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In-situ dating of metamorphism in Adirondack anorthosite

William H. Peck[1,*,†], Bruce W. Selleck[1], Sean P. Regan[2], Graceann E. Howard[1], and Oleg O. Kozel[1]

[1]Department of Geology, Colgate University, Hamilton, New York 13346, U.S.A.
[2]Eastern Geology and Paleoclimate Center, U.S. Geological Survey, P.O. Box 628, Montpelier, Vermont 05602, U.S.A.

Abstract

The 3000 km^2 Marcy anorthosite massif dominates the Adirondack Highlands (Grenville Province, New York). The Marcy massif was metamorphosed to granulite facies conditions, in places preserving igneous textures with metamorphic coronas and is most deformed near its margins. Historically, the relationship between anorthosite emplacement and metamorphism has been controversial, and many workers have argued that anorthosite emplacement coincided with metamorphism. Valley and O'Neil (1982) proposed that high-pressure metamorphic mineral assemblages in the anorthosite could not reflect the same event that formed wollastonite skarns adjacent to anorthosite, which have low $\delta^{18}O$ and formed in the presence of meteoric water during shallow emplacement. This study presents new in-situ geochronology that constrains the timing of metamorphic mineral growth in Adirondack anorthosite to 1050–1035 Ma. The Zr source for metamorphic zircon growth was the breakdown of hemoilmenite and is texturally linked to high-pressure mineral assemblages. These data are consistent with previously determined ca. 1155 Ma magmatic ages and later granulite facies metamorphism during the 1090–1020 Ma Ottawan phase of the Grenvillian orogeny.

Keywords: Adirondack Mountains, granulite facies, zircon, corona, Grenville province, anorthosite; Isotopes, Minerals, and Petrology: Honoring John Valley

Introduction

The Mesoproterozoic Adirondack Highlands is a keystone terrane for understanding the conditions of granulite facies metamorphism in the mid-crust. Early thermometry based on Fe-Ti oxide and feldspar compositions established metamorphic temperatures as high as ca. 800 °C in the Marcy anorthosite massif in the central Highlands (Fig. 1; Bohlen and Essene 1977), which was confirmed by subsequent cation and isotope thermometry (Bohlen et al. 1985; Kitchen and Valley 1995; Spear and Markussen 1997; Quinn et al. 2016). Barometry and phase equilibria constrain maximum metamorphic pressures to ~8 kbar (Bohlen et al. 1985; Spear and Markussen 1997). Since the earliest petrologic studies, the Adirondacks have had an important role as a place for field testing thermometers, barometers, and approaches for retrieving information about the conditions of metamorphism in general (Bohlen et al. 1985; Kitchen and Valley 1995; Darling and Peck 2016). Additionally, phase equilibria and isotope studies in the Adirondacks provided important limits on fluid flow and the origin of low a_{H_2O} during granulite facies metamorphism (Valley et al. 1990).

In spite of the well-constrained metamorphic conditions determined by decades of studies, the polymetamorphic nature of Adirondack rocks has often made it difficult to know which dynamothermal event or events are recorded by mineral compositions. This study approaches this problem by dating zircon texturally associated with metamorphic minerals in meta-anorthosite of the Adirondack Highlands. Adirondack anorthosite commonly shows spectacular garnet and clinopyroxene coronas around igneous pyroxene and hemoilmenite (e.g., McLelland and Whitney 1977). This textural evidence for garnet growth at the expense of ilmenite allows the possibility that metamorphic zircon formed from Zr liberated by ilmenite breakdown reactions can be used to link geochronology to metamorphic phase equilibria (e.g., Bingen et al. 2001). Our new data show that metamorphic zircon in coronitic and recrystallized anorthositic rocks formed during the latter part of the Ottawan phase of the Grenvillian orogeny ca. 100 m.y. after anorthosite intrusion, demonstrating that thermobarometric determinations on metamorphic minerals in these rocks are unrelated to emplacement.

Geologic context

The Adirondack Highlands are dominated by the 1155 Ma anorthosite-mangerite-charnockite-granite (AMCG) suite (McLelland et al. 2004); the largest body of which is the ca. 3000 km^2 Marcy massif that underlies most of the Adirondack High Peaks. The Marcy massif is made up of anorthosites and leucogabbros, with less-abundant gabbroic lithologies, some of which are oxide-rich and form Fe-Ti ore deposits. In general, anorthosite predominates in the interior of the massif while more gabbroic rocks are commonly found in the border zone and correspond to higher degrees of subsolidus strain. Anorthositic rocks of the massif interior ("Marcy facies"; Miller 1919) typically exhibit igneous contact relationships, coarse textures, and preserve abundant gray plagioclase megacrysts. Rocks of the border zone ("Whiteface facies"; Kemp 1898) are deformed and contain

* E-mail: wpeck@colgate.edu
† Special collection papers can be found online at http://www.minsocam.org/MSA/AmMin/special-collections.html.

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white recrystallized plagioclase with few remnant gray megacrysts. The cause of deformation fabrics in the anorthosite has been interpreted as related to emplacement of the massif (Balk 1931), the result of a later orogenic deformation (Buddington 1939; Regan et al. 2018), or a combination of multiple events.

Metamorphic growth of pyroxene, garnet, and other minerals in Adirondack anorthositic rocks has two main styles of paragenesis: as isolated porphyroblasts and as coronas around pyroxenes and Fe-Ti oxides. Peak metamorphic conditions constrained from both textural types is ca. 800–850 °C at 7 to 8 kbar (Bohlen et al. 1985; Spear and Markussen 1997). Metamorphic garnet is interpreted to have grown during near isobaric cooling from peak conditions (at ca. 750–650 °C; Spear and Markussen 1997).

In spite of the good constraints on conditions of metamorphism, the timing and geodynamics of metamorphic mineral growth in Adirondack anorthosite is not well constrained. Many early studies of Adirondack and other metamorphosed anorthosites interpreted garnet as grown during high-pressure cooling after deep magmatic emplacement (e.g., Martignole and Schrijver 1973; Whitney 1978; Basu and Pettingill 1983). Deep emplacement of the Marcy massif was challenged by the recognition that low-$\delta^{18}O$ wollastonite skarns in the contact zone of the massif formed during infiltration of large volumes of hot meteoric water, interpreted to require a shallow emplacement, and suggesting that high-pressure metamorphic assemblages in the anorthosite formed during a subsequent event (Valley and O'Neil 1982; Clechenko and Valley 2003). This model is supported by U-Pb geochronology studies of zircon and other minerals from anorthosite and country rocks that record magmatic ages of ca. 1155 Ma for anorthosite and other members of the AMCG suite (McLelland et al. 2004). Rocks within the Adirondack region preserves evidence for experiencing two high-grade events referred to as the Shawinigan Orogeny (1190–1140 Ma) and Ottawan phase of the Grenvillian orogeny (1090–1020 Ma). Metamorphic ages corresponding to the Ottawan in the Adirondack Highlands sometimes have ages attributed to the contractional phase of the orogeny (1090–1050 Ma), but more often as associated with late-Ottawan collapse and cooling (1050–1020 Ma) (Mezger et al. 1991; Heumann et al. 2006; Wong et al. 2012; Bonamici et al. 2014). In anorthosite, dated metamorphic phases are for the most part either zircon overgrowths on igneous cores or "soccer-ball"-shaped zircon neoblasts, which all have ages broadly consistent with late-Ottawan cooling or younger, ca. 1000–900 Ma, ages associated with the Rigolet phase of the Grenvillian orogeny (McLelland and Chiarenzelli 1990; McLelland et al. 2004). These metamorphic zircon analyses all represent isotope dilution or ion probe determinations on mineral separates, some from very large rock samples, and the petrologic context of these metamorphic zircon ages is not well constrained.

Previous sampling and analytical strategies used in the past has left published geochronology of Adirondack anorthosites and related rocks open to different interpretations. For example, ca. 1040 Ma zircon from anorthosite related to the Sanford Lake Fe-Ti ore deposits has been interpreted as representing metamorphic zircon growth during the Ottawan orogeny (McLelland et al. 2004) and alternatively as igneous growth, suggesting relatively young anorthosite emplacement within the massif (Aleinikoff and Walsh 2016). Similarly, ca. 1050–1040 Ma high-pressure mineral assemblages that show partial melting textures in country rocks of the anorthosite have been interpreted as indicating heating by Ottawan-aged anorthosite, and lower crustal emplacement (Alcock et al. 2004). The thermobarometry study of Spear and Markussen (1997) supports shallow intrusion of anorthosite and subsequent high-pressure metamorphism during the Ottawan orogeny, but without geochronologic constraints on metamorphic mineral as-

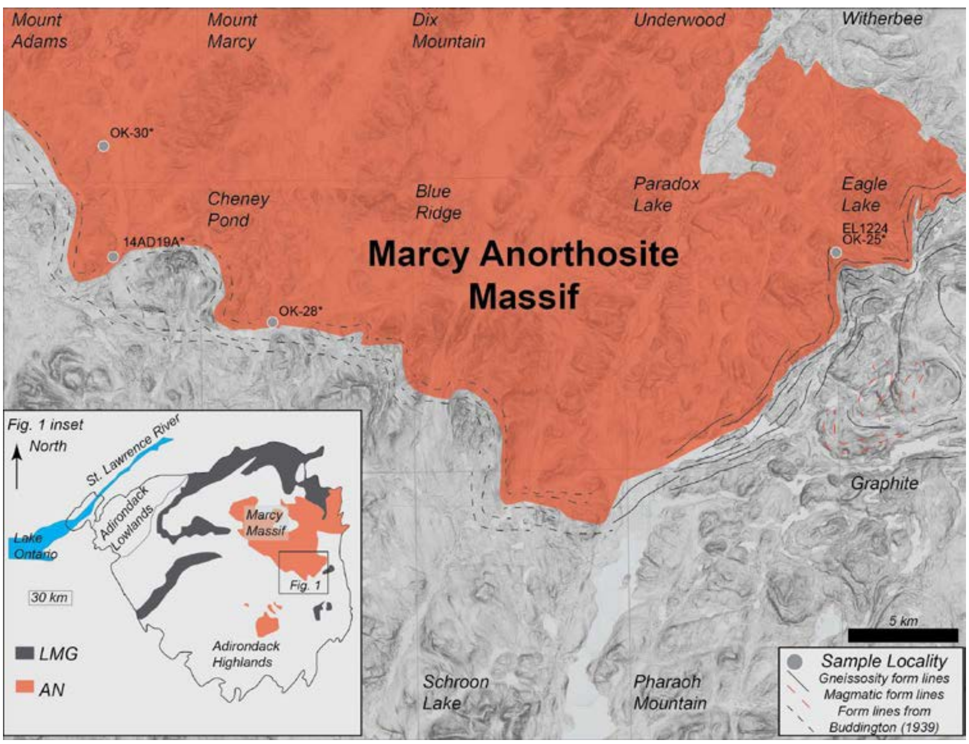

FIGURE 1. Location map of geochronology samples in the southern Marcy anorthosite massif, Adirondack Highlands, underlain by a percent slope map derived from LiDAR. Names of 7.5' quadrangles are shown. In the inset, LMG = Lyon Mountain granite and AN = anorthosite. (Color online.)

semblages. To help evaluate these issues, this study presents in situ dating of zircon associated with garnet-forming reactions in anorthosite to better understand the relationship between anorthosite emplacement and granulite facies metamorphism in the Adirondacks.

Materials and methods

This study focuses on dating metamorphic zircon in anorthositic rocks with clear textural relationship between zircon and metamorphic minerals, for which *P-T* conditions are well understood. Two analytical strategies were employed: dating of zircon separates and zircon in-situ in thin sections. Sample EL1224 was collected for crushing and zircon extraction from a sub-kilometer scale screen of gabbroic (ferrodiorite) gneiss containing coarse andesine porphyroblasts (Fig. 1). The ferrodiorite is interlayered at the map and outcrop scale with protomylonitic leucogabbro. The gneissosity at this locality parallels the southeastern margin of the Marcy Massif (Regan et al. 2018). Zircon crystals from this sample were separated at the U.S. Geological Survey in Reston, Virginia, using standard heavy liquid and magnetic separation techniques and were mounted in epoxy. For in-situ geochronology 81 anorthosite-suite samples were visually surveyed for the abundance of ilmenite and garnet, and thin sections of 30 of these were screened for zircon by backscattered electron imaging. Polished thin sections were made for in-situ geochronology of four representative samples, all from the mapped border zone of the southern Marcy massif (Fig. 1). Sample OK25 is a gabbroic gneiss (ferrodiorite) from the Paradox Lake 15' quadrangle, the same locality as sample EL1224. OK25 has an equigranular granoblastic texture of plagioclase, orthopyroxene, clinopyroxene, hornblende, biotite, and Fe-Ti oxide. Samples OK30 and OK28 are weakly foliated leucogabbros with garnet coronas around deformed aggregates of ilmenite from the Santanoni and Schroon Lake quadrangles, respectively. Leucogabbro sample OK30 is from 4 km south of the Sanford Lake Fe-Ti deposit. Both samples have annealed microtextures of granoblastic plagioclase, clinopyroxene, and garnet. Sample 14AD19A is a plagioclase-clinopyroxene-garnet gneissic leucogabbro from the Newcomb quadrangle, and is texturally similar to samples OK30 and OK28, but lacks garnet coronas. It is from a low $\delta^{18}O$ anorthosite outcrop in the border zone of the massif that is interpreted to have been infiltrated by meteoric water during emplacement (Morrison and Valley 1988; Peck et al. 2017). All samples contain a few texturally early, exolved clinopyroxene porphyroclasts and remnant gray igneous plagioclase megacrysts.

Zircon crystals were imaged using cathodoluminescence (CL) and backscattered electrons (BSE). U-Pb analyses of mineral separates of EL1224 were acquired at the Stanford-U.S. Geological Survey sensitive high-resolution ion microprobe with reverse geometry (SHRIMP-RG). Standard operating conditions (Premo et al. 2008) were utilized during all analytical sessions with a ~20 μm diameter oxygen beam. R33 and MADDER standards were analyzed before, after, and throughout sample analysis. Zircon crystals were dated in polished thin sections of the other samples at the Arizona LaserChron Center using laser ablation with a Photon Machines Analyte G2 Excimer laser online with a Nu HR inductively coupled plasma mass spectrometer (Gehrels et al. 2008). A laser spot size of 10 μm and ion counter detectors were used to measure ^{208}Pb, ^{207}Pb, ^{206}Pb, and ^{204}Pb, while ^{238}U and ^{232}Th were collected on Faraday detectors. The Laserchron Sri Lanka zircon standard was analyzed during each analytical session to correct for Pb/U fractionation and monitor instrument conditions. Analytical details can be found at https://sites.google.com/a/laserchron.org/laserchron/.

Results

Zircon from sample EL1224 are homogenous in BSE and CL, and range from 50–200 μm. 18 analyses of clean portions of these crystals yielded ages ranging from 1119 ± 25 to 957 ± 64 Ma, and lack a coherent population (Fig. 2). See Supplementary Tables[1] for all U-Pb data. The average using all the analyses yields a $^{207}Pb/^{206}Pb$ weighted mean age of 1051 ± 24 Ma and a high MSWD (3.5). A hand sample from the same outcrop (sample OK25) was selected for in-situ geochronology to help resolve the somewhat broad range of ages. Analyzed zircon in sample OK25 is located in-between exolved ilmenite and metamorphic pyroxenes or hornblende (Fig. 3). Four analyzed grains are anhedral and relatively equant, while one grain has a "hat-shaped" morphology. This latter texture is where some zircon crystals extend along the boundary of ilmenite (e.g., top images of Fig. 3), suggesting that ilmenite was the source of zirconium for zircon growth (Bingen et al. 2001). Similarly to zircon analyzed in the mineral separate from EL1224, zircon in sample OK25 has overall dark and, for the most part, featureless CL. The hat-shaped grain shows faint zoning in CL, and the other grains have dark CL with occasional high-CL bands (possibly healed fractures). These features do not correspond with Th/U, which averages 0.38 ± 0.13, or the weighted $^{206}Pb/^{207}Pb$ age, which is 1046 ± 8 Ma (MSWD = 0.98; 16 spot analyses; Fig. 3).

Samples OK28 and OK30 are lithologically similar samples where zircon is found associated with exsolved ilmenite and almandine garnet (Figs. 4 and 5). Analyzed zircon in OK30 has two textures. Some are generally equant in thin section and some have hat-shaped morphologies (Fig. 4). These grains are, for the

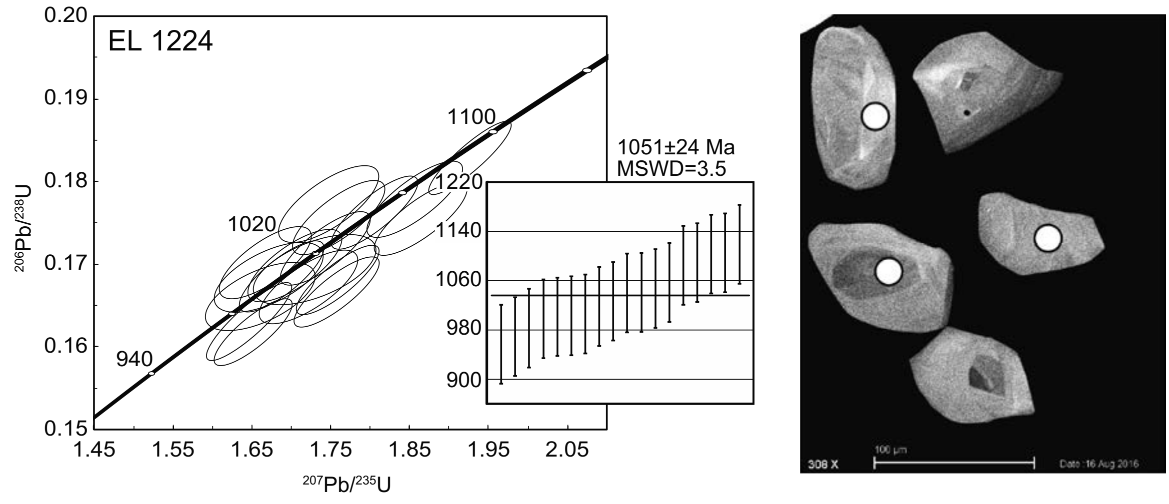

Figure 2. Concordia diagram (**left**) of SHRIMP-RG spot analyses of zircon dated in-situ in ferrodiorite gneiss EL1224. Inset are $^{206}Pb/^{207}Pb$ ages and the weighted age. 2σ errors are shown. Images (**right**) show representative analyzed zircon (left side shows backscattered electrons, right side cathodoluminescence showing ion probe spot locations).

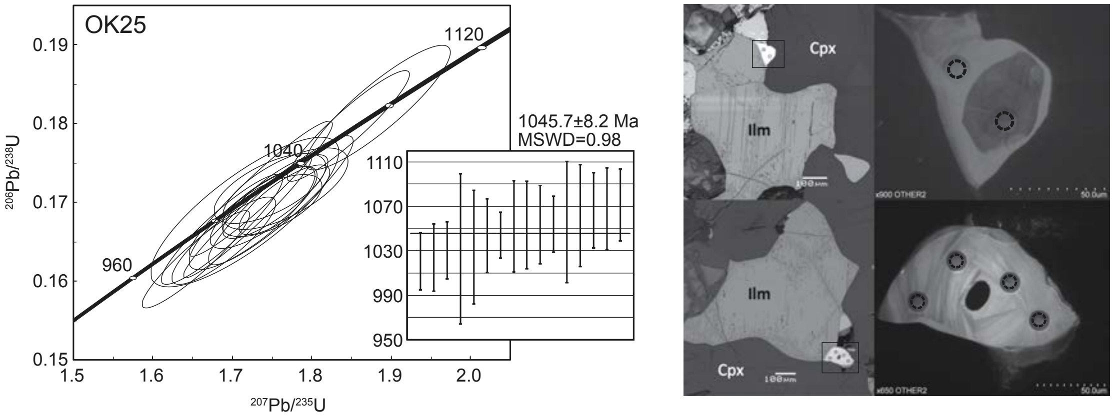

FIGURE 3. Concordia diagram (left) of LA-ICPMS spot analyses of zircon dated in-situ in ferrodiorite gneiss OK25. Inset are $^{206}Pb/^{207}Pb$ ages and the weighted age. 2σ errors are shown. Images on the right show representative analyzed zircon (left side shows backscattered electrons, right side shows cathodoluminescence showing laser spot locations).

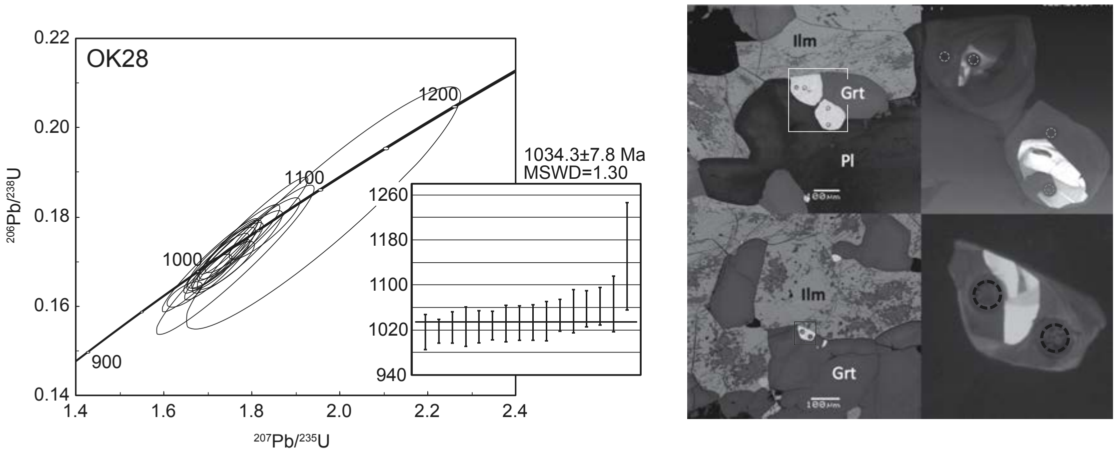

FIGURE 4. Concordia diagram (left) of LA-ICPMS spot analyses of zircon dated in-situ in leucogabbro gneiss OK28. Inset shows $^{206}Pb/^{207}Pb$ ages and the weighted age. 2σ errors are shown. Images on the right show representative analyzed zircon (left side shows backscattered electrons, right side shows cathodoluminescence showing laser spot locations).

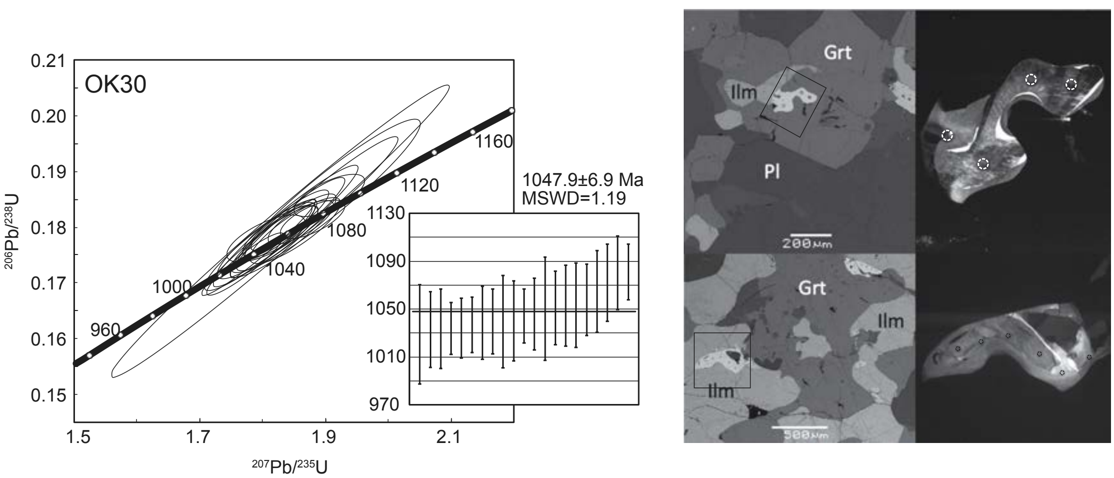

FIGURE 5. Concordia diagram (left) of LA-ICPMS spot analyses of zircon dated in-situ in leucogabbro gneiss OK30. Inset shows $^{206}Pb/^{207}Pb$ ages and the weighted age of the most-coherent 21 spot analyses. 2σ errors are shown. Images on the right show representative analyzed zircon (left side shows backscattered electrons, right side shows cathodoluminescence showing laser spot locations).

most part, not cathodoluminescencent, with a few having bright CL regions and Th/U of 0.48 ± 0.09. Sixteen spot analyses on 10 grains yielded a weighted $^{206}Pb/^{207}Pb$ age of 1034.3 ± 7.8 Ma (Fig. 4; MSWD = 1.3). In contrast with OK28, zircons in sample OK30 are irregular crystals intergrown with coronitic garnet porphyroblasts (Fig. 5). These zircon show patchy, diffuse CL patterns and have Th/U of 0.46 ± 0.06. Twenty-three spot analyses on four grains yielded a weighted $^{206}Pb/^{207}Pb$ age of 1054 ± 11 Ma (MSWD = 2.9). A more precise age of 1047.9 ± 6.9 Ma (MSWD = 1.19) was obtained from the most-coherent 21 spot analyses (Fig. 5).

The thin section for sample 14AD19A contains a variety of zircon sizes and morphologies (Fig. 6). Some large crystals are euhedral with concentric CL zoning and Th/U of 0.57 ± 0.12, while other large crystals are anhedral and have patchy bright CL and higher and more variable Th/U = 0.79 ± 0.41. Small anhedral crystals intergrown with garnet have dark CL (Fig. 6) and similar Th/U to the irregular grains: 0.84 ± 0.24. The weighted $^{206}Pb/^{207}Pb$ age of seven spot analyses of three euhedral grains is of 1140 ± 37 Ma (MSWD = 2.8). Sixteen analyses of anhedral zircon have a coherent age population of 1032 ± 14 Ma (MSWD = 2.2), with one grain that might have formed slightly earlier (4*C*; see Supplementary[1] Table 5).

DISCUSSION

The focus of this study was to identify and analyze metamorphic zircon associated with garnet-pyroxene assemblages to help constrain the age of metamorphic mineral growth. We did not particularly seek to obtain igneous ages and so did not focus on rocks that preserve igneous textures because we see the igneous age of Adirondack anorthosite as being much better understood than the age of metamorphism. Published high-precision thermal ionization mass spectrometry (TIMS) and SHRIMP analysis consistently yield igneous ages of ca. 1155 Ma for Adirondack anorthosite and related rocks (McLelland and Chiarenzelli 1990; McLelland et al. 2004). In addition, the wealth of published geochemical data show coherent geochemistry for these rocks (see Morrison and Valley 1988; Seifert et al. 2010) and do not suggest multiple parent magmas or anorthosite events.

Metamorphic garnet in the Marcy anorthosite forms via clinopyroxene and ilmenite breakdown reactions (McLelland and Whitney 1977; Spear and Markussen 1997), and the zircon grains analyzed in this study have clear textural relationships with both hemoilmenite and metamorphic garnet. The morphology and the CL of the zircon along with the intimate relationship between it and reactant ilmenite are clear indications of metamorphic zircon growth (cf. Bingen et al. 2001). Thorium/uranium ratios are not particularly definitive here for evaluating igneous vs. metamorphic zircon. Metamorphic zircon sometimes has low Th/U (<0.1), and this has been used in some studies as an indicator of the subsolidus formation. However, Th/U has proven to not be a reliable indicator of metamorphic origin, and metamorphic zircon in many rocks has a range in Th/U, depending on the U and Th budget of the rock and element competition among minerals during zircon growth (see Harley et al. 2007). This is especially the case for granulite facies metaigneous rocks, which often have igneous and metamorphic zircon with similar Th/U (Bingen et al. 2001; Möller et al. 2003). This is the case for igneous and metamorphic zircon in the Marcy anorthosite, which both typically have Th/U in the range 0.3 to 0.9 (McLelland et al. 2004).

Granulite facies metamorphism in the Adirondack Highlands had peak conditions of 800–850 °C and 7–8 kbar. Reaction modeling (Spear and Markussen 1997) and oxygen isotope thermometry (Quinn et al. 2016) suggest that garnet-forming reactions in anorthosite suite rocks occurred at lower temperatures, ca. 750–650 °C. The 1050–1035 Ma metamorphic zircon ages correspond well with the time of orogenic collapse and cooling for the Adirondack Highlands from peak metamorphic conditions. 1050–1035 Ma garnet growth suggests relatively rapid cooling after the ~1070 Ma metamorphic peak (ca. 20–35 °C/My), consistent with orogenic collapse and diffusion-modeling calculations of rapid cooling by Bonamici et al. (2014). This period of garnet growth is contemporaneous with emplacement of the Lyon Mountain granite in the Adirondack Highlands, which is also interpreted to be the result of the collapse of the Ottawan orogenic belt (see Selleck et al. 2005; Chiarenzelli et al. 2017).

The ca. 1140 Ma euhedral zircon from sample 14AD19A is

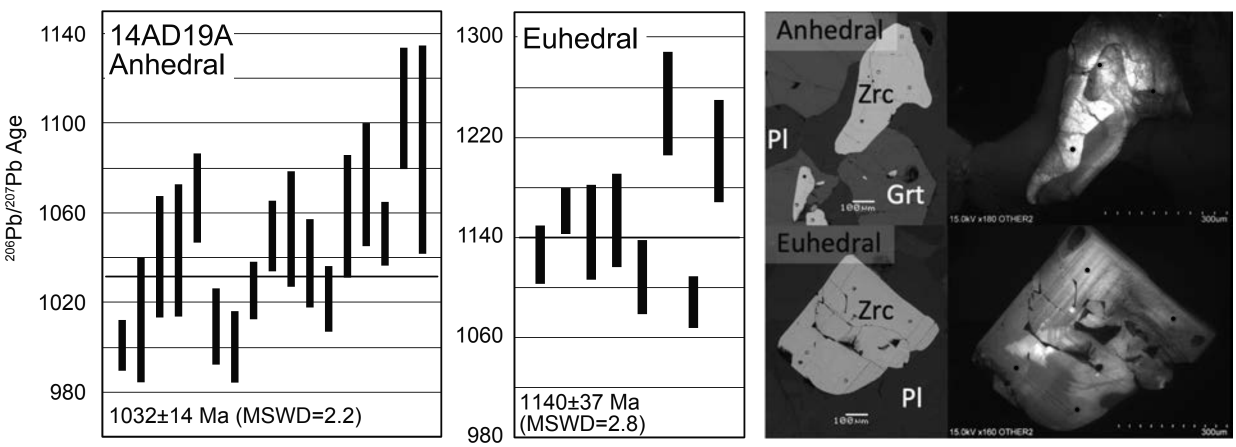

FIGURE 6. Weighted age histograms of LA-ICPMS spot analyses of zircon dated in-situ in leucogabbro gneiss 14AD19A (left). 2σ errors are reported, boxes in this plot are ±1σ . Images on the right show representative analyzed zircon (left side shows backscattered electrons, right side shows cathodoluminescence showing laser spot locations).

consistent with igneous formation during emplacement, and falls within the ages of igneous zircon from Adirondack anorthosite (McLelland and Chiarenzelli 1990; McLelland et al. 2004). The general lack of igneous zircon in the other three samples examined in this study is interesting, and could be a byproduct of selecting samples rich in ilmenite, which may dominate the Zr budget of these rocks during igneous crystallization suppressing igneous zircon formation (see also Morisset and Scoates 2008).

The metamorphic history of the Marcy anorthosite, and especially its depth history, has long been controversial. Many early workers concluded that anorthosite emplacement coincided with granulite facies metamorphism, and that metamorphic garnet grew during cooling after deep emplacement. The important recognition of Valley and O'Neil (1982) that low $\delta^{18}O$ skarns formed in the presence of heated meteoric water during anorthosite emplacement suggested a polymetamorphic model, as the maximum pressures recorded by metamorphic mineral equilibria (~30 km depth) was not compatible with the presence of surface fluids during shallow emplacement. However, low $\delta^{18}O$ skarns are only recognized in the northeastern part of the massif, and the final emplacement depths elsewhere in the massif are unclear. Aluminum contents of igneous orthopyroxene in anorthosite are consistent with polybaric crystallization, yielding a spectrum of pressures from ca. 3 to 12 kbar (Jaffe and Schumacher 1985; Spear and Markussen 1997; Peck and Taylor 2017). In the southern Marcy massif, a small zone with low $\delta^{18}O$ was interpreted by Morrison and Valley (1988) as supporting shallow intrusion of this part of the massif. Metamorphic garnet from these outcrops is in oxygen isotope equilibrium with coexisting plagioclase, which shows that the low $\delta^{18}O$ signature is an early (pre-metamorphic) feature of the anorthosite (Peck et al. 2017). Sample 14AD19A is from this zone, and constrains the low $\delta^{18}O$ of these rocks (and shallow water-rock interaction) to earlier than ~1035 Ma. Existing geochronology is most compatible with shallow emplacement of the anorthosite massif and hydrothermal alteration by meteoric fluids at ca. 1155 Ma, followed by granulite facies metamorphism and garnet growth in the anorthosite at 1050–1035 Ma.

These new data help constrain the timing of deformation and mineral growth during the latter phases of the Ottawan phase of the Grenvillian Orogeny. The Ottawan phase is interpreted as a Himalayan-style collision between Laurentia and Amazonia, producing widespread penetrative deformation, melting, and granulite facies mineral assemblages in the Adirondack Highlands (e.g., McLelland et al. 2013; Darling and Peck 2016). Garnet coronas surround elongate ilmenite and clinopyroxene in deformed anorthosite, so the growth of garnet and dated zircon clearly post-dates deformation in these rocks. The metamorphic mineral growth dated here is synchronous with emplacement of the Lyon Mountain ferroan leucogranite suite, emplaced during the structural collapse of the Adirondack Highlands (Selleck et al. 2005; Chiarenzelli et al. 2017). This suite of leucogranites crosscuts, and lacks evidence for, granulite facies fabrics and assemblages, consistent with a relatively late to post-kinematic origin and a contemporaneous relationship with corona growth in anorthositic rocks. The exact nature of the Ottawan phase of the Grenvillian orogeny in the Adirondack Highlands persists as a major problem, but data presented in this study suggest that granulite-facies assemblages in anorthositic rocks formed during peak Ottawan tectonism, and coronas formed along a retrograde path during tectonic exhumation and emplacement of the Lyon Mountain ferroan leucogranite suite. This interpretation is consistent with in-situ monazite U-Th-total Pb geochronology indicating that strain paralleling the margin of the Marcy anorthosite formed at ca. 1065 Ma, immediately prior to corona growth documented in this study (Regan et al. 2018).

IMPLICATIONS

It was not until broad application of U-Pb geochronology to metaigneous and metasedimentary rocks in the Adirondacks (e.g., McLelland et al. 1988; Mezger et al. 1991) that many of the cutting-edge determinations of metamorphic pressures, temperatures, and fluid composition from the 1970s and 1980s could be understood in a geodynamic context. However, the reaction history of the anorthosite, where many of these petrologic studies were focused, remained poorly constrained. The Adirondack Highlands experienced anorthosite-suite magmatism during the latter parts of the 1190–1140 Ma Shawinigan Orogeny, an accretionary event that caused high-grade metamorphism and melting in the Adirondacks (Mezger et al. 1991; Heumann et al. 2006). Metasedimentary country rocks to the anorthosite experienced both Shawinigan and Ottawan events (e.g., Kitchen and Valley 1995; Heumann et al. 2006; Peck et al. 2010). In the absence of direct dating of metamorphic minerals in these rocks, it is often unclear to what extent pressure and temperature estimates from these rocks represent Shawinigan or Ottawan conditions (or reflect a combination of the two). The recognition that metamorphic mineral assemblages in the anorthosite formed at 1050–1035 Ma and are not related to the Shawinigan orogeny or anorthosite emplacement provides a more clear perspective on Ottawan metamorphic conditions than was previously available. Metamorphic minerals commonly overgrow igneous textures, and texturally late garnet in anorthosite has historically been interpreted as evidence for formation shortly after emplacement in the Marcy massif and elsewhere (e.g., Martignole and Schrijver 1973; Whitney 1978; Basu and Pettingill 1983). However, assigning the 8 kbar peak pressures determined from metamorphic minerals in these rocks to anorthosite emplacement would be erroneous (e.g., Alcock et al. 2004), and the evidence best supports shallow emplacement of the anorthosite at ca. 1155 Ma during the collapse associated with the Shawinigan orogeny followed by granulite facies metamorphism, rapid cooling, and collapse during the 1080–1030 Ma Ottawan orogeny.

Evaluation of the textural context of zircon and in-situ geochronology was critical for constraining the metamorphic history of these rocks. If the samples we analyzed in this study had been crushed, and zircon samples had been examined in grain mounts, their anhedral crystal forms and zoning patterns might easily have been taken for the unusual igneous grains often found in mafic lithologies (e.g., Corfu et al. 2003). This approach might have led to the erroneous interpretation that the ages determined from these grains would reflect the age of igneous emplacement, rather than metamorphic growth during a later orogenic event.

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