REGIONAL METAMORPHISM
IN THE MANHATTAN PRONG, NY AND CT

Pamela C. Brock and Patrick W. G. Brock
Department of Geology, Queens College, Flushing 11367

The metamorphic record provides a key element for understanding the development of mountain belts and for tectonic processes in general. Here we describe regional-scale high-pressure granulite assemblages of early-Taconian age in the Manhattan Prong, rocks reflecting the most extreme P T conditions recorded in the Appalachian belt. These granulites were heavily overprinted by retrograde assemblages, so that their discovery depended on extensive petrographic work; they raise questions about "hidden" high-grade histories in other areas where garnets have been thermally homogenized.

Traditional petrographic study of metamorphic rocks has been largely supplanted by electron-microprobe analysis over the past 25 years. It is commonly assumed that reasonably consistent P-T results from "representative" rocks will faithfully correspond to peak metamorphic conditions. Retrograde metamorphic affects are "avoided" by use of core mineral compositions and by rocks with high biotite:garnet ratios (e.g., Spear, 1991). However, the Manhattan Prong illustrates how microprobe analysis in the absence of extensive petrographic work can lead to dramatically mistaken conclusions.

The Manhattan Prong consists of Grenvillian- through Ordovician-aged rocks which crop out between the Hudson River and the Hartland terrane. Manhattan Prong rocks show nearly-ubiquitous amphibolite-facies metamorphic assemblages, previously interpreted as products of prograde Taconian metamorphism (e.g., Tracy and others, 1996). However, our very extensive petrographic study (of literally thousands of thinsections) has lead to recognition of a complex Paleozoic polymetamorphic history.

The earliest Paleozoic event, recognizable in all post-Grenville units, was an episode of high-pressure granulite-facies metamorphism. Taconian metamorphism of this type has not been recognized before, either in the Manhattan Prong or elsewhere in the northern Appalachians. Our petrography clearly reveals why it has been missed here: early high P-T assemblages have been almost completely overprinted during later events, first by late-Taconian upper-amphibolite-facies metamorphism, and later by a lower-grade (muscovite-producing) Carboniferous event. As a result, early high-P and granulite-facies assemblages survive only as rare relicts.

K-feldspar + aluminosilicate assemblages illustrate the situation. K-feldspar + sillimanite is common in "high-grade" portions of the Manhattan Prong, but we now know that it overprints an older, higher-pressure K-feldspar + kyanite assemblage. We have found K-feldspar + kyanite as early relicts in Ordovician Walloomsac Schist (and other post-Grenville rocks) for the entire length of the Manhattan Prong, from the East River to the Danbury, Connecticut area. The relicts are very, very rare, surviving in fewer than 1 out of 200 specimens of suitable composition. In zones affected by the

Carboniferous event (including the entire island of Manhattan), late-Taconian sillimanite is largely or entirely replaced by young muscovite, which commonly coexists with a new generation of kyanite.

Traces of early-Taconian granulite-facies assemblages have been found in all post-Grenville strata of the Manhattan Prong. Remnants of a cordierite-K-feldspar-garnet assemblage occur in aluminous rocks in three quadrangles. Taconian-aged metabasite assemblages include orthopyroxene + garnet and two-pyroxene granulite; some dolomitic Inwood marbles contain olivine + spinel. Amphibolite-facies overprinting is common in all the granulite occurrences.

The aluminous lithologies preserve the best petrographic record of evolving Taconian P-T conditions. Old cores in garnets contain rutile, and, rarely, kyanite, reflecting high-pressure conditions; in contrast, late-Taconian garnets and overgrowths contain sillimanite, commonly coexisting with ilmenite. When petrographically-zoned garnets are chemically "mapped" with the microprobe, they show flat Fe, Mg, and Mn patterns, except for Mg-depletion on rims and against exchangeable inclusions. Clearly, the garnets were homogenized during late-Taconian time, while sillimanite was stable; their compositions cannot record the older, higher-pressure event.

Petrographic relationships derived from old inclusions in garnets can illuminate the earliest Taconian metamorphic event. Surviving staurolite and spinel inclusions in garnets from the aluminous rocks can be used to map out an early-Taconian granulite-facies isograd. On the low-grade, western side of this isograd, staurolite is preserved as inclusions in uncracked garnets, although the accompanying (late-Taconian) matrix assemblage contains K-feldspar + sillimanite. No spinel is observed. On the high-grade side of the isograd, spinel is fairly common. Staurolite inclusions are rare; where present, they are typically intergrown with, rimmed by, or accompanied by green spinel. Kyanite accompanies spinel +/- staurolite in some garnets. The isograd apparently marks the terminal breakdown of staurolite (in the absence of quartz), by the reaction

staurolite = garnet + spinel + kyanite.

This reaction requires high-pressure granulite conditions; data from Ganguly (1972) and Kerrick (1990) place the Fe-end member reaction at P ~ 12 kilobars and T ~ 900oC. Intersection of the staurolite = spinel + kyanite + sillimanite reaction from petrogenetic grids based on thermodynamically consistent data sets (such as Hiroi and others, 1994) with the sillimanite = kyanite equilibria lead to projected minimum P-T conditions of T ~ 900^{o}C and 13 kilobars. The recognition of the isograd over a distance of at least 40 km confirms the regional character of the early high-pressure granulite metamorphism.

With detailed petrographic work on more than 1,000 aluminous rocks, we can now piece together several stages of Taconian metamorphic history in the Manhattan Prong:

1) Early high-pressure stage, characterized by kyanite-bearing assemblages such as K-feldspar + kyanite and garnet + spinel + kyanite. Projected minimum T ~ 900oC and minimum P = 13 kilobars.

2) Reduced pressure, possibly accompanied by increase in temperature, lead to replacement of kyanite by sillimanite, and then to replacement of garnet + sillimanite by cordierite. Cordierite + sillimanite + garnet was replaced by spinel + quartz in at least Zn-rich compositions. These spinel-quartz-cordierite rocks represent the "peak", highest-temperature, Taconian assemblages.

3) Near-isobaric cooling set in, resulting in progressive replacement of cordierite-bearing assemblages by garnet + biotite + sillimanite (of the upper-amphibolite facies) and, in low-potassium microzones, by orthoamphibole + sillimanite.

4) Replacement of cordierite continued after cessation of Taconian deformation. In many places, syn-Taconian replacement of cordierite is marked by well-foliated, deeply-colored biotite + sillimanite and younger replacement by unfoliated masses of pale green biotite + kyanite. Unfoliated gedrite + kyanite + staurolite overprints older cordierite + gedrite + sillimanite. These relationships imply that the Manhattan Prong remained at substantial pressure (estimated at ~8 kilobars) at the close of Taconian deformation. This estimate is in accord with PT estimates of late-Taconian conditions based on equilibria involving biotite, garnet, plagioclase, and ilmenite.

Further detail on the petrographic relationships is given in Brock (1993).

REFERENCES

Brock, P. C., 1993, Geology of parts of the Peach Lake and Brewster quadrangles, southeastern New York and adjacent Connecticut, and basement blocks of the North-Central Appalachians: [Ph.D. thesis], Department of Earth and Environmental Sciences, City University of New York, 494 p.

Ganguly, J., 1972, Staurolite stability and related parageneses: theory, experiments, and applications: Journal of Petrology, v. 13, p. 335-365.

Hiroi, Y., Ogo, Y., and Namba, K., 1994, Evidence for prograde metamorphic evolution of Sri Lankan pelitic granulites, and implications for the development of continental crust: Precambrian Research, v. 66, p. 245-263.

Kerrick, D. M., 1990, The Al_2SiO_5 Polymorphs: Reviews in Mineralogy v. 22, Mineralogical Society of America, Washington, D. C., 406 p.

Spear, F. S., 1991, On the interpretation of peak metamorphic temperatures in light of garnet diffusion during cooling: Journal of Metamorphic Geology, v. 9, p. 379-388.

Tracy, R. J., Hames, W. E., and Whitney, D. M., 1996, Ages, grade and extent of Taconian metamorphism from New York City to the Vermont-Massachusetts boundary: Geological Society of America Abstracts with Programs, v. 28, p. 105.