphibolite is in contact with late leucogranite, plagioclase has replaced scapolite, an indication of contact metamorphism, and a pre-intrusion age of alteration. Biotite may comprise as much as 25% of altered amphibolites at Wanaque. In contrast, biotite-bearing amphibolites at Ringwood are rather widespread, and show equilibrium textures.

A texturally distinctive amphibolite occurs at Ringwood in close spatial association with ore (Fig. 11). This rock is characterized by its anastomosing bands of hornblende, which create a striped or spotted appearance depending on the surface exposed. This rock occurs within the tonalitic gneiss as elongate pods that are concordant with the foliation. The REE composition of this unit is similar to amphibolites of metabasaltic origin (Fig. 6). However, the hornblende in the anastomosing bands of this amphibolite is enriched in Fe and Cl, compared to hornblendes from other amphibolite pods within the tonalitic gneiss at the same map area (Fig. 12), consistent with alteration by an iron-rich brine. Based on texture and composition, this amphibolite is interpreted have formed from the metamorphism of tectonically dismembered mafic dykes that had undergone stockwork fracturing and associated alteration.

Leucogranite

This ridge-forming rock is pale salmon and white on fresh surfaces, and weathers to light-grey or beige. It is coarse-grained and mafic minerals are generally absent. Most examples of this rock are massive, but elongate quartz grains define a poorly developed lineation and foliation in some outcrops. Quartz and K-feldspar are dominant; plagioclase is a minor constituent. Leucogranite cross-cuts all stratified units and overprints ore-associated alteration, and so must post-date magnetite mineralization.

Discussion

Tectonic Setting

The mapped areas lie within an ancient back-arc basin (Volkert and Drake 1999; Volkert 2004; Volkert and Aleinikoff 2007; Peck 2009; Volkert et al. 2010). The mapped field areas have the following lithological and geochemical characteristics supportive of a back-arc basin tectonic setting: 1) metabasalts exhibit REE enrichments common to modern back-arc basin basalts, and plot on or near the field of back-arc basin basalts on the tectonic discrimination diagram of Cabanis and Lecolle (1989); 2) clastic metasedimentary rocks are immature, with most plotting in the field of greywacke on the diagram of Garrels and McKenzie (1971); 3) felsic metavolcanic rocks have extreme enrichments in LREE, typical of continental rifts and ensialic back-arc environments (Smith and Holm 1990); 4) some metabasalts and felsic metavolcanic rocks show subduction zone influence on mantle normalized trace element plots (not shown) (Sun and McDonough 1989) including enrichments in large ion lithophile elements (Rb, Ba, and K), depletions in high field strength elements (Th, Zr, and Ti) and strong negative anomalies in Nb and Ta; 5) stratiform ore bodies and associated altered rocks have

mineralogical and geochemical characteristics consistent with genesis from a seafloor hydrothermal system. Hydrothermal systems are common in back-arc basins (Gamo et al. 2006; Yang and Scott 2006).

Back-arc settings have been established for the Central Metasedimentary Belt (Smith and Holm 1990; Dickin and McNutt 2007) and for most of the Adirondacks (Chiarenzelli et al. 2015). The Central Metasedimentary Belt is interpreted as the northernmost extension of an aulacogen over 400 km long (Dickin et al. 2016). The Trans-Adirondack back-arc basin is considered a roughly contemporary, but smaller extensional structure which opened ~50 km to the east (Chiarenzelli et al. 2015). Given the regional scale of back-arc extension, it is likely that the New Jersey Highlands is a more southerly, en echelon expression of the same, pre-Shawinigan episode (Chiarenzelli et al. 2015).

Origin of Stratiform Deposits

At Wanaque and Warwick, the bi-mineralic quartz-diopside (Qtz-Di) gneiss lies in close proximity to magnetite ore, and is concordant with the stratiform trend of the deposits. The Qtz-Di gneiss consists of alternating cm-scale layers of quartz and diopside. At Wanaque, layer thickness increases to meter scale with increasing proximity to the Roomy mine. Layers are continuous over metres, and contacts between layers are sharp and non-gradational. No other unit in the study areas displays such distinct layering, and so this texture is consistent with primary layering rather than metamorphic segregation.

Massive diopside is spatially associated with magnetite ore at all three study localities. Al_2O_3 is less than 1% by weight in diopside and Qtz-Di gneiss, and Fe_2O_3 ranges from 8.7-13.8%. It is implausible that the Di-rich units formed as a result of replacement or metasomatic processes affecting siliciclastic or volcanic strata due to the near absence of aluminum in these rocks, and the lack of alteration haloes or gradational contacts with adjacent units. Qtz-Di gneiss, diopside and ore all are more similar chemically to modern metalliferous sediment than to neighboring metasedimentary units (Fig. 10). Therefore, these units are interpreted to have formed as chemical sediments.

The best analogue for these rocks is iron formation (IF). IF is defined as “a chemical sediment, typically thin bedded or laminated, whose principal chemical characteristic is an anomalously high content of iron, commonly but not necessarily containing layers of chert,” (Klein 2005). The quartz-diopside gneiss and spatially related magnetite are consistent with the definition of IF, and the existing diopside-dominated assemblages are compositionally and mineralogically consistent with carbonate-facies IF metamorphosed under granulite conditions:

Variation between diopside and quartz-diopside gneiss can be attributed to variation in the ratio of ankerite to chert in the protolith, with chert-rich protoliths corresponding to Qtz-Di gneiss. Adjacent magnetite and diopside-rich layers can be attributed to shifts between oxide-facies and cherty carbonate-facies IF deposition.

A seafloor exhalative source for iron is supported by the spatial association of amphibolite (metabasalt) and ore at all three localities. Magma chambers beneath the seafloor would drive hydrothermal circulation to and from the surface. The amphibolites, even those considered herein to be altered, plot within or just outside the range of normal composition for andesite and basalt on the alteration box plot of Large (2001) (not shown), indicating that alteration was spatially limited and controlled by proximity to a hydrothermal vent or subsurface conduit.

Felsic metavolcanic rocks at Warwick, as well as the feldspathic interlayer of the Qz-Di gneiss at Wanaque, plot within the range of normal composition for dacite on the Large (2001) alteration box plot, except for one sample which indicates slight sericitic alteration. Taken together, these data for mafic and felsic metavolcanic rocks show that the major-element-based discrimination diagrams referred to herein are appropriate.

Origin of Basement-Hosted Ore and Alteration

Several magnetite showings in the Ringwood map area occur within structurally-concordant, basement-hosted amphibolite pods. These pods are interpreted as a tectonically dismembered mafic dyke, based on their small size, boudin-like form, geochemical composition, and presence within a metaintrusive rock. In each case the mineralization is associated with a distinct anastomosing fabric defined by Fe-Cl-rich amphibole. The distinct texture of these amphibolites is consistent with their having resulted from the compressional deformation of a stockwork vein system, as has been demonstrated in other metamorphosed ore deposits (e.g. Johnston, 1996)). Furthermore, the Fe-Cl-rich composition of these deformed fractures indicates that they

were altered by a Fe-rich brine. The altered amphibolites, and the ore that they host, immediately underlie a wedge of stratabound diopsidite at the base of the supracrustal sequence. The diopsidite grades into Opx gneiss along strike (Fig. 4).

The field relationships described above suggest that all three Fe-rich rock units (basement-hosted ore, diopsidite, Opx-gneiss) are related. This is consistent with spatial relationships that have been documented in exhalative deposits, where a fracture-associated feeder zone underlies stratiform ores that exhibit facies transitions along strike (e.g., Sullivan and Annaraq in (Leach, D.L. et al. 2005); Jason in (Gardner and Hutcheon 1985).

In the case of the Ringwood ores, rift-related faults may have served as conduits for both mafic magmas and hydrothermal fluids. The Fe-rich brines altered host rock along the flow path, formed a mineralized stockwork system beneath the seafloor, and vented into seawater where stratiform IF formed through precipitation and deposition. Carbonate-facies IF strata accumulated proximal to the vent, and was subsequently metamorphosed to diopsidite. More distally, less abundant Fe-rich precipitates contributed to immature clastic sediments, which were metamorphosed to form Opx-gneiss (Fig. 13).

Conclusions

Magnetite ore from our study sites is interpreted as metamorphosed iron formation. Sharp contacts between ore and diopsidite or Qz-Di gneiss represent changes between oxide and cherty carbonate facies IF. Spatially associated volcanic strata, including both metabasalts and felsic alkaline metavolcanic rocks, are evidence

for localized heat sources to drive the hydrothermal transport of iron. Distinctively textured, Fe-enriched amphibolite at Ringwood is evidence for a hydrothermal vent that created small, vent-proximal deposits of massive magnetite and Fe-enrichment in the vent-distal sediments.

The syngenetic, sedimentary exhalative model for carbonate-hosted zinc and iron deposits in the western New Jersey Highlands (Johnson and Skinner 2003; Peck 2009) is here extended to a larger variety of host rocks, including the regional basement. Given the variety of siliciclastic, volcanoclastic, and chemical sediments common to back-arc basins, it is not surprising to find syngenetic deposits from such settings in a variety of hosts. The associated rock units and ore facies would be dependent upon the location of the vent, distance from the vent, and intrabasinal circulation capable of distributing ore-bearing fluids to vent-distal and vent-proximal positions (Leach et al. 2005). The sedimentary exhalative model is appealing for its simplicity. It avoids the need to invoke an assortment of genetic processes based on host lithologies (Puffer 2001), and explains the consistency of ore-body mineralogy (primarily massive magnetite) as a characteristic of intrabasinal hydrothermal fluid chemistry and seawater oxidation state.

Figure 1. Grenville Province of Eastern North America (Modified from Tollo et al. 2010). CMB- Central Metasedimentary Belt; LMG-Lyon Mountain Granite.

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Figure 2: Mines of the New Jersey Highlands, with nearby Pine Swamp and Hogencamp mines in the New York Hudson Highlands. Large circles are larger deposits. (Modified from <http://www.mindat.org/photo-539329.html>, accessed 3/25/2016)

Figure 3: Study Site Location Map

Figure 4. Geological maps of the Wanaque (upper left), Warwick (right) and Ringwood (lower left) Areas

Figure 5: Clastic and mixed calcareous/clastic gneisses, after Garrels and McKenzie (1971)

Figure 6: Chondrite Normalized REE Abundances, using the values of Boynton (1984). A.-Tonalitic gneiss and basement amphibolite; B.-Clastic metasedimentary rocks; PAAS is post-Archaeon Australian shale. C.-Mixed calcareous-clastic gneisses; D.-Back-arc basin-type amphibolites; Smith is a basalt from the Central Metasedimentary Belt (CMB) (Smith and Holm 1990). Fretzdorff is a basalt from the Scotia Sea(Fretzdorff et al. 2002). E.-Rocks with rifted-arc affinity; Warwick rocks include Cpx-Kfs gneiss and amphibolite. Wanaque rocks are felsic interlayers in Qtz-Di gneiss. Smith Ultra-K is a leucitite from the CMB(Smith and Holm 1990).

Figure 7: AFM Diagram for Warwick felsic and mafic metavolcanics. Calc-alkaline trend from Irvine and Baragar (1971)

Figure 8: Modified volcanic discrimination diagram of Winchester and Floyd (Pearce, 1996). Fields are: 1- rhyolite and dacite; 2-andesite and basaltic andesite; 3-basalt; 4-alkali rhyolite; 5-trachyte; 6-trachy-andesite; 7-alkali basalt; 8-phonolite; 9-tephri-phonolite; 10-foidite

Figure 9: La-Y-Nb Discrimination Diagram of Cabanis and Lecolle (1989). Field symbols: 1 contains volcanic arc basalts. 1a, calc-alkali; 1c, tholeiites; 1b, overlap between 1a and 1c. 2a, continental basalts; 2b, back-arc basin basalts (not well defined). 3a, alkali basalts from continental rifts; 3b and 3c, E-MORB (3c is weakly enriched); 3d, N-MORB

Figure 10: Iron enrichment in metasedimentary rocks and tonalitic gneiss, showing fields for modern metalliferous sediments, terrigenous sediments and pelagic sediments (Peter and Goodfellow 1996). Diagram after Bostrom (1973).

Figure 11: Textural difference between unaltered (left) and altered (right) amphibolites from Ringwood map area. Note anastomosing bands of hornblende in altered rock. Fields of view are 2 mm, left; 5 mm, right.

Figure 12: Hornblendes in basement-hosted massive and altered amphibolites at Ringwood. Hornblendes from amphibolites are enriched in Cl and Fe compared to massive amphibolites.

Figure 13: Development of massive magnetite in basement amphibolite at Ringwood study area. A) Ascending hydrothermal fluid is channeled through a fault previously exploited by basaltic dike. Fluid fractures the dike, alters its chemistry and vents onto the sea floor as an Fe- and Si-rich brine. Brine collects above the vent and overflows down the paleoslope. B) Sediments fill the basin. Carbonate facies iron formation precipitates from the brine pool. Iron-enriched carbonate and clastic sediments collect above paleoslope. Mixed carbonate and clastic sediments are deposited above the mineralized sediments, followed by dominantly clastic input. C) High-grade metamorphism alters carbonate facies IF to diopside, iron enriched clastic and carbonate sedimentary rock to Opx-gneiss, mixed calcareous-clastic sedimentary rock to Cpx-gneiss. Amphibolite dykes are deformed and dismembered. Compare to Fig. 4.

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TONALITIC GNEISS			METAVOLCANIC ROCKS										
Major source			Cpx-Mc Gneiss (Warwick)			Felsic Interlayers (Wanaque)		K-rich Amphibolites (Warwick)					
	R9	R11	M3	M5	M7	W26	W7	M2	M4	M6	R4	R5	R12
	EDS	EDS	EDS	EDS	EDS	EDS	MSU	EDS	EDS	EDS	EDS	EDS	EDS
SiO ₂	76.18	73.41	58.11	67.76	60.95	57.45	63.12	44.49	45.20	47.32	48.24	50.36	46.45
TiO ₂	0.21	0.34	0.48	0.42	0.22	2.69	0.54	1.50	1.53	1.69	1.47	1.00	1.18
Al ₂ O ₃	12.03	12.94	16.88	12.70	13.58	13.61	12.68	16.07	15.33	15.72	15.71	14.53	17.12
Fe ₂ O ₃	2.43	2.81	7.81	3.41	6.19	3.31	5.25	14.10	11.91	12.34	13.19	12.87	15.24
MnO	-	0.07	0.18	0.14	0.25	0.08	0.31	0.42	0.40	0.11	0.28	0.20	0.27
MgO	1.44	1.81	2.45	1.09	1.67	3.26	2.53	6.94	5.62	6.87	9.95	6.11	5.66
CaO	2.80	3.28	4.02	2.58	5.52	12.60	7.62	8.41	11.33	5.06	6.13	7.81	8.29
Na ₂ O	3.40	3.95	4.39	1.87	2.27	5.29	5.84	4.32	2.83	3.53	2.84	3.13	4.09
K ₂ O	1.42	1.20	5.37	9.88	9.19	0.20	1.74	2.78	3.81	5.69	1.99	3.17	1.40
P ₂ O ₅	0.09	0.20	0.31	0.15	0.17	1.52	0.12	0.97	1.47	1.18	0.19	0.16	0.31
S	-	-	-	-	-	0.00	-	-	-	-	-	0.08	-
Cl	-	-	-	-	-	0.00	-	-	0.57	0.49	-	0.59	-
LOI													
Total	100.00	100.00	100.00	100.00	100.00	100.01	99.76	100.00	100.00	100.00	100.00	100.00	100.00

										METASEDIMENT				
Amphibolites (Ringwood and Wanaque)										Opx Gneiss	Cpx Gneiss	Cpx-Pl Gneiss		
R13	W8	W13	W16	W18	W19	W20	W21	W11	W25	R2	R14	W22	W24	R1
EDS	MSU	MSU	MSU	MSU	MSU	MSU	MSU	EDS	EDS	ACT	ACT	EDS	EDS	ACT
49.34	48.91	49.20	49.37	52.42	53.31	53.18	54.40	55.01	52.15	47.88	59.76	63.74	61.90	62.30
1.46	1.55	0.75	0.99	1.06	2.70	2.48	2.95	0.51	0.78	1.67	0.15	0.39	0.51	0.72
15.74	16.59	10.28	16.02	15.50	11.81	12.91	13.86	15.70	9.99	13.12	10.28	15.49	13.77	15.80
12.59	15.61	11.14	9.80	7.67	11.06	10.21	10.62	8.07	7.07	15.35	5.81	6.12	4.50	5.74
0.48	0.02	0.08	0.06	0.05	0.07	0.07	0.04	0.30	0.19	0.21	0.23	0.20	0.14	0.03
6.73	4.86	5.91	6.68	6.26	5.35	4.95	3.32	5.92	16.30	9.11	6.70	3.31	4.38	2.44
7.60	5.75	19.30	9.47	9.96	10.33	10.26	8.70	9.02	8.09	8.19	12.76	4.93	8.78	1.24
3.72	5.47	2.70	5.34	5.05	5.40	5.52	6.43	4.69	2.83	2.68	2.81	4.23	5.25	2.47
2.09	1.21	0.26	0.50	0.50	0.16	0.20	0.19	0.52	1.10	1.14	0.41	1.44	0.44	7.37
0.24	0.13	0.24	0.07	0.08	0.91	0.91	1.00	0.26	0.12	0.32	0.22	0.15	0.33	0.16
-								-	-			-	-	
-								-	1.38			-	-	
										0.58	0.74			1.52
100.00	100.09	99.85	98.30	98.55	101.10	100.69	101.51	100.00	100.00	100.25	99.87	100.00	100.00	99.79

NTARY ROCKS					ORE AND ALTERED ROCKS						
Bt-Qz Gniess			Marble		Amphibolites			Qz-DI Gneiss	Massive Diopside		Ore
R16	W4	W10	W5	W6	W15	W9	R8	M1	R15	W2	W1
ACT	EDS	EDS	ACT	ACT	MSU	EDS	EDS	ACT	EDS	EDS	ACT
63.68	72.35	75.98	13.20	18.35	46.58	44.00	47.68	70.01	51.76	47.21	0.17
0.87	0.61	0.92	0.04	0.01	0.93	3.40	2.33	0.07	0.18	0.21	1.23
16.23	11.42	8.85	0.28	0.16	14.24	14.47	14.48	0.88	-	-	2.06
5.86	5.75	3.37	3.55	2.54	10.36	15.00	14.00	8.72	12.29	13.75	98.54
0.06	0.48	0.14	0.42	0.29	0.09	0.08	0.64	0.19	0.37	0.13	0.12
2.94	2.17	3.25	17.72	23.71	8.72	5.30	5.64	6.28	13.48	14.52	0.50
1.69	3.73	2.88	32.88	29.39	11.80	9.29	10.57	12.31	21.41	23.42	< 0.01
3.87	1.83	2.28	0.03	0.04	4.22	5.91	3.28	0.42	0.43	0.69	< 0.01
2.65	1.46	2.13	0.12	0.03	0.69	0.44	0.37	0.03	-	-	< 0.01
0.09	0.20	0.19	0.03	0.02	0.07	0.37	0.72	0.05	0.09	0.06	< 0.01
	-	-			-	-	0.28		-	-	
	-	-			1.43	1.73	0.01		-	-	
0.77			30.00	25.92				0.15			(2.83)
98.71	100.00	100.00	98.27	100.46	99.12	100.00	100.00	99.11	100.00	100.00	99.79

	BASEMENT							
	Tonalitic Gneiss (Ringwood)		Cpx-Mc Gneiss (Warwick)			Felsic Interlayers (Wanaque)		K-rich Am
	R9	R11	M3	M5	M7	W26	W7	M2
Ag								
As								
Ba	387.31	453.80	1346.41	1078.02	907.59	57.49	14.19	1026.32
Bi								
Ce	24.68	16.19	304.33	450.12	125.68	276.21	241.70	452.78
Co								
Cr	5.59	9.81	8.27	10.67	23.63	14.10	18.05	5.44
Cs	0.05	0.12	0.30	2.23	1.58	0.03	0.09	0.26
Cu								
Dy	1.63	1.85	8.25	4.01	2.98	23.26	23.74	13.35
Er	1.29	1.16	4.50	2.07	1.65	9.01	11.75	4.99
Eu	0.72	0.62	3.63	2.88	1.81	5.45	6.59	5.88
Ga								
Gd	2.38	1.84	12.04	7.40	4.61	19.68	25.48	17.07
Hf	1.37	2.64	9.35	6.00	5.04	6.75	7.81	3.51
Ho	0.32	0.38	1.71	0.73	0.52	5.15	4.79	2.66
K	10288.00	11659.00	67310.00	100665.00	110932.00	2535.00	16866.00	38296.00
La	13.64	10.40	156.56	286.66	43.86	102.93	146.49	224.63
Lu	0.18	0.20	0.60	0.33	0.34	1.66	1.59	0.76
Mo								
Nb	5.92	6.66	21.29	20.74	41.05	19.56	23.38	28.36
Nd	12.55	5.29	129.50	185.96	62.82	120.58	144.79	200.79
Ni	4.84	10.84	7.66	6.03	21.66	13.54	16.77	14.26
P	336.28	352.46	2244.25	707.78	52.48	7036.27	8932.95	9760.89
Pb		43.00	5.08				2.02	9.07
Pr	3.00	1.75	34.74	34.67	14.71	25.56	26.80	44.93
Rb	11.48	11.15	106.45	268.79	326.73	3.51	5.67	33.42
Sb								
Sc	4.54	6.95	3.84	-0.85	4.11	39.12	31.61	18.55
Sm	1.60	0.77	20.11	11.43	7.88	25.32	24.06	30.15
Sn								
Sr	87.48	102.11	440.09	195.19	123.34	119.25	122.58	750.73
Ta	0.88	1.14	1.32	2.28	2.83	1.42	1.25	1.69
Tb	0.28	0.24	1.76	0.78	0.55	3.43	4.36	2.30
Th	0.56		12.97	63.14	5.14	9.51	8.80	17.71
Ti	1685.53	1774.10	4433.27	2221.26	2665.35	20455.49	24306.44	12834.03
Tl								
Tm	0.18	0.21	0.68	0.30	0.26	1.50	1.49	0.60
U	0.59	0.88	4.93	20.69	13.25	21.36	20.86	5.28
V	25.69	39.32	48.89	21.11	35.73	253.77	282.15	192.12
W								
Y	10.44	7.75	54.39	21.30	13.81	148.03	187.32	57.06
Yb	1.03	1.21	4.28	2.09	1.90	11.55		4.96
Zn	23.04	12.54	53.25	36.61	91.58	40.93	60.35	73.29

Zr		47.99	85.20	422.09	208.08	194.00	188.88	236.02	133.61
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Draft

METAVOLCANIC ROCKS									
phibolites (Warwick)		Amphibolites (Ringv							
M4	M6	R17	R18	R19	R4	R5	R12	R13	W8
1406.40	1272.43	510.99	389.16	192.83			244.09		87.12
376.90	350.75	9.44	15.16	11.00	19.89	137.82	21.41	20.15	79.66
7.01	5.30	109.76	202.11	232.50	121.46	72.10	140.24	146.06	91.85
0.79	1.82				0.56	1.14	0.76	1.23	0.24
8.78	9.20	4.18	4.05	3.74	11.77	5.16	5.27	5.37	19.23
3.50	3.56	2.30	2.34	2.11	4.84	2.50	2.87	2.62	7.83
4.22	3.94	1.16	1.19	0.91	1.64	1.46	1.39	1.42	5.28
12.65	12.73	3.74	3.60	3.45	7.98	4.77	4.49	4.52	16.01
2.78	3.59	1.02	1.11	1.51	0.41	6.45	1.23	1.27	3.59
1.71	1.77	0.87	0.84	0.79	2.54	1.11	1.19	1.20	3.56
51536.00	70275.00				21018.00	39554.00	16090.00	24739.00	13588.00
197.13	186.00	3.10	8.18	3.59	6.60	69.14	5.85	7.31	60.22
0.53	0.50	0.34	0.36	0.31	0.69	0.44	0.50	0.44	0.70
		0.95	0.61	0.40					
16.44	16.20	1.47	1.10	3.59	4.24	18.84	2.77	3.35	5.82
176.74	184.94	9.79	8.35	7.99	19.00	24.34	14.33	15.75	44.23
42.27	15.27	78.06	65.82	96.97	88.24	38.50	57.16	66.24	85.69
10606.04	7316.08	1132.50	941.85	438.80	558.73	841.36	1208.88	1248.92	449.59
5.74					13.40	12.25			1.37
36.39	34.60	1.93	1.99	1.84	3.61	7.49	3.11	3.33	10.82
82.07	146.40	8.53	7.60	5.71	53.62	271.91	33.80	54.74	26.54
10.99	9.66	18.82	24.43	13.98	29.86	22.25	36.92	39.66	20.14
21.23	22.02	3.02	2.55	2.36	7.94	6.00	4.05	4.43	16.86
500.78	702.87	192.99	257.29	138.68	53.71	125.94	181.88	183.44	366.70
1.11	0.94	0.09	0.12	0.34	0.44	2.11	0.26	0.34	0.40
1.58	1.64	0.65	0.63	0.60	1.54	0.75	0.82	0.75	3.29
11.14	16.50				0.30	14.51	0.12	0.30	1.01
11228.87	10127.65	7279.03	7310.84	6848.17	5137.30	6377.52	6752.12	6778.23	8410.51
0.52	0.52	0.37	0.35	0.33	0.67	0.40	0.49	0.42	0.93
5.71	4.23	bdl	0.06	0.44	0.24	10.50	0.73	0.39	5.39
186.62	168.90	239.54	251.70	235.78	251.01	150.04	248.76	244.89	913.55
47.96	46.53	22.23	22.44	19.40	20.13	29.28	32.50	30.94	97.65
3.07	3.22	2.37	2.37	2.15	5.79	2.79	3.12	2.96	
88.19	86.28	69.47	59.60	49.26	74.85	37.47	132.77	76.97	24.59

92.70	168.99	35.93	38.70	46.46	14.01	220.89	28.29	27.39	139.97
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Draft

wood and Wanaque)								Opx G	
W13	W16	W18	W19	W20	W21	W11	W25	R20	R21
2.22	47.34	15.27	8.60	6.05	6.17	96.91	435.37	1147.16	1198.79
56.73	22.05	13.30	39.94	53.24	48.76	44.72	55.99	15.95	14.82
52.71	238.93	183.46	31.75	21.22	9.84	99.04	25.90	137.91	151.31
0.08	0.10	0.09	0.13	0.12	0.10	0.12	0.18		
5.07	5.94	4.12	7.80	10.83	10.15	4.71	7.82	0.43	1.14
3.10	3.21	2.35	4.00	5.46	5.03	2.65	4.35	0.35	0.67
1.10	1.09	0.97	1.72	2.32	2.16	1.05	1.51	0.87	0.83
5.07	5.03	3.63	7.34	10.29	9.43	5.42	7.30	2.11	2.44
4.51	1.98	2.16	2.58	2.41	2.02	0.94	2.36	0.86	0.63
1.11	1.25	0.89	1.60	2.22	2.08	0.99	1.71	0.09	0.24
2882.00	4935.00	3696.00	1708.00	1253.00	1025.00	8436.00	30142.00		
20.32	11.06	5.30	18.72	23.65	20.29	18.04	25.00	8.04	6.85
0.65	0.43	0.36	0.56	0.72	0.66	0.40	0.58	bdl	0.03
								0.41	0.49
5.67	3.76	5.73	12.89	15.31	17.31	3.12	13.70	7.83	4.67
20.69	17.62	11.39	25.47	35.17	29.58	27.55	31.69	6.04	6.68
54.57	54.77	40.75	19.90	20.64	32.30	58.82	15.23	98.97	108.51
988.26	243.14	284.11	3138.12	4129.67	4292.92	1672.69	567.71	723.68	961.62
1.18	1.09	1.33	1.26	1.19	1.36	1.15	1.03		
6.88	3.75	2.31	5.82	7.97	6.84	6.25	7.45	1.79	1.71
9.89	6.40	6.45	7.50	5.32	6.23	5.08	40.11	129.13	59.89
20.15	35.31	34.89	31.85	32.73	27.68	38.33	15.34	6.26	11.39
4.65	4.42	3.11	6.78	9.63	8.60	6.16	8.52	0.96	1.49
24.46	107.94	90.97	80.29	78.73	124.72	363.05	75.05	57.17	48.13
0.33	0.22	0.28	1.59	1.06	1.27	0.53	1.62	0.40	0.29
0.85	0.96	0.66	1.31	1.85	1.74	0.86	1.33	0.24	0.32
2.53	1.00	0.70	3.37	3.94	2.36	-0.33	-1.57		
4008.95	5582.67	6222.80	12997.28	14004.92	15291.65	5474.44	4372.87	10181.45	9970.94
0.47	0.45	0.35	0.54	0.71	0.65	0.41	0.67	bdl	0.03
4.85	0.16	0.10	0.52	0.60	0.48	0.27	0.50	0.19	0.18
134.75	192.32	214.71	214.53	187.81	131.77	258.34	56.77	197.74	255.80
34.91	33.47	23.09	43.77	78.05	75.50	31.59	43.41	0.43	5.03
						2.54	4.21	bdl	0.14
32.46	31.69	22.59	41.84	45.01	43.25	87.47	17.44	18.65	26.47

167.81	73.83	73.50	48.76	46.04	39.19	25.16	76.18	36.50	28.16

Draft

METASEDIMENTS

neiss (Ringwood)			Cpx Gneiss (Ringwood)		Cpx-Pl Gneiss (Wanaque)		Bt-Qz		
R2	R22	R23	R24	R14	W23	W24	R1	R16	W4
1.80				0.90			3.40	4.20	
< 5				< 5			< 5	< 5	
280.00	147.24	163.40	262.00	113.00	677.65	169.93	1549.00	623.00	183.38
< 0.4				< 0.4			< 0.4	< 0.4	
88.00	245.13	75.87	12.96	51.10	31.04	40.32	58.00	123.00	63.73
47.00				13.00			33.00	11.00	
170.00	7.24	247.58	20.96	70.00	30.39	23.06	60.00	70.00	25.79
< 0.5				< 0.5	0.17	0.09	1.10	< 0.5	0.45
230.00				40.00			10.00	< 10	
20.20	3.76	25.17	2.60	19.00	2.09	4.71	6.20	7.50	12.17
12.40	2.48	14.38	1.44	12.00	1.03	2.74	4.40	4.80	7.96
3.05	1.80	2.89	0.60	2.04	1.05	1.43	1.19	1.78	0.91
19				14			22	20	
16.70	5.98	12.65	2.75	14.20	2.92	4.86	4.80	6.40	8.94
2.30	0.36	1.80	0.00	1.20	0.75	1.95	5.80	7.30	3.33
4.10	0.77	5.32	0.54	3.80	0.37	1.02	1.40	1.50	2.95
					9359.00	5240.00			11255.00
29.70	172.35	22.36	5.72	18.70	16.92	17.90	28.80	67.00	28.96
1.65	0.58	2.60	0.14	1.68	0.14	0.41	0.69	0.75	1.30
< 2	11.78	0.21	0.30	< 2			< 2	< 2	
10.00	3.01	15.58	bdl	< 1	5.83	5.17	15.00	11.00	11.07
58.90	56.82	53.65	7.14	37.80	16.77	19.88	24.80	45.00	30.71
50.00	10.28	59.86	28.41	30.00	13.50	29.02	20.00	20.00	20.40
	1295.07	542.02	419.12		730.86	1735.64			370.05
< 5				< 5	4.15	8.50	20.00	6.00	8.00
12.90	20.10	11.58	1.84	7.90	4.18	4.93	6.75	13.10	7.79
20.00	1.40	9.02	22.38	7.00	11.35	1.08	237.00	100.00	36.11
< 0.5				< 0.5			< 0.5	< 0.5	
63.00	8.13	31.23	9.11	61.00	9.99	22.01	15.00	19.00	11.17
16.40	6.23	17.65	1.73	12.70	3.10	4.92	5.10	7.70	8.64
7				2.00			3	5	
63.00	42.45	53.33	85.27	60.00	408.22	353.14	69.00	94.00	36.77
0.50	0.21	0.88	0.11	< 0.1	0.44	1.51	1.30	0.70	1.80
3.10	0.72	2.91	0.45	2.90	0.39	0.81	0.90	1.10	1.93
0.40				0.20	0.23	3.39	11.30	11.70	9.56
	1505.61	8003.38	130.93		3465.33	6011.75			2423.88
0.1				< 0.1			0.5	0.3	
1.79	0.42	2.89	0.20	1.79	0.15	0.43	0.65	0.72	1.32
0.30	0.11	0.08	0.08	0.10	0.14	0.58	9.90	0.90	1.03
347.00	349.60	313.73	60.37	146.00	63.56	183.38	118.00	121.00	41.80
5.00				17.00			212.00	< 1	
117.00	19.48	143.74	5.28	107.00	7.27	31.60	41.00	42.00	79.79
11.30	3.37	19.67	1.08	11.10	0.82	2.72	4.60	4.70	9.24
40.00	44.57	18.53	bdl	< 30	55.37	53.45	< 30	30.00	27.27

80.00	6.89	37.61	2.70	29.00	28.49	61.43	212.00	248.00	90.27

Draft

Gniess			Marble (Wanaque)		Amphibolites			
W10	W12	W22	W5	W6	R25	R26	R27	W14
			< 0.5	0.50				
			< 5	< 5				
324.62	184.69	1125.41	258.00	26.00	275.97	299.05	312.66	54.83
			< 0.4	< 0.4				
3.52	84.93	18.67	21.60	25.40	46.89	60.24	59.77	15.72
			6.00	5.00				
46.46	31.12	80.87	< 20	< 20	67.72	64.62	68.54	344.30
0.18	0.45	4.68	< 0.5	< 0.5				0.05
			< 10	10.00				
3.89	16.18	3.32	1.10	0.70	10.92	13.89	13.06	3.38
2.13	11.76	1.90	0.60	0.50	5.77	7.29	6.93	1.94
0.36	0.94	1.18	0.31	0.27	2.45	2.89	2.60	0.88
			< 1	< 1				
3.02	11.35	3.18	1.20	0.60	7.55	9.40	8.98	3.00
1.53	3.06	8.32	< 0.2	< 0.2	0.95	0.91	1.53	1.34
0.80	4.23	0.77	0.20	0.10	2.23	2.81	2.65	0.74
14000.00	11031.00	123462.00						8021.00
1.27	38.75	9.19	13.50	16.40	19.15	23.95	24.59	5.95
0.29	2.19	0.34	0.11	0.07	1.00	1.17	1.10	0.30
			< 2	< 2	0.45	0.71	0.67	
27.79	13.69	12.82	< 1	< 1	7.07	8.16	8.39	2.54
2.79	43.09	12.35	6.70	6.20	32.54	42.87	41.59	10.36
22.72	18.97	55.15	< 20	< 20	33.90	26.43	30.76	105.92
621.11	486.85	489.95			3709.49	3899.20	4199.89	273.49
9.21	8.90	25.71	< 5	< 5				
0.71	10.46	2.88	2.06	2.17	6.88	8.79	8.59	2.20
36.13	37.64	96.67	7.00	< 2	2.18	3.39	2.79	9.26
			< 0.5	< 0.5				
11.32	16.00	23.65	2.00	< 1	55.27	36.17	31.53	46.96
1.59	11.51	3.35	1.20	0.90	9.19	12.16	11.52	1.98
			< 1	< 1				
111.94	39.92	26.37	93.00	72.00	266.40	122.24	157.51	107.21
3.53	2.02	11.72	< 0.1	< 0.1	0.45	0.48	0.46	0.31
0.59	2.54	0.63	0.20	0.10	1.44	1.81	1.71	0.49
-0.69	14.49	2.16	0.60	0.20				0.56
3724.46	2927.89	4734.60			17392.38	18334.57	18841.30	5623.29
			< 0.1	< 0.1				
0.32	2.08	0.34	0.10	0.07	1.04	1.30	1.24	0.29
0.84	1.19	0.54	0.20	0.10	bdl	0.10	bdl	1.04
48.34	49.76	112.02	10.00	9.00	506.36	501.23	544.15	253.28
			1.00	< 1				
19.77	126.48	19.22	6.00	5.00	63.16	71.96	69.68	20.24
1.89	14.91		0.70	0.40	6.93	8.38	8.20	2.09
16.82	30.25	43.02	40.00	410.00	94.27	76.79	119.62	40.51

48.02	95.31	42.05	5.00	5.00	16.84	20.33	27.14	49.83
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ORE AND ALTERED ROCKS								
		Qz-Di Gneiss	Massive Diopside			Ore		
W9	R7	M1	R15	W3	W2	R6	R10	
		0.80			< 0.5			
		< 5			< 5			
67.80	167.09	13.00	16.00	-6.85	< 3	38.18	43.53	
		< 0.4			< 0.4			
51.46	41.61	47.90	45.86	21.75	0.20	211.00	23.79	
		26.00			89.00			
89.94	55.98	< 20	37.51	23.36	50.00	7.22	11.00	
0.13	0.04	< 0.5	0.26	0.12	< 0.5	0.04	0.01	
		110.00			< 10			
10.86	9.78	1.80	10.40	2.65	< 0.1	2.61	0.97	
5.97	4.30	0.90	6.39	1.61	< 0.1	1.44	0.98	
2.43	2.16	1.02	1.02	0.65	< 0.05	1.61	0.23	
		3			56.00			
10.13	7.83	2.40	8.01	2.71	< 0.1	12.86	1.69	
5.66	1.05	0.30	0.95	0.90	< 0.2	0.05	0.10	
2.41	2.22	0.30	2.42	0.54	< 0.1	0.32	0.16	
7730.00	8090.00						798.00	
19.65	15.69	18.80	13.11	5.78	< 0.1	192.73	11.64	
0.83	0.71	0.16	1.22	0.29	< 0.04	0.11	0.14	
		< 2			< 2	19.00		
14.14	7.00	< 1	-0.39	-0.64	< 1	5.39	10.71	
36.35	27.90	26.10	31.17	10.88	< 0.1	93.17	8.81	
38.10	59.75	< 20	23.65	22.51	70.00	23.05	21.69	
1447.08	3655.65		46.71	105.74		905.01	288.35	
2.34		7.00	1.45	-0.93	< 5	1088.00	1393.00	
7.63	6.57	6.47	7.06	3.09	< 0.05	30.64	2.20	
6.66	2.04	4.00	6.04	-1.01	< 2	1.30	1.28	
		< 0.5			< 0.5			
42.38	58.63	2.00	43.12	16.16	< 1	2.22	3.48	
11.10	7.66	4.60	9.08	2.04	< 0.1	16.08	0.52	
		4			4.00			
157.72	128.39	17.00	8.39	20.89	< 2	6.82	3.78	
1.14	0.73	< 0.1	0.48	0.30	< 0.1	0.74	0.80	
1.89	1.36	0.30	1.68	0.44	< 0.1	0.63	0.18	
0.93	0.84	0.70	-0.72	-0.17	< 0.1	6.64	0.47	
17015.58	17490.30		800.09	865.33		7276.19	1833.74	
		< 0.1			< 0.1			
0.92	0.69	0.13	1.07	0.26	< 0.05	0.12	0.14	
0.81	0.44	2.10	0.58	0.56	< 0.1	1.10	0.89	
310.28	499.62	45.00	98.89	109.12	1608.00	1348.37	787.79	
		< 1			20.00			
63.23	57.26	9.00	66.62	12.31	< 2	10.84	5.75	
5.75	4.66	0.90	7.70	1.71	< 0.1	0.61	0.82	
56.28	111.77	110.00	43.11	21.55	120.00	177.68	103.86	

153.00	22.27	16.00	24.82	42.41	< 4	0.64	8.06
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