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Hydrothermal alteration, mass transfer and magnetite mineralization in dextral shear zones, western Hudson Highlands, New York, United States

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ABSTRACT

Massive magnetite veins formed during hydrothermal mineralization within northeast striking dextral shear zones in Proterozoic-age crystalline bedrock of the western Hudson Highlands. The veins formed in an open fracture system in right step-over dilational jogs during the late stages of movement. Acidic metamorphic fluids derived from metavolcanic country rock and saturated with iron, flushed through fractures, reacted with wall rock, and exchanged chemical species. Buffered by the composition of the local country rock, fluids migrated and mixed along the fault during 'seismic pumping' events. The fluids deposited mineral assemblages in the fractures that reflect the changing flux, fluid buffering, and/or physical conditions.

This process produced three zones, outward from the unaltered country rock which are: 1) a bleached zone of altered wall rock adjacent to the vein, 2) an outer banded zone in the vein, of ferromagnesian-rich bands, and 3) a core of massive magnetite ore and gangue minerals. Bleached zones are dominated by amphibole and/or pyroxene, with scapolite, biotite, and apatite, within metavolcanic and quartzofeldspathic gneiss, or phlogopite and calcite within calc-silicate country rock. Calc-silicate banded and massive assemblages contain clinopyroxene, calcite, amphibole, and/or biotite or phlogopite. Quartzofeldspathic and metavolcanic banded and massive assemblages are dominated by amphibole and/or orthopyroxene, with quartz and/or sulfides locally. Both assemblages contain magnetite central to the deposits.

Geochemical modeling of the bleached zone shows overall gains in volume (2.5–20.3%) and mass (3.1–18.1 g relative to 100 g of wall rock). In all cases, iron (2.4–5.3 g), magnesium (1.0–2.8 g), and calcium (0.6–6.5 g) were gained, especially adjacent to calc-silicates. Deposits adjacent to quartzofeldspathic country rock had large gains in silica (4.4–7.4 g), whereas deposits in mafic metavolcanic rock lost silica (1.4–3.8 g). Based on the mobility of silica, fluid fluxes were calculated between 5.3×10^5 and 6.6×10^6 cm^3/cm^2 for bleached zone alteration. Elements in abundance in the country rock contributed to the composition of the deposits, dominantly silica, carbonate, and sulfides.

1. Introduction

The Hudson Highlands in southeastern New York, hosts several hundred iron deposits (Foose and McLelland, 1995; Puffer, 2001) that were extensively mined throughout the 18th and 19th centuries. The Highlands are located within the Reading Prong, a Grenville basement massif that forms the spine of the Appalachians within New York, New Jersey, Pennsylvania, and Connecticut (Fig. 1). The Highlands contain many types of magnetite deposits (e.g. Buddington, 1966; Hotz, 1954; Puffer, 2001; Sims, 1958), reflecting multiple modes of emplacement (Baker and Buddington, 1970; Collins, 1969; Hagner and Collins, 1955; Puffer and Gorring, 2005). Gundersen (2000), Puffer (2001), and Volkert et al. (2005) recognized vein deposits created by hydrothermal remobilization of magnetite into faults and fractures, as well as deposits that are related to plutonism. In this study, two ~3 to 5 km long veins formed by hydrothermal fluids and containing massive magnetite bodies within shear zones were analyzed. The northeast striking dextral shear zones and veins, formed late in the Grenville orogenic cycle (Gates, 1995), and are exposed at several abandoned magnetite mines.

The extent of mineralization, element transport, and the deformation-enhanced fluid-rock interactions in the fault rocks and their host lithologies were analyzed to model their formation. Geochemical and petrological evidence leads to an interpretation of the formation and chemical evolution of the fluids and vein deposits. Mass transfer modeling is applied to wall rock geochemistry, to constrain the chemistry of the fluids responsible for the deposits within the shear zones. Finally, a model for the development of the vein deposits is proposed.

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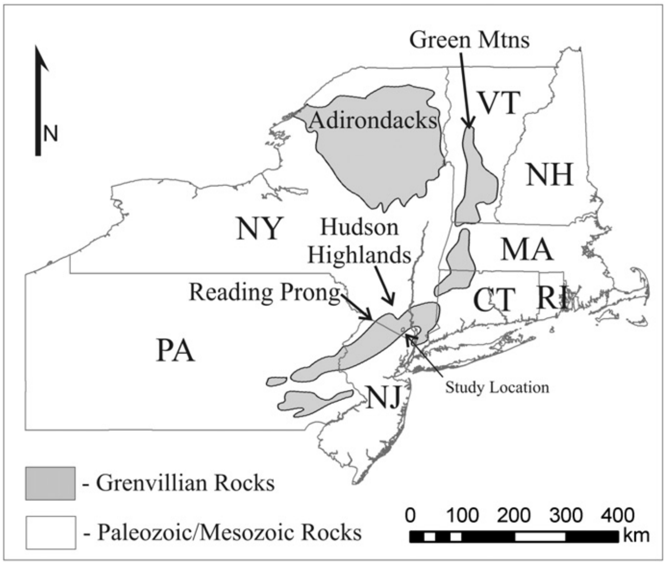

Fig. 1. Map of the Northeastern United States showing the distribution of Appalachian/Grenville rocks, the Reading Prong, Hudson Highlands, and study location.

2. Geology of the Hudson Highlands

Several models currently exist for the formation of the crystalline bedrock of the Hudson Highlands. Recent geochemical investigations found that some of the rocks are of plutonic origin (Gates et al., 2006; Gundersen, 2004; Volkert, 2004; Volkert and Drake, 1999), but based upon major element geochemistry, some of the layered gneisses have been interpreted to have a volcanic protolith (Drake, 1984; Gates et al., 2006; Helenek, 1971; Puffer and Gorring, 2005; Volkert, 2004). Gundersen (2004), and Volkert et al. (2010) proposed that many of these gneisses formed in an extensional backarc marginal basin, with a bimodal, volcanic origin whereas Gates et al. (2006) proposed formation of a volcanic pile with a volcaniclastic apron in an island arc or marine magmatic arc setting.

According to Gates et al. (2006), a volcanic pile initiated in an arc setting around 1.29 to 1.25 Ga (Volkert et al., 2010), and is characterized by layered intermediate and mafic rocks, associated plutons, and volcaniclastic sediments. Continental collision of the arc with another continent (likely Amazonia) occurred during the building of the Rodinian supercontinent, ~1050 to 1020 Ma (Gates et al., 2006). This sequence underwent granulite facies metamorphism, between 1045 to 1024 Ma associated with the Ottawan phase of the Grenville orogeny (Volkert et al., 2010). Locally, anatexis produced migmatites, granite sheets, and the early pegmatites (Gates et al., 2006; Volkert et al., 2005). Subsequent diorite intrusions occurred around 1008 Ma either the result of delamination at the end stages of the collision event, or the early dilational stages of a second tectonic event (Gates et al., 2006). This second event is characterized by dextral strike-slip movement during a period of rapid uplift and unroofing at approximately 1008 to 924 Ma (Gates and Krol, 1998). A ~35 km wide zone of anastomosing near vertical mylonite zones overprinted early shallowly dipping foliations. Total dextral offset was on the order of several hundred kilometers (Gates et al., 2006).

Previous geologic mapping in this region sub divided gneisses based upon the individual varietal ferromagnesian minerals (Dallmeyer, 1974; Dodd, 1965). Considering that 80% of these rocks are quartzofeldspathic gneisses (Gates et al., 2006), this paper follows the system proposed by Gundersen (1986), and adapted by Gates et al. (2006). Units are grouped into lithofacies based on various rock types, to define quartzofeldspathic, interpreted metasedimentary (calc-silicate, metapelite, and metapsammite), and metavolcanic (plagioclase–amphibole–pyroxene) assemblages (Fig. 2).

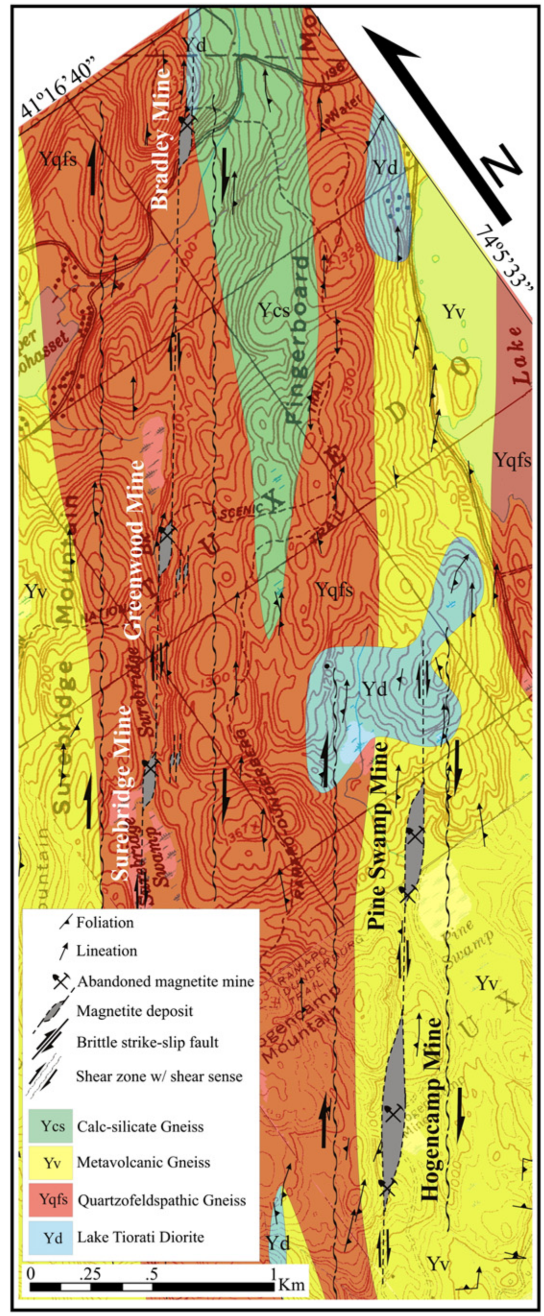

Fig. 2. Geologic map of the study area, located within Harriman State Park, New York.

2.1. Metavolcanic gneiss

The metavolcanic unit consists of strongly banded sequences of interlayered mafic and intermediate gneisses, with interpreted volcanic protoliths (Gates et al., 2006). Compositional banding ranges in thickness from 5 cm to 5 m with varying quantities of each rock type. Mafic assemblages are composed primarily of medium to coarse grained amphibole, plagioclase, clinopyroxene and orthopyroxene, with minor sulfides and magnetite locally. Intermediate bands are primarily medium to coarse grained plagioclase and quartz, with minor amounts of amphibole, biotite, clinopyroxene and orthopyroxene. This unit also contains localized interlayers of interpreted metasediments such as, quartzite, marble, and calc-silicate gneiss, as well as migmatites. The contacts with the quartzofeldspathic unit are interstratal gradational.