Megacrystic Gore Mountain–type garnets in the Adirondack Highlands: Age, origin, and tectonic implications

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ABSTRACT

Spectacular exposures of the world’s largest megacrystic garnets (to 35 cm diameter) occur in a coarse-grained amphibolite at the Barton Garnet Mine in the Adirondack Highlands (Gore Mountain, New York State, USA). Over the years, numerous geologists have concluded that the large size of the garnets resulted from an influx of fluids during the ca. 1050 Ma upper amphibolite facies metamorphism of a ca. 1155 Ma olivine metagabbro. The presence of fluids under such mid-crustal pressure-temperature conditions is anomalous and warrants explanation. Evidence indicates that the fluids were introduced along, and close to, a steep border fault that juxtaposes charnockite against the garnet ore at the southern margin of the mine. Granitic pegmatites and quartz veins are present in the border zone and locally intrude the garnet ore.

Geochronology has played a critical role in resolving the genesis of the Gore Mountain garnets. Over the past 20 yr Sm-Nd and Lu-Hf techniques have been used to date the crystallization of the garnets as 1049 ± 5 Ma, an age that coincides with the termination of the contractional phase of the Ottawan orogeny, the onset of extensional orogen collapse, and the emplacement of the Lyon Mountain Granite. New U-Pb zircon age determinations of 1045 ± 7.5 (Barton Garnet Mine) and 1055 ± 7.4 (New York State Route 3 near Cranberry Lake) for Lyon Mountain granite pegmatites directly associated with megacrystic garnet amphibolites corroborate the synchronicity of emplacement of Lyon Mountain megacrystic garnets and the growth of the garnet megacrysts.

It is argued that during the ca. 1050 Ma extensional collapse of the Ottawan orogen, fluids gained access to extensional fault networks and interacted with country rocks. We further suggest that increasing temperature due to advected heat from Lyon Mountain Granite carried the Gore Mountain megacrystic garnet amphibolite into granulite facies conditions that resulted in reactions between hornblende and garnet that produced orthopyroxene and calcic plagioclase intergrowths, both as symplectites and coarsely textured pods developed in pressure shadows. Geothermal modeling of garnet zoning in metapelites (Storm and Spear, 2005) and oxygen isotope zoning in titanite (Bonamici et al., 2011) require a short period of rapid cooling ca. 1050 Ma, which we interpret to be related to the extensional collapse of the Ottawan orogen at that time (Rivers, 2008; McLelland et al., 2010a, 2010b). Reconnaissance of the southern and central Adirondacks reveals that a number of megacrystic garnet occurrences similar to those at Gore Mountain are present in areas that contain both metagabbros and megacrystic garnet amphibolites, and we propose that all of these formed during orogen collapse, intrusion of Lyon Mountain Granite, and fluid-related alteration at high temperature.

INTRODUCTION

The Adirondack Mountains of New York State (USA) are an outlier of the Canadian Grenville Province (Fig. 1) and are divided into the amphibolite facies Lowlands terrane on the northwest and the granulite facies Highlands terrane to the southeast (Fig. 2). The Lowlands are principally underlain by metasediments, notably marbles, whereas the Highlands consist mainly of metagneous rocks. The northwest-dipping Carthage-Colton shear zone (Fig. 2) separates the two terranes. The latest displacement along the Carthage-Colton shear zone has been shown to be top down to the northwest ca. 1047 Ma (Selleck et al., 2005), and to have proceeded very rapidly (Bonamici et al., 2011). The Lowlands are part of Rivers (2008) collapsed “orogenic lid” (i.e., orogen suprastructure) and exhibit only minor, low-grade Ottawan metamorphism, whereas the Highlands belong to the high-grade infrastructure of the large, hot allochthonous polycyclic belt that forms the hinterland of the Ottawan orogen (Fig. 1).

Metamorphosed gabbroic rocks of the Adirondack Highlands are well known for the occurrence of garnet crystals of unusual size, homogeneity, and purity. The open-pit Barton Garnet Mine, located at Gore Mountain (Fig. 3) in the central Highlands (Fig. 4) was first worked in 1878 and is famed for the presence the world’s largest single crystals of garnet; diameters range from 5 to 35 cm and commonly average 10–18 cm. The largest crystal ever extracted measured 1 m in diameter and current drilling indicates that crystals as large as ~1.5 m across exist at depth (B. Barton, 2010, personal commun.). After being milled and pulverized, the garnets are used for a variety of abrasives, ranging from sandpaper to rouge used for polishing of telescope mirrors and television screens. The most important current use is as the major abrasive component in high-pressure jets of water used to cut rock slabs in quarries. Garnet is the state gem of New York, and the cornerstone of the new World Trade Center memorial is a block of garnet-bearing ore from Gore’s sister mine at Ruby Mountain (R, Fig. 3).

Megacrystic garnets are not confined to Gore Mountain; they occur in less spectacular fashion elsewhere in the Adirondack Mountains. Given this, it is essential to identify the features shared in common by such deposits and how these clarify the conditions and variables requisite for the formation of megacrystic garnet deposits. Here we present observations relevant to this goal and link them to the tectonic evolution of the Adirondack Highlands.

GEOLOGICAL DESCRIPTION OF MAJOR MEGACRYSTIC GARNET OCCURRENCES

Megacrystic garnet occurrences have been identified at a number of localities in the Adirondack Highlands (Fig. 3). The greatest concentration is within the central Highlands near the Oregon (Fig. 3) and Snowy Mountain...
Adirondack megacrystic garnets

Figure 1. Generalized map shows the Grenville Province; three major tectonic divisions (Rivers, 1997) are indicated. The orogenic lid of Rivers (2008) is shown in blue and green. The accreted ca. 1.3–1.4 Ga Montauban–La Bostonnais arc is shown in red. Abbreviations: A-LD—Algonquin–Lac Dumoine domain; AL—Adirondack Lowlands; AH—Adirondack Highlands; APB—allochthonous polycyclic belt; CMB—Central Metasedimentary Belt; CMBTZ—Central Metasedimentary Belt thrust zone; F—Frontenac terrane; GFTZ—Grenville Front tectonic zone; LRI—Long Range inlier; M—Morin terrane; MK—Muskoka domain; ML—Mont Laurier domain; MM—Mealy Mountains; MZ—Mazinaw terrane; O—Oregon dome; PB—Parautochthonous Belt; PS—Parry Sound domain; RR—Romaine River; S—Shawanaga domain; SLR—St. Lawrence River; TSZ—Tawachiche shear zone with its southern projection; W—Wakeham terrane. Metamorphic divisions in key: p-MP—parautochthonous medium-pressure belt; aM-LP—allochthonous medium- to low-pressure belt; aHP—allochthonous high-pressure belt; pHP—parautochthonous high-pressure belt. Major anorthosite massifs (with ages and numbered age references): AT—Atikonak (ca. 1130 Ma, 2); HL—Harp Lake (ca. 1450 Ma); HSP—Havre-St-Pierre (ca. 1126 Ma, 2), dashed white line is the Abbe-Huard lineament; L—Labrieville (1060 Ma, 12); LA—Lac Allard lobe (ca. 1060 Ma, 10); LSJ—Lac-St.-Jean (ca. 1155 Ma; 3, 4, 7, 8); MA—Marcy (ca. 1150 Ma; 1, 6); MO—Morin anorthosite (ca. 1153 Ma); MI—Mistastin (ca. 1420 Ma, 9); MU—Michikamau (ca. 1460 Ma, 9); MR—Maggie River (ca. 1060 Ma, 4); N—Nain (ca. 1383–1269 Ma, 9); P—Pentecôte (ca. 1350 Ma, 5); SU—St. Urbain (ca. 1060 Ma, 10). Age references: (1) Hamilton et al. (2004); (2) Emslie and Hunt (1990); (3) Higgins and van Bremen (1992, 1996); (4) van Bremen and Higgins (1993); (5) Machado and Martignole (1988); (6) McLelland et al. (2004); (7) Hébert and van Bremen (2004); (8) Hervét et al. (1994); (9) Gower and Krogh (2002; summarized references); (10) Morisset et al. (2009); (11) Corrigan and van Bremen, 1997; (12) Owens et al. (1994). Modified after Rivers (2008) and McLelland et al. (2010a).
Two types of garnet ore are found at Gore Mountain; the most spectacular is a garnet amphibolite (Figs. 5A, 6A, and 6B), and the other is a garnetiferous gabbro anorthosite known as “white ore” (Fig. 5B). Within both varieties, garnets are normally idiomorphic and exhibit crystal faces known as “white ore” (Fig. 5B). Currently the white ore is the only variety produced, and it is mined at the nearby Ruby Mountain Mine (R, Fig. 3). Garnets in both varieties are numerous but rarely exceed 5 cm in diameter. We discuss both varieties, but the initial focus is on the megacrystic garnet amphibolite.

The Gore Mountain megacrystic garnet amphibolite body is 50–150 m wide and lies between a coronitic olivine metagabbro to the north and a steep mining highwall along a fault to the south, all of which trend approximately east-west (Fig. 4). The metagabbro and associated garnet amphibolite ore deposit are hosted in a small pluton of metanorthosite that is enveloped by a much larger mass of charnockite-granite (AMCG suite) present in both the HL and LL. Unpatterned areas consist of metasediments, glacial cover, or undivided units. Other abbreviations: AF—Ausable Falls; CCZ—Carthage-Colton shear zone; CL—Cranberry Lake; CM—Gore Mountain; HM—Hermon Granite; IL—Indian Lake; LM—Lyon Mountain; LP—Lake Placid; MCG—mangerite-charnockite-granite; OD—Oregon dome anorthosite massif; P—Piseco dome; ScL—Schroon Lake; SM—Snowy Mountain anorthosite; TL—Tupper Lake. Modified after McLelland et al. (2004).

The age of corona formation is not known with certainty, but may have taken place during ca. 1150–1140 Ma postintrusion cooling at depth (Whitney, 1978; Whitney and McLelland, 1973). As the metagabbro is traversed to the south, a narrow 2–3 m transition zone is encountered (Luther, 1976; Goldblum and Hill, 1992). Within this zone, garnet size increases dramatically to 3 mm and then to 5–35 cm just beyond the transition zone. Hornblende also increases in size tenfold, and does so at the expense of olivine, pyroxene, and spinel clouded plagioclase that grades into clear, inclusion-free plagioclase. As a consequence of the transition, the coronitic olivine metagabbro is transformed into a coarse garnet amphibolite that extends southward to the border fault. Both garnet and hornblende become coarser toward the southern border fault (Goldblum and Hill, 1992), although there are no discernible changes in bulk composition or trace element or isotopic concentrations. As shown in Figure 5, the garnets and coarse hornblende occur within a gray to black granoblastic matrix consisting of subequal amounts of medium-grained, green to brown hornblende (45%–70%), anhedral white plagioclase (20%–45%), sparse orthopyroxene (<5%), and minor biotite and sulfides (Stack, 2008). Whole-rock analyses and norms are given in Table 1 (Luther,
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1976; Sharga, 1986), and demonstrate that they have essentially the same composition as the coronitic olivine metagabbro. Likewise, modal analyses demonstrate that the metagabbro and garnet-amphibolite contain the same percent garnet, i.e., ~13% (Luther, 1976; Sharga, 1986). Together these observations have led researchers to propose that the genesis of the garnet amphibolite was due to a copious influx of fluid along and within ductile shear zones near the steep east-west border fault at temperatures of ~700–750 °C and mid-crustal pressures of 6–8 kbar (Buddington, 1939; Bartholomé, 1960; Luther, 1976; Sharga, 1986; Goldblum and Hill, 1992). Some observers have informally suggested that tonalitic partial melts of the amphibolite matrix were involved in garnet formation and enhanced the transfer of constituents, thus enabling the growth of unusually large crystals. It has been further suggested that somewhat diffuse, coarser grained, and lighter colored matrix near the garnets represents the anatectic material. However, Hollocher (2008) reported that the apparently

Figure 3. Generalized geologic map of the southern and central Adirondacks. Ages (Ga) of units are shown in legend. Major faults are shown as dashed black lines. Localities discussed in text are shown by white circles and identified by letters. B—Buck Mountain; BL—Brant Lake; G—Gore Mountain; GSL—Great Sacandaga Lake; H—Humphrey Mountain; I—Indian Lake fault; LG—Lake George; M—Moose Mountain; N—North Creek; O—Oregon dome; P—Paleozoic inliers in the Adirondacks and Paleozoic outcrops abutting the northeastern corner of the figure; Pi—Piseco anorthosite; PL—Piseco Lake; R—Ruby Mountain; S—Speculator (includes occurrences at 1, 2, 3, and 4); SL—Schroon Lake; T—Ticonderoga; W—Warrensburg. Modified after McLelland and Isachsen (1986).

Figure 4. Generalized geology at the open pit, Barton Garnet Mine at Gore Mountain. The hachured line designates the southern boundary fault. Modified after Goldblum and Hill (1995).
lighter, coarser patches have mineralogy identical to the rest of the amphibolite matrix (i.e., they are not tonalitic) and do not exhibit igneous textures, thus making the melt hypothesis highly unlikely. Repeated analyses of the Gore Mountain megagarnets demonstrate that they are unzoned or, at best, weakly zoned (Basu et al., 1989; Mezger et al., 1992; Connelly, 2006). This important observation is consistent with the presence of hot fluids that provided a steady flow of chemical constituents during growth.

Near the border fault, hornblende crystals in the amphibolite define a lineation subparallel to the border fault, and this tectonic fabric has been interpreted to reflect late ductile shearing that promoted fluid flow (Sharga, 1986; Goldblum and Hill, 1992). Research by Woolley (1987) and Martin (2006) demonstrated the importance of fluids in the deep crust, and the presence of fluids moving along ductile shear zones at mid- to deep-crustal depths is consistent with studies regarding eclogite formation (Austrheim, 1987; Jamtveit et al., 2000). The transport of aluminas needed to form garnet has been shown to be greatly enhanced by hot, saline fluids at mid-crustal depths at 8 kbar and 800 °C (Newton and Manning, 2008, 2010). The presence of saline fluid inclusions in the rocks involved (McLelland et al., 2002) thus removes the aluminas transport problem.

The mode of occurrence of garnet in the megacrystic amphibolite is unusual and deserves comment. A majority of the megacrystic garnets occur as idiomorphic single crystals surrounded by coarse rims (shells in three dimensions) of black hornblende 2–4 cm wide (Figs. 5A, 6A, and 6B). As described by Bartholomé (1960), the hornblende rims do not represent post-garnet reaction rims, but are properly understood as reaction products formed at the same time as the garnet. The presence of fluids at high temperature facilitates the transport of chemical constituents and greatly favors growth over nucleation. Accordingly, the garnet nuclei grew rapidly via reactions approximated by the generalized reaction: plagioclase + mafic phases + H2O → garnet + hornblende. As hornblende formed, it was pushed aside by garnet to form the black hornblende rims or shells. The process that we envision involves fluid becoming available to the already hot rocks and serving as the medium for local (i.e., tens of centimeters scale) transport of garnet-forming components. In essence the fluid is a catalyst but not a reactant. In the white ore (Fig. 5B) hosted by the gabbroic anorthosite, plagioclase is far more abundant than required to form garnet, and white rims of residual plagioclase are left surrounding the garnet. As discussed herein, it is not unusual for sets of hornblende-rimmed garnets to define linear trends as if they had formed in response to fluids moving along a fracture (Fig. 6A), and hornblende-rimmed veins of garnet are found in the Gore Mountain Mine (Fig. 6B). Sharga (1986) noted the presence of lavender spessartine-rich garnets in the charnockite along the south boundary fault. The largest of these reported was ~3.5 cm in diameter, but most of these garnets rarely exceed 1–2 cm, and decrease away from the fault so that they are absent at distances of 4–5 m or more.

An important characteristic of the megacrystic garnet-hornblende association is the occurrence of reaction rims between hornblende and garnet (Fig. 6D). In many cases, the only visible manifestation of this is a narrow, discontinuous rim of fine-grained white plagioclase and orthopyroxene. DeWaard (1965) described and discussed these narrow rims and showed them to be the result of a dehydration reaction between garnet and hornblende to yield anorthite-rich plagioclase (An90) that replaces garnet at the contact and orthopyroxene that replaces hornblende in the rim. This reaction is typomorphic of passage from the amphibolite to the granulite facies, and reflects equilibration at temperatures near or slightly above ~800 °C (DeWaard, 1965; Spear, 1981 [reaction 11–35]). In many cases, the orthopyroxene-in reaction is much farther advanced than described above, and coarse pods of plagioclase (An40–60; Stack, 2008) and orthopyroxene (enstatite, En50–60; Stack, 2008) embay and replace both garnet and hornblende (Fig. 6D) in configurations best accounted for as pressure shadows formed during extension sub-parallel to earlier shear zones (Hollocher, 2008; Stack, 2008). The generation of orthopyroxene at the expense of...
homblende ± garnet is indicative of a prograde transition into the granulate facies (DeWaard, 1965; Spear, 1981). Given geochronological constraints (discussed herein), this transition took place shortly before the region began to undergo terminal extensional collapse ca. 1050–1040 Ma. Hollocher (2007, personal commun. reported in Stack, 2008) suggests that plagioclase-orthopyroxene symplectites (Fig. 7) were the result of rapid cooling in late granulate facies grade during depressurization, and this fits well with late extensional collapse of the orogen (Rivers, 2008; McLelland et al., 2010a; Bonamici et al., 2011). This sequence of events is inconsistent with a counterclockwise path with slow isobaric, post-peak cooling, as proposed here for Ottawan metamorphism would suggest the rapid cooling may have resulted from exhumation and refrigeration due to thrusting up a cooler ramp. However, there is no evidence for such thrusting; on the contrary, we note that a clockwise prograde path is not inconsistent with the fluid inclusion investigations of Darling and Bassett (2002).

Gore Mountain garnets are unique in many respects, so it is not surprising that considerable effort has been made to determine the timing of garnet growth. The first dating was that of Basu et al. (1989), who used plagioclase-hornblende-garnet to produce a Sm/Nd isochron that yielded an age of 1059 ± 19 Ma. Mezger et al. (1992) conducted their own Sm/Nd investigation using hornblende and the drilled core of a 50 cm garnet to produce an isochron age of 1051 ± 4 Ma. Connelly (2006) utilized 7 different fractions of a Gore Mountain garnet to obtain a Lu-Hf isochron age of 1046.6 ± 6 Ma. We therefore conclude with confidence that the garnets formed at 1049 ± 5 Ma, the average of the three determinations. This is also the local age of peak metamorphism in the 1090–1040 Ma Ottawan phase of the Grenvillian orogeny and serves as a critical data point in ascertaining the evolution of the megacrystic garnet deposits.

Granitic pegmatites and veins are common in the Gore Mountain Mine, increase toward, and are present in the southern border fault. These dikes and veins crosscut the megacrystic garnet deposits, but the time interval between formation of the garnets and intrusion of the pegmatites remains uncertain. We
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collected samples from several dikes at the Gore Mountain Mine. One of these, a coarse quartz-microcline pegmatite, yielded abundant well-zoned zircons interpreted to be magmatic in origin. These were dated by sensitive high-resolution ion microprobe (SHRIMP) methods at the Stanford Menlo Park facility of the U.S. Geological Survey, using a primary ion beam diameter of 20 μm and analysis times of ~18 min per spot. Concentration data for U, Th, and trace elements were standardized using zircon standards MAD-green or CZ3 (Mazdab and Wooden, 2006). Age data for zircons were standardized against VP10 (in-house standard, 1200 Ma monzonite, southern California; A.P. Barth and J.L. Wooden, 2010 personal commun.) and corrected for common Pb using measured 206Pb. Data reduction for geochronology was accomplished using the Squid and Isoplot programs of Ludwig (2003). The analyses yielded a reliable upper intercept age of 1045 ± 7.5 Ma (Fig. 8A), a result that is within error of published Gore Mountain garnet age determinations. The Gore Mountain zircon results for two analyses exhibit very minor reverse discordance (~4% and ~6%), possibly due to some what elevated U content in these analysis spots, relative to the standard. Such minor reverse discordance is not uncommon in SHRIMP analyses (e.g., Guan, et al., 2002).

Zircon cores from the Gore Mountain pegmatite show normal magmatic chondrite-normalized rare earth element (REE) patterns with generally positive slopes and Ce anomaly. Rims and mantles of some grains (Fig. 9A) show modest relative depletion of heavy rare earths (Gd, Lu) compared to cores. This pattern is best explained by growth of these zircon mantles and rims synchronously with growth of garnet, which preferentially sequesters heavy (H) REEs (Whitehouse and Platt, 2003).

Cranberry Lake, Western Highlands

This occurrence is well exposed in large roadcuts along New York State Route 3, ~4 km east of Cranberry Lake Village (CL, Fig. 2), and is the sample farthest removed from the central Highlands. In this sector of the north-central Highlands, Lyon Mountain Granite is widely exposed in granitic plutons and pegmatite dikes and veins. The outcrop of interest consists of coarse-grained orthopyroxene meta gabbro that locally grades into deformed garnetiferous hornblende gabbro. Megacrystic garnets are not abundant, but where developed, their mode of occurrence is highly instructive. As shown in Figure 10A, a string of 5–10 cm deformed, hornblende-rimmed garnets is localized along a shear zone in lineated hornblende gabbro, and is interpreted to have formed by the influx of hydrothermal fluids along the shear zone at upper amphibolite grade. Deformation of the garnets shows clearly that shearing outlasted garnet formation. The white areas associated with the garnet megacrysts shown in Figure 10B consist of plagioclase and orthopyroxene formed by the previously discussed garnet + hornblende reaction defining passage into the granulite facies.

At the eastern end of the roadcut, the megagabbro is in contact with garnetiferous metasediments and both are cut by a coarse pegmatite. SHRIMP dating of this pegmatite (Fig. 8B) yields an age of 1055 ± 7.5 Ma (Table 2), coincident with Lyon Mountain Granite emplacement. Chondrite-normalized REE patterns for the Cranberry Lake locality zircons (Fig. 9)
Megacrystic Garnet Amphibolite near Warrensburg, New York

This spectacular exposure is located just east of the town of Warrensburg at the junction of Wall Street and the Schroon River Road immediately east of the Interstate 87 overpass (Hollocher, 2008; Stack, 2008). A large roadcut exposes megacrystic garnet amphibolite (Fig. 11A) that contains garnets as large as 10–12 cm in diameter, but none as large as the >12 cm examples at Gore Mountain. As at Gore Mountain, the garnets are rimmed by black hornblendite shells set in a dark gray matrix of granoblastic plagioclase and hornblende (Fig. 11B). The Warrensburg amphibolite is more iron rich than the one at Gore Mountain, and this difference is expressed in matrix mineral compositions (Stack, 2008): sparse orthopyroxene ($E_{54}$); brown hornblende; garnet (almandine, Alm$_{62}$); plagioclase (An$_{43}$). Together these compositions suggest a more evolved parental gabbro than at Gore Mountain (Hollocher, 2008). In many cases, 5–10-cm-scale garnets are lined up in stringers parallel to host rock lineation (Fig. 11B), and, as at Cranberry Lake, these suggest that the growth-promoting hydrothermal fluids penetrated along shear zones. It is not uncommon for plagioclase (An$_{44}$) and orthopyroxene ($E_{54}$) products (granulite facies) of garnet-hornblende reactions to be concentrated in extensional pressure shadows (Fig. 11B). At its northern terminus, the garnet amphibolite is in contact with a 3–5 m-wide, steeply dipping, north-northeast–trending coarse white pegmatite with variable concentrations of hornblende. The dike was intruded into a fault zone between olivine metagabbro on the south and intensely lineated ca. 1155 Ma charnockite to the north, and parallels a much larger north-northeast–trending fault that follows Interstate I-87 (Fig. 3). Offshoots of the pegmatite extend into the garnet amphibolite. A moderate foliation is developed in the dike parallel to the contact, but internally there is little deformation and large feldspar crystals are intact. A crushed sample yielded large zircons, but these were metamict, fractured, and altered precluding analysis. The chemical and mineralogical composition of the dike (Table 2) places it within the ca. 1050 Ma Lyon Mountain Granite clan.

The close similarities between this locality, Gore Mountain, and Cranberry Lake are interpreted as reflecting the parallelism in the timing and mechanisms of megacrystic garnet formation in all of these localities.

Megacrystic Garnet Amphibolite at Speculator, New York

The region around Speculator (S, Fig. 3) contains the greatest abundance of megacrystic garnet amphibolites in the Adirondacks (Figs. 3, 11C, and 11D). In many cases, these are demonstrably derived from ca. 1155 Ma coronoitic olivine metagabbros into which they grade locally. The metagabbros form a belt that sweeps eastward from the southern Snowy Mountain dome (Fig. 2) and passes south of the Oregon dome anorthosite massif (Fig. 3; circles 1 and 4...
indicate the belt, circles 3 and 4 are associated with separate metagabbros within the general area). The most accessible of the occurrences is located along New York State Route 30 as it passes over Page Hill and crosses the northern village limit; a roadcut at the crest of the hill exposes garnetiferous amphibolite in which most garnets are only 2–3 cm across, but a few have diameters of 8–10 cm and are rimmed by black hornblende set in a gray to dark hornblende-plagioclase matrix. White plagioclase-orthopyroxene reaction products are present and manifest the transition into granulite facies conditions.

The Speculator megacrystic garnet body is cut by a steep, fault-hosted oligoclase-potassium feldspar-quartz ± hornblende and/or biotite pegmatite that was largely excavated during the construction of Route 30. Substantial remnants of the pegmatite are present on the western wall of the roadcut (Fig. 11C), but the zircons recovered are so altered and metamict that no SHRIMP analyses were undertaken.

The same general description can be extended to all the garnet amphibolites in the Speculator region. In particular, they are all associated with faults and characteristic late Lyon Mountain Granite pegmatites and, hence, late hydrothermal fluids introduced at garnet-amphibolite grade. This generalization can be extended to all the megacrystic garnet amphibolites shown in Figure 3.

Additional Occurrences of Megacrystic Garnet in the Adirondack Highlands

A number of miscellaneous occurrences of megacrystic garnet are represented in Figure 3. This is by no means an exhaustive summary of these and other occurrences, but we are reasonably certain that they provide a fair representation of the distribution of these lithologies in the Adirondacks. Here we briefly summarize some of the larger examples of the amphibolites.

**Ticonderoga, New York State Route 74**

A large, very coarse pegmatite is well exposed in a roadcut on the north side of Route 74 (Figs. 12A, 12B) ~0.5 km west of the junction with Route 9, as Route 74 begins to climb to the west. The pegmatite contains excellent decimeter to centimeter scale, gray to pale green crystals of oligoclase that display exceptionally good polysynthetic twinning. Pink microcline and clear quartz are also present together with small quantities of hornblende and biotite. A few feet to the east of the pegmatite the roadcut contains a metagabbro body, the western margin of which is amphibolitic and contains numerous large garnets rimmed by black hornblende (Fig. 12B).
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Piseco Anticline Anorthosite
A small anorthosite body (Pi in Fig. 3) is associated with several peripheral metagabbros that grade into amphibolites and contain large percentages of hornblende-rimmed megacrystic garnet amphibolite similar to that at Warrensburg. Both north-northeast–trending faults and smaller east-west–trending faults are present in the area.

Humphrey Mountain
Situated in the middle of a large metagabbro body, the Humphrey Mountain occurrence is one of the best exposures of megacrystic garnet amphibolite in the region. Although the garnets are in the 5–10 cm range, they are well developed. Strong north-northeast–trending faults pass up the Indian Lake valley close to the amphibolite locality and would have served as fluid conduits. A second occurrence is on the large hill, underlain by metagabbro (white circle with letter N, Fig. 3). Here much larger exposures of megagarnet amphibolite are found and are similar in appearance to those behind the service station on Route 28.

Oregon Dome
This locality was mined for garnet at some time in the past as evidenced by angular blocks and an old roadbed from Route 8 to the site. It is one of the few occurrences within an anorthosite and is located along a large northeast-trending fault that contains pegmatite and was reactivated during the Phanerozoic. The garnets are similar in size and association to those at Warrensburg; some are 10–15 cm across.

North Creek, New York State Route 28
Megacrystic garnet amphibolite crops out behind an old service station along the west side of Route 28 just south of the southern entrance road into North Creek Village. The outcrop is part of a 20–30-m-wide sheet that extends uphill to west for ~0.25 km. Hornblende rimmed garnets in the 5–10 cm range are common. Large north-northeast–trending faults pass through the area and could have served as fluid conduits. A second occurrence is on the large hill, underlain by metagabbro (white circle with letter N, Fig. 3). Here much larger exposures of megagarnet amphibolite are found and are similar in appearance to those behind the service station on Route 28.

Indian Lake, North of Southeastern Entrance to Moose River Recreation Plain
Sporadic outcrops of megacrystic garnet amphibolite are exposed beginning a few hundred meters north of the access road to the Moose River Recreation Plain. Some of the garnets have diameters of 15–20 cm, but most are in the 5–10 cm size range. A prominent north-northeast–trending fault passes through the area and represents a good conduit for hydrothermal fluids.

LATE OTTAWAN PEGMATITITES
The emplacement of late Ottawan granitic pegmatites within the Gore Mountain metagabbro and formation of megagarnets were nearly simultaneous events in the late Ottawan history of the Adirondacks. This assertion is based upon the U-Pb zircon ages of the pegmatites presented herein, and the published dates of Gore Mountain garnet growth. The pattern of HREE depletion observed in the Gore and Cranberry Lake zircon strongly suggests that pegmatite melts were in contact with rocks in which garnet was growing. We interpret the pegmatites to be the immediate source of the fluids that promoted the growth of megacrystic garnets at high temperatures. Because of the importance of these pegmatites, we briefly discuss the ages and compositions of these intrusive rocks, and their relationship to the late Ottawan Lyon Mountain Granite.

With the exception of the southern Adirondack region, the outer margins of the Adirondack Highlands (Fig. 2) contain abundant intrusive bodies of Lyon Mountain Granite, the emplacement age of which, based on SHRIMP analyses, ranges from ca. 1060 Ma to ca. 1040 Ma. The average of 11 samples of Lyon Mountain...
TABLE 2. AGES OF LATE PEGMATITE DIKES, ADIRONDACK HIGHLANDS

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<tr>
<th>Method and locality</th>
<th>Age (Ma)</th>
<th>Error 2σ</th>
<th>Mineralogy</th>
<th>References</th>
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<tr>
<td>Gore Mountain</td>
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<td>7.5</td>
<td>Mc, Pl, Qz, Hbl, Bt, Zrn</td>
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</tr>
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<td>Cranberry Lake</td>
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<td>7.4</td>
<td>Mc, Pl, Qz, Hbl, Bt, Zrn</td>
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<td>Comstock b</td>
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<td>McLelland et al. (2002)</td>
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<td>Mc, Qz, Hbl, Bt</td>
<td>Selleck et al. (2005)</td>
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<td>21</td>
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<td>Lupulescu et al. (2011)</td>
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<td>Lupulescu et al. (2011)</td>
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<td>Crown Point</td>
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<td>Tan (1966)</td>
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<tr>
<td>Sugar Hill</td>
<td>1052</td>
<td>17</td>
<td>Mc, Ab, Qz, Mag</td>
<td>Lupulescu et al. (2011)</td>
</tr>
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</table>

Note: SHRIMP—sensitive high-resolution ion microprobe; LA-MC-ICP-MS—laser ablation–multicollector–inductively coupled plasma–mass spectrometry. Other abbreviations: Mc—microcline; Pl—plagioclase; Qz—quartz; Hbl—hornblende; Bt—biotite; Zrn—zircon; Mag—magnetite; Tur—tourmaline; Sil—sillimanite; Ab—albite; Aln—allanite; Scp—scapolite; Adr—andradite.

Figure 11. (A) Light colored pegmatite in contact with megacrystic garnet amphibolite at Warrensburg locality. (B) Aligned garnets with hornblende rims and white plagioclase-orthopyroxene intergrowths embaying garnet and forming in apparent pressure shadows at Warrensburg locality. Arrows point to grains of orthopyroxene. Scale is in centimeters. (C) Pegmatite (white) above megacrystic garnet amphibolite at Speculator locality. (D) 1–3-cm-diameter garnets, Speculator locality. Scale is in centimeters.
Granite yields 1049.9 ± 10 Ma; therefore, it is the youngest major igneous rock unit in the Adirondacks (McLelland et al., 2010a). Associated with Lyon Mountain Granite are numerous coarse pegmatites, granitic dikes (Table 3), and quartz veins that crosscut all other lithologies, and, in general, are minimally deformed or even undeformed. SHRIMP, laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) and single-grain thermal ionization mass spectrometry (TIMS) methods have been utilized to date several of these late intrusives. Of these, eight SHRIMP ages yield an average age of 1044 ± 7 Ma. Six other ages obtained by LA-multicollector-ICP-MS methods (Lupulescu et al., 2011) give an average of 1041 ± 10.5 Ma. The average of all 15 pegmatite ages is 1041.2 ± 9. These ages are slightly younger than, but within error of, the average age of Lyon Mountain Granite, and we conclude that the pegmatites represent the terminal phase of Lyon Mountain Granite magmatism. Ages and compositions of representative dikes are summarized in Tables 2 and 3.

Many pegmatites associated with Lyon Mountain Granite are characterized by a distinctive mineralogy defined by subequal amounts of white to gray-green oligoclase with clearly visible twinning striations, white to pink potassium feldspar, and abundant quartz. This common feature, together with minimal deformation, serves to identify these pegmatites in the field even when the absence or alteration of zircon precludes absolute dating. They appear to be unusually abundant in the eastern Adirondacks, but this may be an artifact of the greater number of roadcuts in this region, especially along Route 22 between Fort Ann and Ticonderoga.

**INTERPRETATION AND CONCLUSIONS**

The observations presented herein lead to the following conclusion: the megacrystic garnet amphibolites of the Adirondacks are the result of interaction between hydrous fluids and gabbroic rocks at upper amphibolite grade. The fluids were spatially associated with Lyon Mountain Granite, including its pegmatic derivatives (McLelland et al., 2002), and gained access through steep faults and ductile shear zones. Although we are currently unable to specify the ultimate sources of the fluids, we concur with recent studies that assign a mantle source (Austrheim, 1987; Woolley, 1987; Martin, 2006; Jamtveit et al., 2000; Jackson et al., 2004). The fluids may be derived from subducted or overridden slabs (Jackson et al., 2004), or may have been the result of mantle degassing (Woolley, 1987; Martin, 2006). They percolated into the deep continental crust through seismically related shear fractures (Jackson et al., 2004) and were involved in triggering eclogitization of the deep, dry, metastably rigid granulites in the lower crust (Jamtveit et al., 2000). This led to a sudden change from crustal rigidity to weakness and ductility as well as causing the eclogitized portion of the deep crust to delaminate (England and Platt, 1994). We propose that delamination took place beneath the Adirondack portion of the orogen and was followed by an influx of hot asthenosphere to the base of the thinner, but still deep and, as yet, uneclogitized crust (McLelland et al., 2010a, 2010b). Depressurization of the asthenosphere produced gabbroic melts that ponded at the mantle-crust interface and underwent high pressure crystallization to form plagioclase-rich crystal mushes (McLelland et al., 2010b). At the same time, the asthenospheric diapir degassed, and fluid rose into the overlying crust and fertilized the otherwise barren granulitic deep crustal restites, transforming them into approximately A-type granite compositions that then underwent large percentages of melting (Woolley, 1987; Martin, 2006). The anatectic A-type granitic magmas were at temperatures well above the wet solidus and ascended into the mid-crust carrying H2O, and heat to elevate the local temperature regime. This, we submit, is basically the link between the Lyon Mountain Granite, introduction of hydrous fluids, and the generation of Adirondack Highlands megagarnets, including those of Gore Mountain. In addition to fluids transported by the granitic magmas, there must have been a substantial volume of mantle-derived fluid that made its way directly into the mid-crust. The presence of the fluids...
and melts greatly lowered the viscosity of the crust (Jackson et al., 2004), and orogen collapse ensued with rapid cooling (Storm and Spear, 2005; Bonamici et al., 2011). The ca. 1050 Ma delamination and asthenospheric upwelling described here have been cited as important mechanical agents that resulted in the post-Ottawan AMCG suite in the eastern Grenville Province (McLelland et al., 2010b).

Because of the rapid cooling and extensional collapse of the Adirondack portion of the Grenville orogen, it is likely that pre-collapse high pressure-temperature conditions were quenched. Given this, past pressure-temperature records are recoverable only by careful analysis of zoning patterns in minerals such as Fe, Mg in garnet (Storm and Spear, 2005), or oxygen isotopes in titanite (Bonamici et al., 2011). The latter research demonstrates that ca. 1050 Ma collapse along the Carthage-Colton mylonite zone (Fig. 2) was 6–60 times more rapid than previously supposed. Accordingly, the emplacement of substantial volumes of the Lyon Mountain Granite may have taken place at lower pressures than recorded by standard geobarometry. This possibility is supported by the observation that the leucogranite commonly contains coarsely crystalline, ca. 1050 Ma pegmatites and quartz veins that attest to the presence of substantial fluid in the magma, although most of Lyon Mountain Granite is a hypersolvus, one-feldspar granite. In order for this to be possible, the soli-
dus must have been above the solvus dome, and this requires pressures <4.5 kbar (Morse, 1970).

The foregoing scenario is consistent with, and shown (Selleck et al., 2005) that 1047 ± 5 Ma Lyon Mountain Granite intruded the northwest-dipping Carthage-Colton shear zone during its topside down to the west normal displacement. In the eastern Adirondacks, intense, southeast-dipping shear zones have been identified, and it has been shown that kinematic indicators demonstrate topside down to the southeast (McLelland et al., 2010a; Kong et al., 2012). In situ electron microprobe Ultrachron (http://www.geo.umass.edu/probe/UMass%20Probe%20UC%20main.html) dating of oriented monazite grains in the shear zones reveals cores, mantles, and rims. The cores, which are embayed, yield an average (n = 9) age of 1176 ± 17 Ma, and the mantles (n = 14) produce an average age of 1046 ± 14 Ma, or 1051 ± 5 Ma if one anomalous age is omitted (Wong et al., 2012). Thin rims yield ages of 1026 ± 5 Ma. The mantles are preferentially developed along the long axis of the grains in the direction of extension (southeast). Many of the rims are present as asymmetric tips on oriented grains and indicate topside down to the southeast. Moreover, the tips are Y enriched, attributed to the breakdown of garnet according to the approximate reaction garnet + hornblende → orthopyroxene + plagioclase feldspar + Y fluid. These results have been interpreted (Selleck et al., 2005; McLelland et al., 2010a; Wong et al., 2012) as reflecting the ca. 1040–1050 Ma evolution of the Adirondacks as a symmetrical core complex or gneiss dome, with the Adirondack Lowlands and eastern Adirondack Highlands collapsing as the central Highlands rose as a deep crustal horst.

The late Grenvillian history of the Adiron-
dacks, as proposed here, is consistent with the Rivers (2008) model of late collapse of the Ottawa orogen. Specifically, Lowland titanite ages range from 1170 to 1100 Ma and thus record cooling from peak Shawinigan metamorphism. In addition, hornblende Ar/Ar ages are older than 1100 Ma, demonstrating that the Lowlands did not undergo temperatures exceeding 500 °C after that time (Streepey et al., 2001).

In contrast, titanite ages in the eastern Highlands are in the 1030–980 Ma range, and hornblende Ar/Ar ages cluster around 980 Ma, typical of Ottawa cooling ages. Accordingly, any repre-
sentatives of eastern Highlands remnants of an orogenic lid must be sought farther to the east. Unfortunately, the search is precluded by Phanerozoic border faults that drop early Paleozoic sedimentary rocks into contact with the mid-crustal sequences of the Highlands. Notwithstanding this, the interpretation of the eastern Adirondack shear zones is that they represent examples of the extensional faults associated with the local collapse of the Gren-
ville orogen. The widespread occurrence of ca. 1050 Ma Lyon Mountain Granite in the eastern Adirondacks (Fig. 3) is thought to reflect magmatic emplacement into the extensional fault network during collapse. This fault network coincides with the approximate western limit of Lyon Mountain Granite plutons in the eastern Highlands (Fig. 3). This is consistent with the results of Bickford et al. (2008) that demon-
strated Ottawan fluid activity and anatexis in the eastern, but not southeastern, Adirondacks. The absence of Lyon Mountain Granite from the southeastern Adirondacks suggests that the geo-
graphic termination of the extensional fault net-
work coincides with the approximate western limit of Lyon Mountain Granite plutons in the eastern Highlands (Fig. 3). It is important that Wong et al. (2012) noted that two hornblende Ar/Ar ages (Sutter, 1975) from the Mount Holly Complex (Fig. 1) yield ages of 1127 and 1028 Ma, suggesting that this block may be the eastern representative of the orogenic lid that did not undergo Ottawan granulite facies temperatures. Clearly more data are required, but the possibil-
ity is intriguing.

On a regional basis, it is instructive to review the geology near the eastern terminus of the Mesoproterozoic Morin terrane near Shawini-
gan Falls (SF, Fig. 1). Here a major, east-
to-southeast-dipping oblique normal fault, the Tawachiche shear zone (TWZ, Fig. 1; Corrigan and van Breenen, 1997) has dropped low-grade rocks in the hanging wall against granulite facies gneisses in the footwall. The normal faulting appears to have taken place ca. 1050–1070 Ma, although there may have been an earlier history along the fault zone. If this fault is projected along strike to the south, its trace passes beneath

### TABLE 3. WHOLE-ROCK COMPOSITIONS OF REPRESENTATIVE LATE OTTAWAN PEGMATITES

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Quartz-oligoclase dikes</th>
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<th>Warrensburg Dike light</th>
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<tr>
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<td>Fe₂O₃</td>
<td>MnO</td>
<td>MgO</td>
<td>CaO</td>
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<tr>
<td>63.77</td>
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<td>MgO</td>
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**Note:** Analyses are from this report except for those in column a, which are from Valley et al. (2011). Qz—quartz; Or—orthoclase; Ab—albite; An—anorthite; AN%—percent anorthite in plagioclase; dark—darker-colored facies; light—lighter-colored facies.


