Preliminary Metamorphic P–T Paths for the Manhattan and Hartland Schists

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1. Introduction

The bedrock of New York City is thought to record a complex history of metamorphism and deformation associated with the Cambro-Ordovician Taconic orogeny (e.g., Baskerville et al., 1989; Dietsch et al., 2006; Macdonald et al., 2014; Hibbard et al., 2006; Van Staal and Barr, 2012). More specifically, the Manhattan and Hartland Formations are thought to represent metasedimentary sources from the Laurentian passive margin, and peri-Laurentian Dashwoods arc (e.g., Karabinos et al., 2017). The contact between these units is the regional-scale thrust fault Cameron's Line, which is typically presented as the terminal suture between Laurentia (the Manhattan Formation) and the Dashwoods arc (Hartland Formation) (see Jaret et al., 2021 and citations therein). While this makes a compelling narrative, there is a lack of quantitative metamorphic petrology corroborating this model. If Cameron's Line is indeed a terminal suture or fundamental terrane boundary, we would expect to find different metamorphic pressure-temperature-time (P–T–t) paths on either side of the boundary (e.g., Spear et al., 2008; Weller et al., 2021). In this study, we seek to address this gap and present the preliminary investigation of two samples from the Manhattan and Hartland formations and current efforts to elucidate their respective pressure–temperature (P–T) histories through petrographic analysis and cutting-edge phase equilibria modeling.

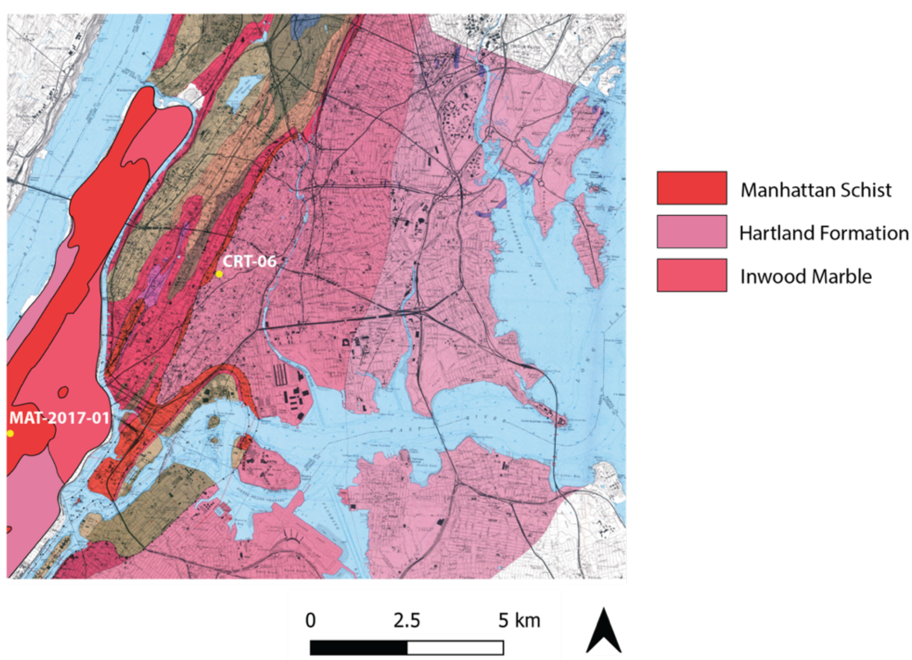

Figure 1*: Bedrock geologic map of the Bronx and Northern Manhattan highlighting the Manhattan Schist, Hartland Formation, and Inwood Marble. Sample locations shown as yellow dots. Modified from Baskerville (1992) and Merguerian and Merguerian (2004).*

2. Sample Location and Petrography

CRT-06 is a garnet-kyanite-sillimanite-biotite-muscovite-plagioclase-quartz migmatite schist from the Hartland formation outcropping in Crotona Park, the Bronx (Fig. 2). MAT-2017-01a is a garnet-kyanite-sillimanite migmatite schist from the Manhattan formation located in Central Park, Manhattan (Fig. 3). Formation names and lithological boundaries are taken from Baskerville (1992).

2.1 CRT-06 Petrography

CRT-06 is characterized by ~1-2 mm subidioblastic garnet often replaced by muscovite+sillimanite and containing quartz+plagioclase+ilmenite inclusions (Fig. 2 a, b). Kyanite occurs as ~200 um long subidioblastic porphyroblasts within a foliated muscovite+biotite+quartz matrix and in ~0.3-1.00 mm long nodules with interstitial muscovite+plagioclase. These nodules are considered to be recrystallized leucosomes pseudomorphed by fibrolite (Fig. 2 c, d). Fibrolite also occurs as needles in garnet strain shadows.

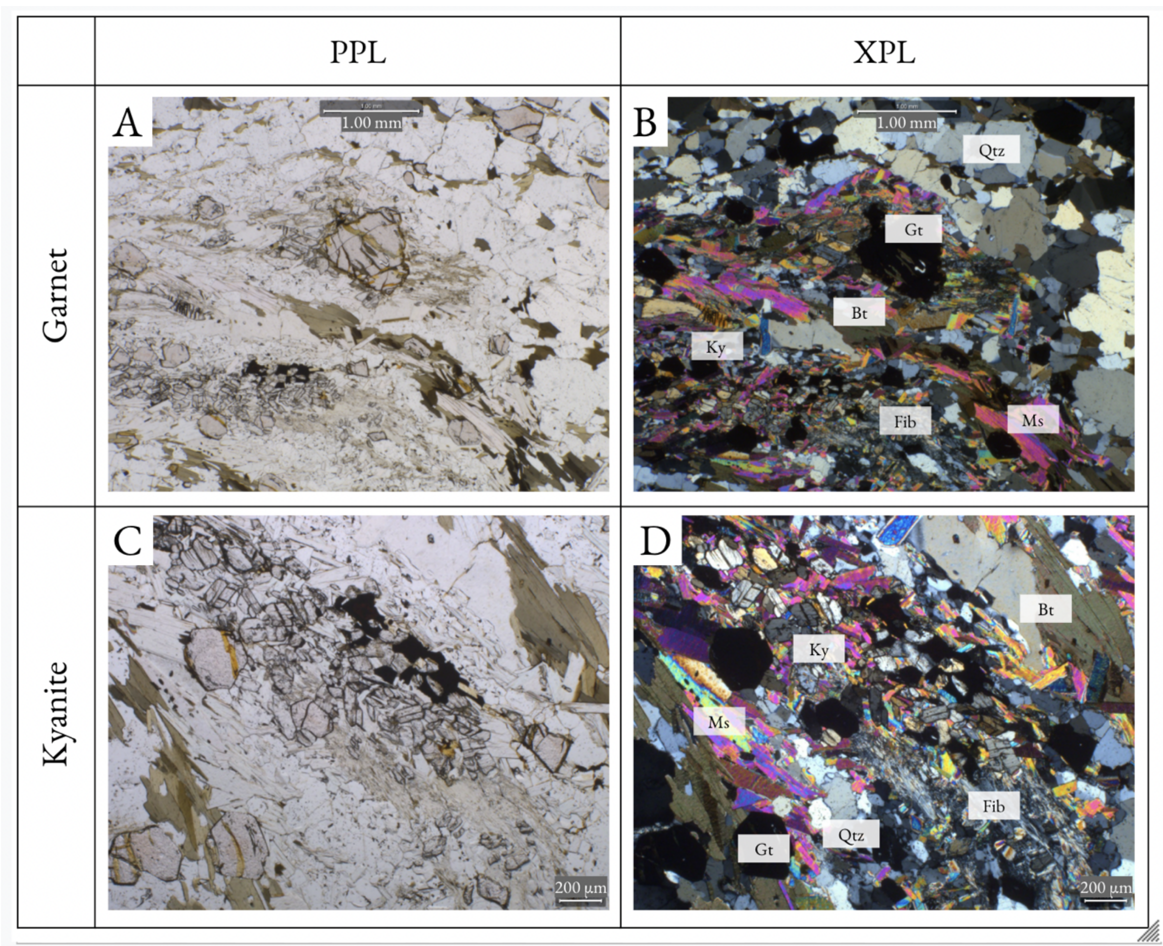

Figure 2: *Representative photomicrographs of garnet and kyanite in PPL (a,c) and XPL (b,d) in CRT-06.*

2.2 MAT Petrography

MAT-2017-01a contains similar garnets, typically ~1-3 mm in diameter, subidioblastic, and containing quartz+plagioclase+ilmenite inclusions (Fig. 3 a, b). ~0.3-1.00 mm nodules of randomly oriented kyanite are also present with interstitial muscovite+plagioclase. These grains are cross-cut by ~0.5-0.7 mm long blades of sillimanite, which also occurs as fibrolite needles in texturally late muscovite (Fig. 3 c, d).

2.3 Mineral Assemblages

CRT-06 and MAT-2017-01a preserve strikingly similar mineralogy and texture. We have identified three successive mineral assemblages in both samples, M1-M3. M1 consists of Qtz+Pl+Ms+Bt+Chl+Grt+Ilm, and represents the assemblage at the time of initial garnet nucleation and growth. The subsequent assemblage, M2, consists of Qtz+Ms+Bt+Grt+Ky+Melt and represents the assemblage after heating and loading beyond the muscovite-out melt reaction. This assemblage is best preserved in the recrystallized kyanite-bearing leucosomes described above. M3 is the final "equilibrium" assemblage and consists of Qtz+Pl+Ms+Bt+Grt+Sil+Ilm.

3. Thermodynamic Modeling
3.1 Methods

Mineral Assemblage Diagrams (MADS), or pseudosections, are phase diagrams that display the stable mineral assemblages for a given bulk composition over a range of P-T space. The MADs calculated for this study were created using the FORTRAN program GIBBS, which employs a Gibbs energy minimization algorithm to determine the stable mineral assemblages, modes, and compositions at a given P–T condition (Spear and Wolfe, 2022). MADs were calculated in the MnNCKFMASHTi chemical system with the SPaC thermodynamic dataset (e.g. Castro and Spear, 2017; Wolfe and Spear,

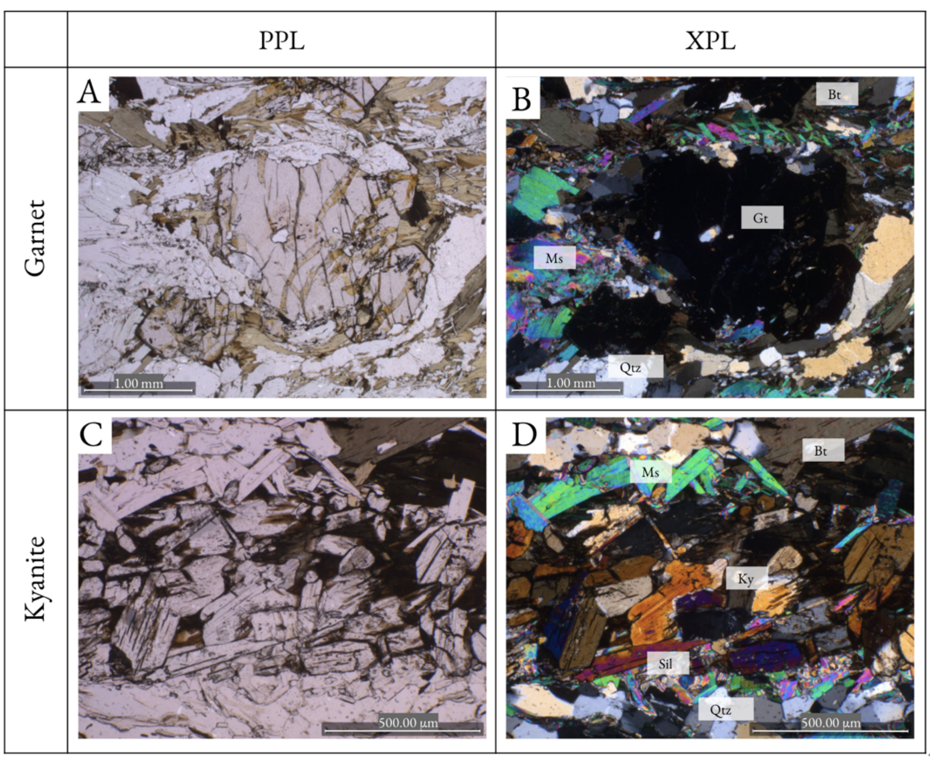

Figure 3: *Representative photomicrographs of garnet and kyanite in PPL (a,c) and XPL (b,d) in MAT-2017-01a.*

2018). The bulk compositions used for modeling were determined via glass bead XRF of representative hand samples at the Hamilton College Analytical Lab.

3.2 Thermodynamic Modeling results

Figure 4 presents the results of phase equilibria modeling for samples CRT-06 (Fig. 4a) and MAT-2017-01a (Fig. 4b). M1 assemblages are constrained to ~540-650 °C and 4-9 kbar in CRT-06, and ~550 °C and 4-6 kbar in MAT-2017-01a. M2 assemblages are constrained to ~850 °C and 8-11 kbar for CRT-06 and ~750 °C and 8-11 kbar in MAT-2017-01a. M3 assemblages are constrained to 650-750 °C and 4-7 kbar in CRT-06, and 700 °C and 6.5 kbar for MAT-2017-01a.

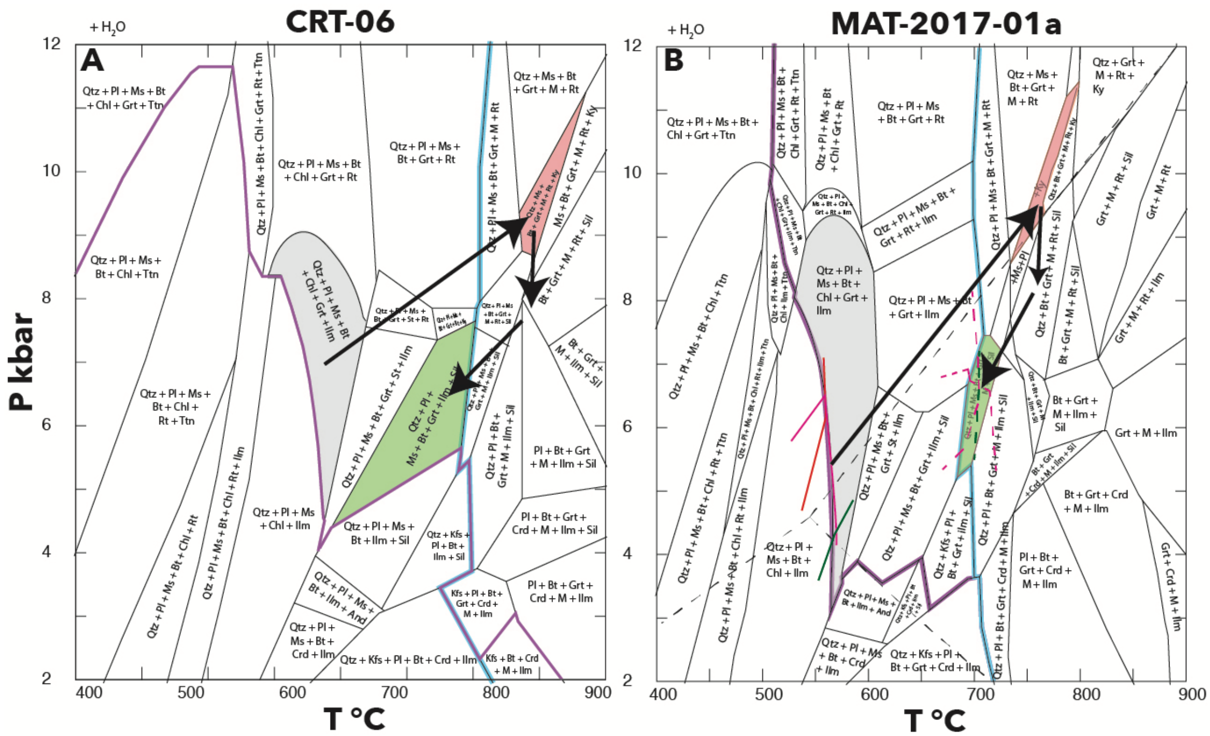

Figure 4: MADs for samples MAT-2017-01a (a) and CRT-06 (b). The gray, pink, and green fields represent the M1, M2, and M3 events respectively. Garnet compositional isopleths are indicated by red (Alm), green (Grs), and magenta (Sps) curves. Dashed lines represent rim isopleths while solid lines represent core isopleths. The blue curves represent the melt-in isograd and the purple lines represent the garnet isograd. The black arrows indicate the P-T paths. Mineral abbreviations are from Kretz (1983).

4. Discussion and conclusion

The results of thermodynamic modeling and petrographic analysis suggest the following clockwise P–T path for both samples: 1) Garnet-grade conditions at ~550-600 °C and 4-8 kbar, 2) continued heating and loading to kyanite-grade muscovite-out anatexis at ~750 °C and 8-11 kbar, 3) a period of rapid (melt-facilitated?) exhumation to fibrolite stability, and 4) continued exhumation to our final assemblage at ~700 °C and 6.5 kbar. This preliminary data suggests that the Manhattan and Hartland schists experienced similar P–T histories. This lack of metamorphic break suggests Cameron's Line is not a fundamental terrane boundary. Instead, it may be a pre- to syn-metamorphic thrust fault that juxtaposes different stratigraphic units of the Laurentian margin. Full characterization of the nature of Cameron's Line is currently in progress and requires more detailed microstructural analysis, monazite, zircon, and garnet petrochronology, and detrital zircon provenance studies.

5. Acknowledgements

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