# Using pegmatite geochronology to constrain temporal events in the Adirondack Mountains

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## ABSTRACT

**U-Pb laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) ages have been determined from large zircon crystals separated from pegmatites of the Adirondack Mountains, New York. Emplacement and metamorphic ages ranging from 949 ± 10 to 1222 ± 12 Ma help constrain the timing of igneous, metamorphic, and deformational history of the region, and are associated with Shawinigan, Ottawan, and Rigolet orogenesis. Geologically reasonable ages were obtained from most zircon separates despite large size, a limited number of grains, high uranium and thorium contents, dark and opaque interiors, high density of fractures, and widespread areas of metamictization and Pb loss. However, few grains show zoning or differences in composition when viewed with the backscattered mode on the scanning electron microscope. Large, clear, internally featureless, U-poor grains yield the best constrained ages. U-Th-Pb monazite ages, determined by electron probe, vary from 874 ± 27 Ma to 297 ± 62; the younger age may reflect the timing of hydrothermal fluid infiltration related to late Acadian events. This study suggests that, with appropriate care, zircons from pegmatites are a reasonable target for LA-MC-ICP-MS geochronology, widening the current arsenal of sampling targets.**

## INTRODUCTION

In this paper we discuss results from initial attempts to date zircon and monazite from pegmatites from the Adirondack Mountain portion of the Grenville Province (Fig. 1). Our principal goal is to present the timing of the pegmatite emplacement using U-Th-Pb zircon ages determined by laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) and monazite ages by electron microprobe analysis (EMPA). These new data are used to constrain the timing of the Adirondack igneous, metamorphic, and deformational events. We selected the pegmatites for U-Pb geochronology because these rocks are sufficiently abundant in the Adirondacks, often occur as medium-size rock bodies associated with important economic deposits, have syn- or post-tectonic emplacement, and contain minerals that are readily observed in hand samples that are easily manipulated under the binocular microscope and are capable of concentrating incompatible elements including U and Th.

Despite their interesting petrographic features, geological location, and mineralogy, there are only a few modern studies and references in the geological literature about the pegmatite bodies from New York (Tan, 1966; Putman and Sullivan, 1979). The interest in the pegmatites of the Highlands commenced with the rush for high-quality feldspar and muscovite suitable for electrical applications, enamel, crushed stone for concrete structures, chicken grit, and at a small scale for quartz used in glass manufacturing and later for radioactive minerals; they were mined between 1906 and 1934 (Newland, 1916, 1921; Miller, 1921; Newland and Hartnagel, 1939; Tan, 1966). The pegmatites from the Lowlands were mined for high-quality feldspar between 1907 and 1938 (Newland, 1916; Cushing and Newland, 1925; Shaub, 1929; Newland and Hartnagel, 1939; Tan, 1966).

New York pegmatite bodies remain largely undated except the U-Th-Pb zircon ages for the Lyonsdale Bridge Falls in the western Highlands at 1034 ± 10 Ma (McLelland et al., 2001) and pegmatitic phase of the Lyon Mountain Granite at Brouse's Corners in the Lowlands at 1044 ± 7 Ma (Selleck et al., 2005). Older U-Th-Pb dating on uraninite from the McLear pegmatite in the Lowlands (Shaub, 1940) yielded an age of 1094 Ma. In this study we report geochronological U-Th-Pb data for 11 pegmatite bodies from the Adirondack Mountains (two from the Lowlands and nine from the Highlands), and one from a pegmatitic intrusion in the Old Bed magnetite-apatite ore from Mineville. These ages are summarized in Table 1. Additional U-Th-Pb data on monazite from two pegmatite bodies from the southern Adirondack Highlands are reported.

## OCCURRENCES

The Adirondack Mountains are part of the Grenville Province (for recent summaries, see Rivers, 2008; McLelland et al., 2010). Based on the metamorphic grade, rock type, and composition, they are divided into Adirondack Highlands and Adirondack Lowlands by a deformation zone known as Colton-Carthage Mylonite Zone (Geraghty et al., 1981; Streepey et al., 2001). The juxtaposition of the Lowlands against Highlands is interpreted as the result of an orogenic collapse (Selleck et al., 2005).

The Lowlands contains supracrustal rocks that were metamorphosed to mid-upper amphibolites facies and were deformed during the Shawinigan orogeny (Corrigan, 1995; Wasteneys et al., 1999; Rivers, 2008). The lithotectonic sequences of the Lowlands start with the Lower Marble Formation overlain by the Popple Hill Gneiss (Carl, 1988) and Upper Marble Formation (de Lorraine and Sangster, 1997). The composition of the basement of these metasedimentary sequences is not known, but Chiarenzelli et al. (2010a) suggested the metasedimentary rocks are either allochthonous or were deposited on oceanic crust. The marbles and gneisses were intruded between 1150 and 1200 Ma by varied igneous rocks (Wasteneys et al., 1999; Heumann et al., 2006; Chiarenzelli et al., 2010b). The pegmatites

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**Figure 1. Location of the Adirondack Mountains within the greater Grenville Province (modified after Tollo et al., 2004).**

from the Lowlands presented in this study, McLear and Rossie, were both intruded into the Lower Marble Formation.

The Highlands contains supracrustal and igneous rocks that were metamorphosed under granulite facies conditions during the Shawinigan and Ottawan orogenies, although the production of leucosome related to these events in pelitic gneisses in the Highlands appears to be geographically variable (Heumann et al., 2006). A simplified geochronology of the Highlands records the oldest rocks as arc-related tonalites of calc-alkaline affinity with ages ranging from 1330 to 1307 Ma (McLelland and Chiarenzelli, 1990a). Around 1155 Ma, a voluminous anorthosite-charnockite-mangerite-granite (AMCG) suite was emplaced (McLelland et al., 2004; McLelland and Chiarenzelli, 1990b); other younger igneous rocks such as A-type Hawkeye granite (1100–1090 Ma), the mangerites from the northern Highlands (1080 Ma), and the A-type Lyon Mountain granite (1070–1040 Ma) (McLelland et al., 1996) are recognized. These geochronological data prove the presence of the Elzevirian, Shawinigan, and Ottawan deformation and igneous activity in the Highlands. The distribution of these rocks can be seen in Figure 2.

The pegmatites from the Highlands, analyzed in this study, were collected from the

TABLE 1. SUMMARY OF U-PB AGES (IN MA) ON ZIRCON FROM PEGMATITES FROM THE ADIRONDACK MOUNTAINS

| | Concordia plot | | | Concordant age | | | Weighted mean age | | | Other | | | | Best age |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Upper intercept | Lower intercept | MSWD | Weighted mean | MSWD | Probability | Weighted mean | MSWD | Probability | Upper intercept | Lower intercept | MSWD | | (2σ) |
| Lowlands | | | | | | | | | | | | | | |
| 1. McLear | 1396 ± 820 | 1216 ± 110 | 0.18 | 1195.1 ± 7.2 | 0.09 | 0.76 | 1198 ± 13 | 0.78 | 0.73 | 1197 ± 13 | 250 ± 50 | 0.00 | F | 1195.1 ± 7.2 |
| 2. Rossie | 1185 ± 19 | 215 ± 18 | 0.10 | 1195.1 ± 8.3 | 0.14 | 0.71 | 1193 ± 16 | 0.37 | 0.98 | 1217 ± 15 | 225 ± 17 | 1.40 | | 1195.1 ± 8.3 |
| Highlands | | | | | | | | | | | | | | |
| 3. Hulls Falls #1 | 1180 ± 14 | 215 ± 100 | 0.31 | | | | 1178 ± 12 | 0.26 | 1.00 | | | | | 1178 ± 12 |
| 4. Hulls Falls #2 | 1222 ± 15 | 256 ± 50 | 0.85 | | | | 1222 ± 12 | 1.09 | 0.36 | | | | | 1222 ± 12 |
| 5. Batchellerville | 1054 ± 110 | 246 ± 27 | 1.40 | | | | | | | 1090 ± 28 | | 0.00 | SP | 1090 ± 28 |
| 6. Scott's Farm | 1063 ± 19 | 335 ± 280 | 0.19 | 1064.0 ± 6.5 | 0.12 | 0.73 | 1062 ± 14 | 0.21 | 1.00 | | | | | 1062 ± 14 |
| 7. Sugar Hill | 1037 ± 31 | –621 ± 3700 | 0.20 | 1021.7 ± 5.4 | 10.30 | 0.00 | 1048 ± 14 | 0.23 | 1.00 | 1052 ± 18 | 250 ± 50 | 0.20 | F | 1048 ± 14 |
| 8. Roe's Spar Bed | 1042 ± 42 | 248 ± 650 | 0.09 | | | | 1030.7 ± 9.9 | 0.11 | 1.00 | 1042 ± 13 | 250 ± 50 | 0.08 | F | 1030.7 ± 9.9 |
| 9. Mineville OBM | 1148 ± 450 | 807 ± 470 | 1.80 | 981.6 ± 2.5 | 30.00 | 0.00 | 1013 ± 10 | 0.31 | 1.00 | 1022.4 ± 13 | 250 ± 50 | 0.98 | F | 1022.4 ± 13 |
| 10. Mineville BH-1 | 873 ± 1300 | 649 ± 5500 | 0.15 | 949 ± 10 | 0.15 | 0.23 | 939 ± 18 | 0.15 | 0.99 | | | | | 949 ± 10 |
| 11. Mineville BH-2 | 1022 ± 130 | 605 ± 2100 | 0.06 | 1039 ± 11 | 0.13 | 0.71 | 1034 ± 29 | 0.08 | 1.00 | | | | | 1039 ± 11 |
| 12. Crown Point | 1023 ± 23 | 126 ± 1100 | 0.07 | 1024.8 ± 2.8 | 0.07 | 0.79 | 1022 ± 18 | 0.07 | 1.00 | | | | | 1024.8 ± 2.8 |
| 13. Lewis | 995 ± 3.4 | 553 ± 860 | 0.17 | 1003.0 ± 5.2 | 0.39 | 0.53 | 991 ± 12 | 0.31 | 1.00 | | | | | 1003.0 ± 5.2 |
| 14. Mayfield | 986 ± 53 | 137 ± 46 | 0.14 | | | | | | | 1009 ± 22 | 0.094 | 0.76 | SP | 1009 ± 22 |

*Note:* All data include inherited spots of 1271–1312 Ma. SP—single point; F—forced intercept; OBM—Old Bed Mine; BH—Barton Hill Mine; MSWD—mean square of weighted deviates.

metasedimentary rocks from the northwestern Adirondacks close to the Lowlands (Scott's Farm), the periphery of the Marcy anorthosite (Hulls Falls), southern (Mayfield, Batchellerville, and Day) and eastern side (Roe's Spar Bed, Crown Point, and Sugar Hill) of the Adirondack Highlands, a small pegmatite body intruded into the wollastonite skarn at the Lewis Quarry, and from a dike cutting the Lyon Mountain granite in the Mineville mining district (Figs. 2 and 3). Additionally, we analyzed a zircon from a coarse-grained pegmatitic segregation containing feldspar-quartz-magnetite-apatite from the Old Bed Mine from Mineville.

## MINERALOGY AND SYSTEMATICS

The pegmatites found in the metamorphic rocks of the Adirondack Mountains have a simple to complex mineral composition. The pegmatites from the Lowlands do not show compositional zoning; however, this is a common feature for the pegmatites from the southern and eastern Highlands, excepting the Sugar Hill and Barton Hill pegmatites.

The most used pegmatite classification today is based on the depth of emplacement, metamorphic grade, and minor element content (Cerny, 1991). Most of the pegmatites of the Adirondack Mountains fit into Cerny's rare-element class (low temperature and low pressure), NYF-type (niobium-yttrium-fluorine), but also into his abyssal (low- to high-pressure granulite-facies) to muscovite (high-pressure kyanite-sillimanite Barrovian amphibolite-facies) classes. These three categories partially overlap in mineral composition but differ by their relation to granitic bodies. Some minerals such as fluoro-edenite, fluorian tremolite, and titanite found in the McLear pegmatite hinder classification of this pegmatite using this schema. Because the dominant mineral is microcline, we consider that the best classification is probably the abyssal class of potassium feldspar type; the Rossie and Sugar Hill pegmatites could be other candidates for this class. The McLear and Rossie pegmatites were emplaced into the Lower Marble Formation of the Lowlands, where the metamorphism reached the upper amphibolite facies. The presence of the Ca- and F-dominant and/or -rich amphiboles and diopside probably could be explained through the contamination of the pegmatitic fluid with elements derived from the siliceous marble host.

Some pegmatites from the southern Adirondack Highlands (Batchellerville, Mayfield, and Greenfield) contain Al-rich silicates with or without Be and B such as sillimanite, beryl, chrysoberyl, dumortierite, and tourmaline as well as monazite-Ce and uraninite. The Batchellerville

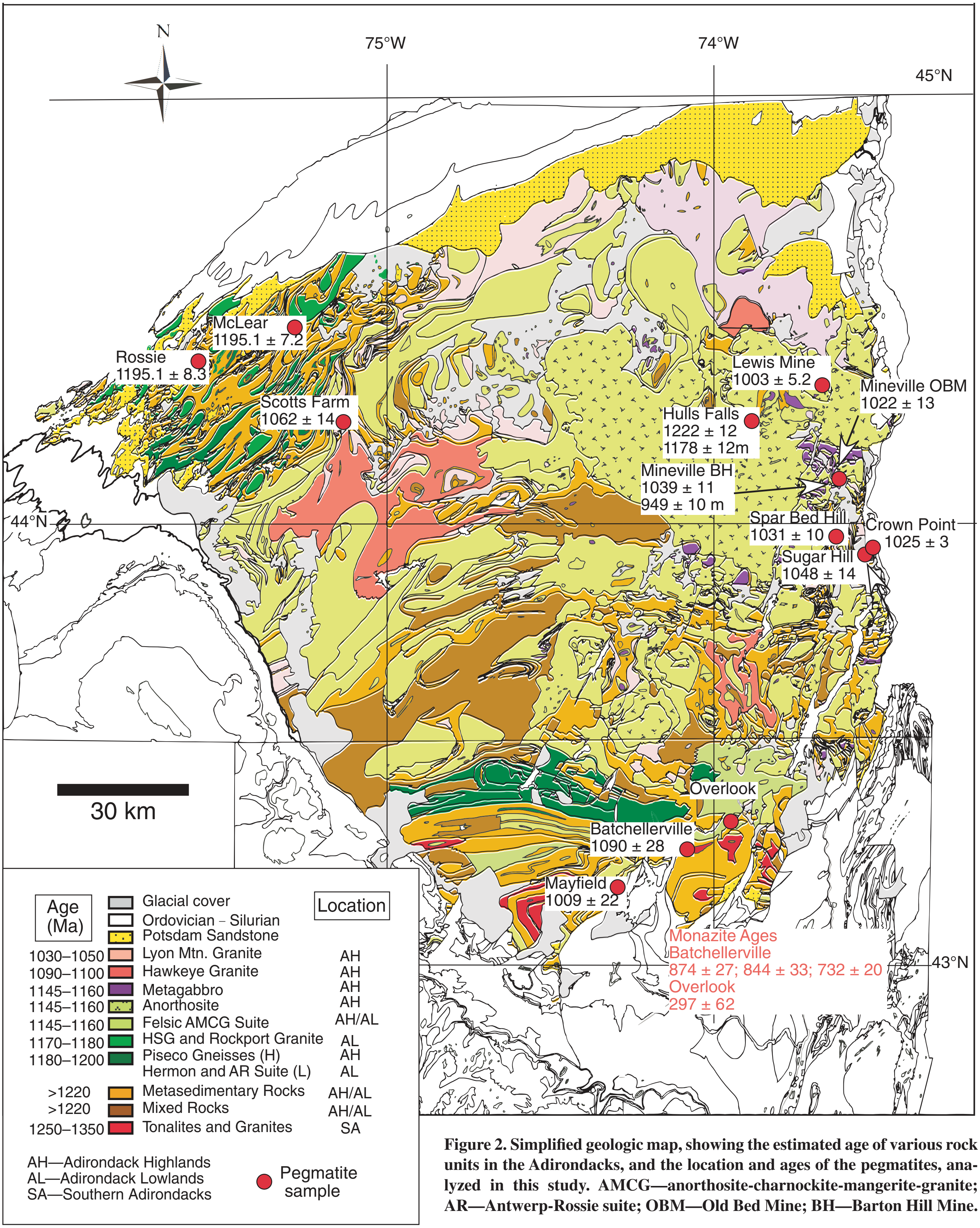

**Figure 2.** Simplified geologic map, showing the estimated age of various rock units in the Adirondacks, and the location and ages of the pegmatites, analyzed in this study. AMCG—anorthosite-charnockite-mangerite-granite; AR—Antwerp-Rossie suite; OBM—Old Bed Mine; BH—Barton Hill Mine.

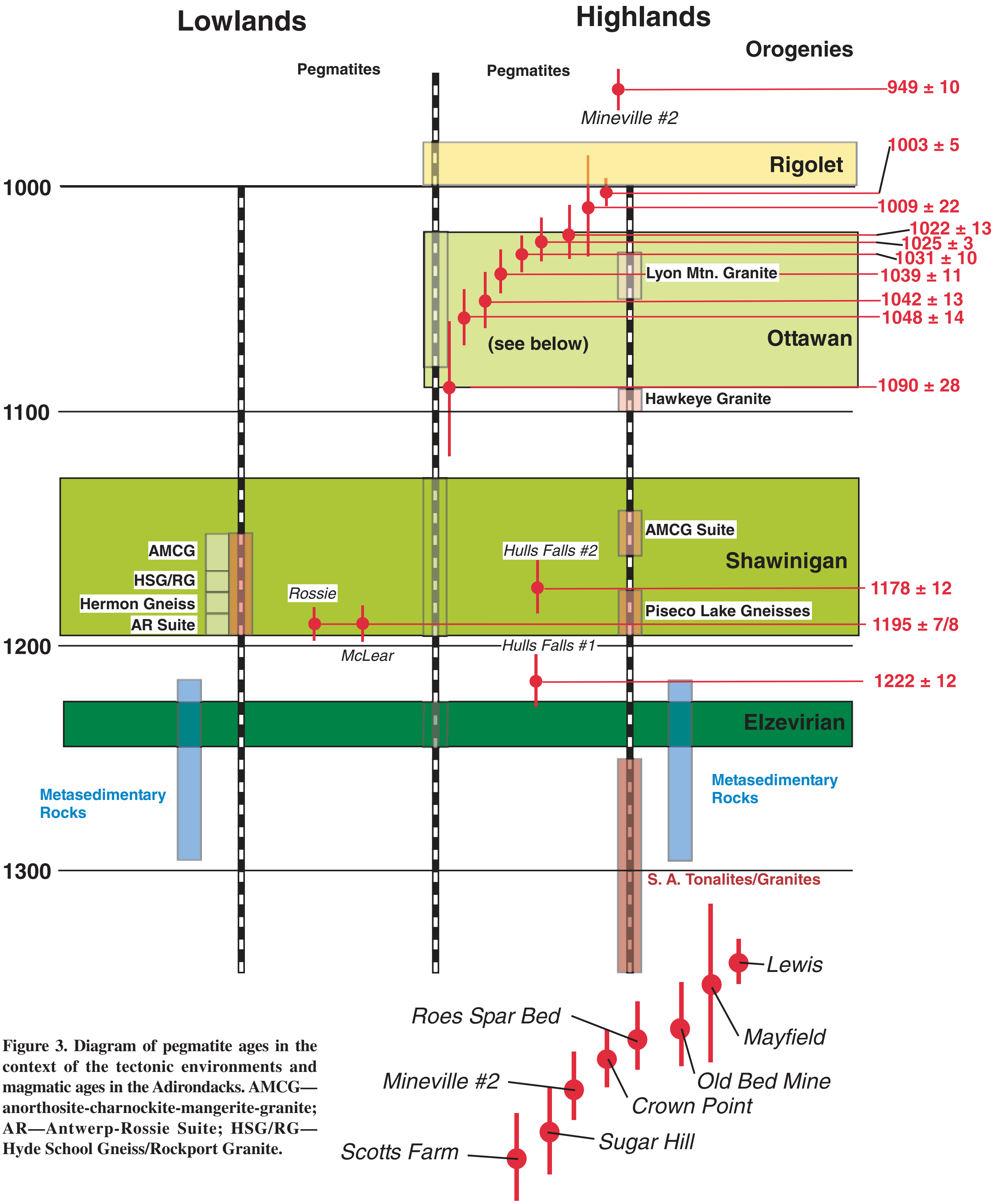

**Figure 3.** Diagram of pegmatite ages in the context of the tectonic environments and magmatic ages in the Adirondacks. AMCG—anorthosite-charnockite-mangerite-granite; AR—Antwerp-Rossie Suite; HSG/RG—Hyde School Gneiss/Rockport Granite.

and Mayfield pegmatites are clusters of small bodies; the Greenfield pegmatite is a singular small body. They have the characteristics of Cerny's muscovite class and could be of anatectic origin.

According to their mineral composition (allanite-Ce, polycrase-Y, titanite, zircon, fluorite, microcline, and albite), the Scott's Farm, Crown Point, Roe's Spar Bed, Day (Overlook), and Lewis pegmatites could be part of the rare-earth element (REE) class, NYF-type. The pegmatites from the Crown Point are related to the A-type Lyon Mountain granite that has abundant occurrences in this area.

## METHODS

### U-Th-Pb geochronology by LA-MC-ICPMS

U-Pb geochronology of zircons was conducted by laser ablation–multicollector–inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the Arizona LaserChron Center. The analyses involve ablation of zircon with New Wave/Lambda Physik DUV193 Excimer laser (operating at a wavelength of 193 nm) using spot diameters of 25 and 35 microns. The ablated material is carried with helium gas into the plasma source of a GV Instruments Isoprobe, which is equipped with a flight tube of sufficient width that U, Th, and Pb isotopes are measured simultaneously. All measurements are made in static mode, using Faraday detectors for $^{238}$U and $^{232}$Th, an ion-counting channel for $^{204}$Pb, and either Faraday collectors or ion-counting channels for $^{208-206}$Pb. Ion yields are ~1 mv per ppm. Each analysis consists of one 12-second integration on peaks with the laser off (for backgrounds), 12 one-second integrations with the laser firing, and a 30-second delay to purge the previous sample and prepare for the next analysis. The ablation pit is ~12 microns in depth.

For each analysis, the errors in determining $^{206}$Pb/$^{238}$U and $^{206}$Pb/$^{204}$Pb result in a measurement error of ~1% (at 2σ level) in the $^{206}$Pb/$^{238}$U age. The errors in measurement of $^{206}$Pb/$^{207}$Pb and $^{206}$Pb/$^{204}$Pb also result in ~1% (2σ) uncertainty in age for grains that are >1.0 Ga, but they are substantially larger for younger grains due to the low intensity of the $^{207}$Pb signal. For most analyses, the crossover in precision of $^{206}$Pb/$^{238}$U and $^{206}$Pb/$^{207}$Pb ages occurs at ca. 1.0 Ga.

Common Pb correction is accomplished by using the measured $^{204}$Pb and assuming an initial Pb composition from Stacey and Kramers (1975) (with uncertainties of 1.0 for $^{206}$Pb/$^{204}$Pb and 0.3 for $^{207}$Pb/$^{204}$Pb). The measurement of $^{204}$Pb is unaffected by the presence of $^{204}$Hg because backgrounds are measured on peaks (thereby subtracting any background $^{204}$Hg and $^{204}$Pb), and because very little Hg is present in the argon gas.

Interelement fractionation of Pb/U is generally ~20%, whereas apparent fractionation of Pb isotopes is generally <2%. In-run analysis of fragments of a large zircon crystal (generally every fifth measurement) with known age of 564 ± 4 Ma (2σ error) is used to correct for this fractionation. The uncertainty resulting from the calibration correction is generally ~1% (2σ) for both $^{206}$Pb/$^{207}$Pb and $^{206}$Pb/$^{238}$U ages. The analytical data are reported in the Supplemental Table File[1]. Uncertainties shown in these tables are at the 1σ level, and include only measurement errors. The analyses are also shown on Pb/U concordia diagrams (Figs. 4, 5, and 6).

The reported ages are determined using Isoplot (Ludwig, 2008) either from: (1) the upper intercept on the concordia diagram; (2) weighted mean of the $^{206}$Pb/$^{238}$U or $^{206}$Pb/$^{207}$Pb ages of the concordant and overlapping analyses; or (3) the $^{206}$Pb/$^{207}$Pb age of a concordant analysis. The first method is used when discordant points define a linear array on the concordia diagram. The second method is used for sets of overlapping concordant analyses. The third method is used for metamict zircons with mostly highly discordant analyses, if a concordant analysis was measured.

Concordia diagrams (Figs. 4, 5, and 6) show two sigma uncertainties. The smaller uncertainty (labeled mean) is based on the scatter and precision of the set of $^{206}$Pb/$^{238}$U or $^{206}$Pb/$^{207}$Pb ages, weighted according to their measurement errors (shown at 2σ). The larger uncertainty (labeled age), which is the reported uncertainty of the age, is determined as the quadratic sum of the weighted mean error plus the total systematic error for the set of analyses. The systematic error, which includes contributions from the standard calibration, age of the calibration standard, composition of common Pb, and U decay constants, is generally ~1%–2% (2σ).

### U-Pb Monazite Geochronology by EMPA

Electron microprobe analysis (EMPA) of two selected monazite crystals used the Cameca SX100 housed within the Department of Earth and Environmental Sciences at Rensselaer Polytechnic Institute. Chemical dating closely followed the procedures outlined in Spear et al. (2009), an exhaustive study of monazite dating techniques conducted on the very same instrument. This fortunately meant that we could employ the individual spectrometer corrections presented in the paper to our analysis. Furthermore, we could use the primary subject of that study, the "Moacyr" monazite crystal (Seydoux-Guillaume et al., 2002), for an internal standard. This permitted us to verify our analytical routine, monitor drift over time, and directly compare our age dates with well-characterized values.

In order to correctly calculate the concentrations of U, Th, and Pb, it is advantageous to determine the composition of the monazite to be dated. We did so using EMPA, with a 15 keV accelerating voltage applied over a minimized spot (2–3 μm) at 40 nA. Along with the internal standard, we analyzed two crystals from Adirondack pegmatites, one crystal from the Day (Overlook) pegmatite, and the three distinct zones (bulk, gray, and fracture) within a crystal from the Batchellerville pegmatite grain, for Th, P, Na, La, Si, Sr, Ce, Nd, Fe, Y, Ca, Pr, Gd, and Sm, using a combination of U.S. National Museum of Natural History (Smithsonian Institution), Harvard University, and synthetic standards, including a suite of Pb-free, REE phosphates (Cherniak et al., 2004). We used the correction protocol within Cameca's *Peaksight* program to remove the interferences from La and Ce on the heavier REEs. Intensities were corrected using *X-Phi*, a Phi-Rho-Z process (Merlet, 1994) incorporated into *Peaksight*. Because of the interferences amongst X-ray lines from the lanthanides, analyzing REE with the EMPA is not ideal, and we hoped merely to achieve "ball-park" figures needed to strengthen monazite-dating element corrections. However, we found that our analytical routine produced concentrations for Moacyr that matched those reported in the literature (Spear et al., 2009).

We separately analyzed U, Th, and Y on the Day crystal and the three Bachellerville zones using a 15 keV, 200 nA beam applied to a minimized spot employing the same pulse height analysis (PHA) and background settings recorded in Spear et al. (2009). We standardized by applying a 20 nA current to synthetic $UO_2$, $ThSiO_4$, and $YPO_4$ standards (Pyle et al., 2005). The resulting intensities were corrected using *X-Phi* on Y-U-Th-Pb and the elemental components listed in the preceding paragraph. The calculated Pb concentrations determined from each spectrometer were then corrected using the values in Spear et al. (2009).

The ages were calculated from these corrected values. Spear et al. (2009) recognized that assessment errors on each spectrometer typically result in disparate ages that exceed those predicted by counting statistics. In recognition of this, in Tables 2 and 15 in the Supplemental Table File (see footnote 1), we report ages as

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[1] Supplemental Table File. PDF file of Tables 3–15, which provide U-Th-Pb LA-MC-ICPMS analyses and data. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00596.S1 or the full-text article on www.gsapubs.org to view the Supplemental Table File.

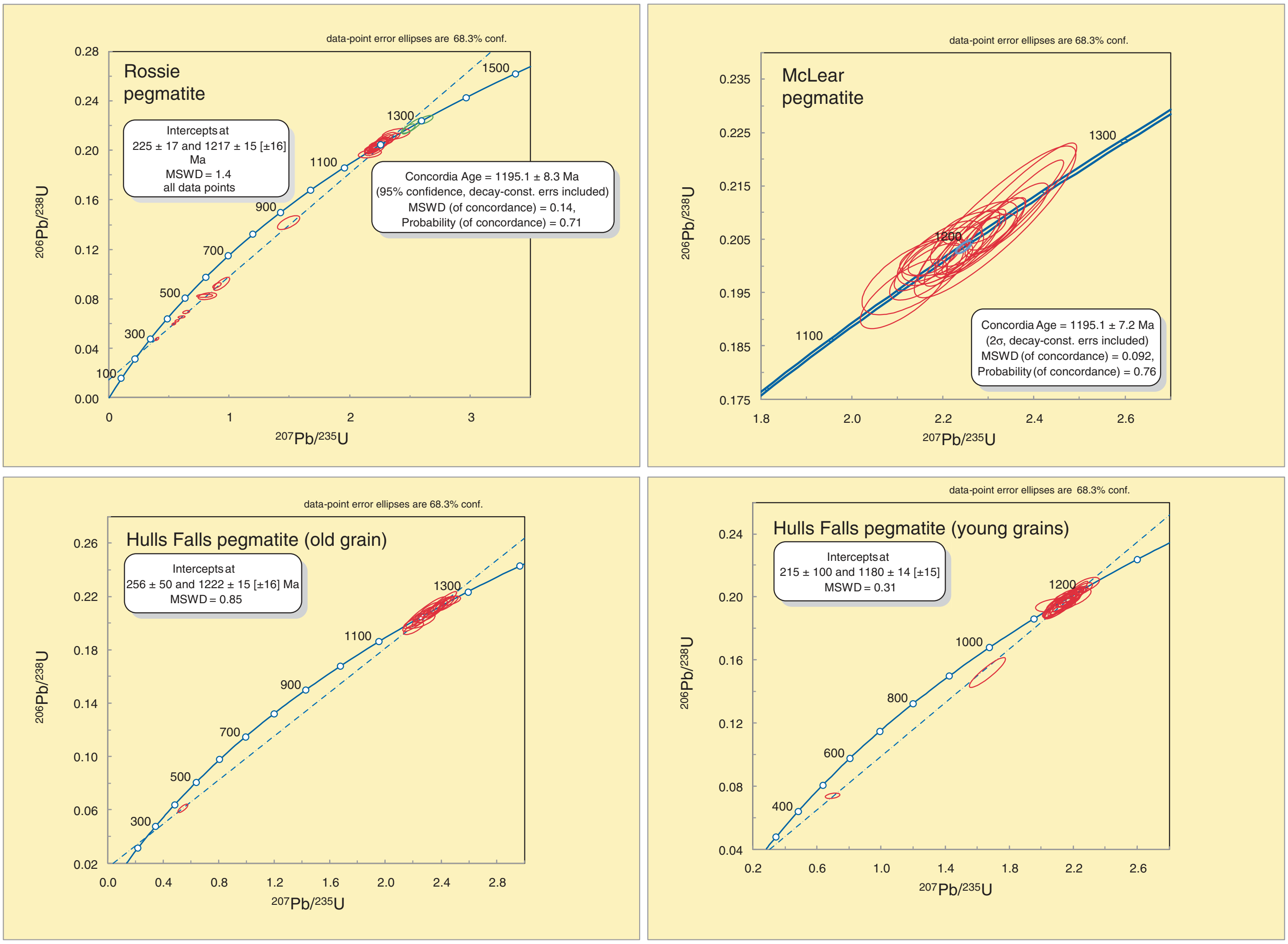

**Figure 4. Concordia diagrams for the McLear, Rossie, and Hulls Falls pegmatites. MSWD—mean square of weighted deviates.**

determined by the Pb counts acquired on each spectrometer. We use the average of these individual spectrometer ages as our estimate of the monazite crystallization age. We also report the statistical deviation of the population of points on each crystal or crystal domain for each spectrometer as an indicator of sample heterogeneity: low standard deviation (S.D.) measured for a population of spectrometer ages suggests sample homogeneity. We additionally report the standard deviation of the Poisson distribution (S.D. Poisson) based on the peak and background counts as an indication of measurement robustness for each point. For example, the relatively high S.D. Poisson seen on age estimates for the Day (Overlook) crystal results from difficulties in accurately assessing U on each point, given its low concentration. Finally, the error on the monazite crystallization age is taken to be the larger of either the standard deviation of the individual spectrometer ages (column S.D.) or the S.D. measured of the average ages of the population, because the greatest error in assessing crystallization age results from either spectrometer irregularities or sample heterogeneity.

## RESULTS

### Zircon Geochronology

A summary of the U-Th-Pb zircon ages is presented in Table 1 and Figures 7, 8, and 9. The complete set of isotopic data is available in Tables 4–15 in Supplemental Table 1 [see footnote 1]). Figures 7, 8, and 9 show scanning electron microscope images of each sample analyzed captured in backscattered electron (BSE) mode. On these photos, ablation pits are visible, and derived ages are shown. Two samples from the Lowlands have almost complete metamict zircons (Cream of the Valley and Natural Bridge in Fig. 9), and the data are not reported in this paper.

#### *Lowlands*

***McLear pegmatite (N 41°27′32.4″; W 75°18′39.6″).*** A single large (5.1-mm-long), dipyramidal, euhedral, pink, clear grain from the McLear pegmatite was analyzed. The areas analyzed contained between 324 and 874 ppm uranium and had a mean U/Th ratio of 9.5. The mean $^{206}$Pb/$^{204}$Pb ratio was 61,461. Twenty analyses, 35 microns in diameter, yielded concordant (98.4%–102.2%) analyses. The $^{206}$Pb/$^{207}$Pb ages ranged from 1153 ± 53 to 1230 ± 25 Ma. In general, a traverse across the width of the center of the grain yielded the oldest ages. Because of the highly concordant nature of all of the grains, a lower intercept was forced through 215 Ma (lower intercept of the Rossie pegmatite discussed below). This yielded an upper intercept age of 1217 ± 15 Ma with a mean square of weighted deviates (MSWD) of 1. Without anchoring of the lower intercept, the upper intercept age is 1396 ± 820 Ma and the

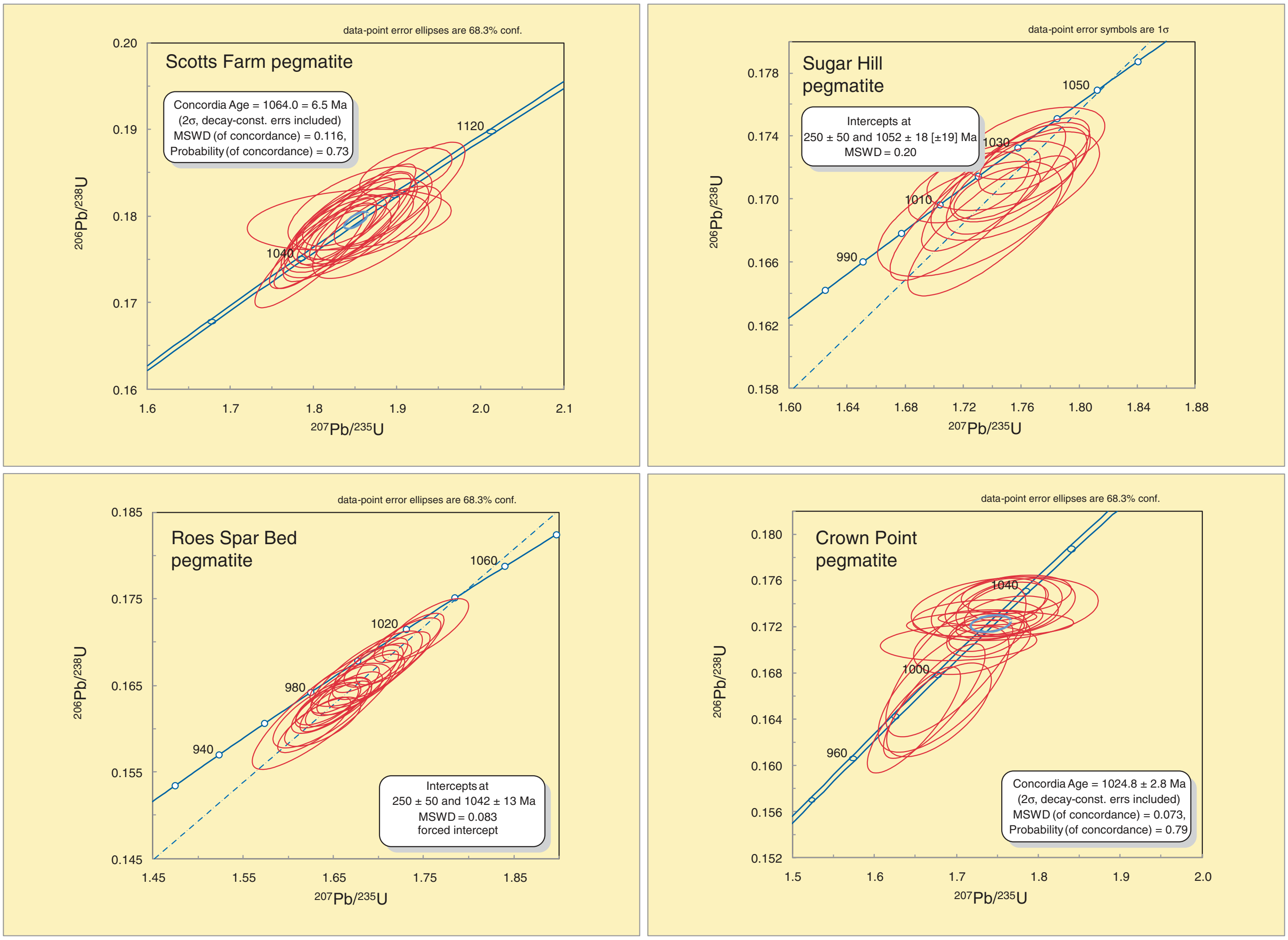

**Figure 5. Concordia diagrams for the Scotts Farm, Sugar Hill, Roe's Spar Bed, and Crown Point pegmatites. MSWD—mean square of weighted deviates.**

lower intercept age is 1216 ± 100 Ma. The calculated weighted mean $^{206}Pb/^{207}Pb$ age is 1198 ± 13 Ma with a MSWD of 0.78. A concordant age of 1195.1 ± 7.2 Ma with a MSWD of 0.09 was also obtained and is interpreted to be the crystallization for this sample because most points lie on concordia (Fig. 4).

***Rossie pegmatite (N 43°21′11.4″; W 75°42′05.7″).*** Two large (up to 3.10-mm-long), dipyramidal, euhedral, brown, opaque grains from the Rossie pegmatite were analyzed. The areas analyzed contained between 880 and 4338 ppm uranium and had a mean U/Th ratio of 27. The mean $^{206}Pb/^{204}Pb$ ratio was 73,021. Twenty eight analyses, 35 microns in diameter, yielded a range of concordancy (48.5% to 102.0%). The $^{206}Pb/^{207}Pb$ ages ranged from 620 ± 51 to 1312 ± 23 Ma. Three distinctly older ages, 1271, 1278, and 1312 Ma, occurred in the approximate center of both crystals. Regression of all the analyses yields an upper intercept age of 1217 ± 15 Ma, a lower intercept of 225 ± 17 Ma, and a MSWD of 1.4. However, if the three older, likely inherited, ages are excluded, an upper intercept age of 1185.1 ± 19 Ma, a lower intercept of 215 ± 18 Ma, and a MSWD of 0.10 is obtained. The calculated weighted mean age of the concordant analyses (excluding the three inherited analyses) was 1193 ± 16 Ma with a MSWD of 0.98. A concordant age of 1195.1 ± 8.3 Ma with a MSWD of 0.71 was also obtained and is interpreted as the crystallization age of the pegmatite (Fig. 4).

### *Highlands*

***Hulls Falls pegmatite (N 44°13′58.5″: W 73°47′44.7″).*** Five large (up to 2.05-mm-long), sub-anhedral, fractured, light brown, clear grains from the Hulls Falls pegmatite were analyzed. The areas analyzed contained between 308 and 1287 ppm uranium and had a mean U/Th ratio of 5.6. The mean $^{206}Pb/^{204}Pb$ ratio was 38,682. Twenty-four analyses, 25 microns in diameter, yielded a range of concordancy (77.3% to 102.1%); however, 23 analyses were between 96.0% and 102.1% concordant. With the exception of two highly discordant analyses, the $^{206}Pb/^{207}Pb$ ages ranged from 1140 ± 72 to 1203 ± 46 Ma. An upper intercept age of 1180 ± 14 with a lower intercept of 215 ± 100 Ma and a MSWD of 0.31 was obtained. The calculated weighted mean age of the concordant analyses was 1178 ± 12 Ma with a MSWD of 0.26. Both the upper intercept age and the weighted mean age overlap given the analytical uncertainty. The crystallization age of the zircon is interpreted to be 1178 ± 12 Ma, as determined by the weighted mean age of the concordant zircon fractions (Fig. 4).

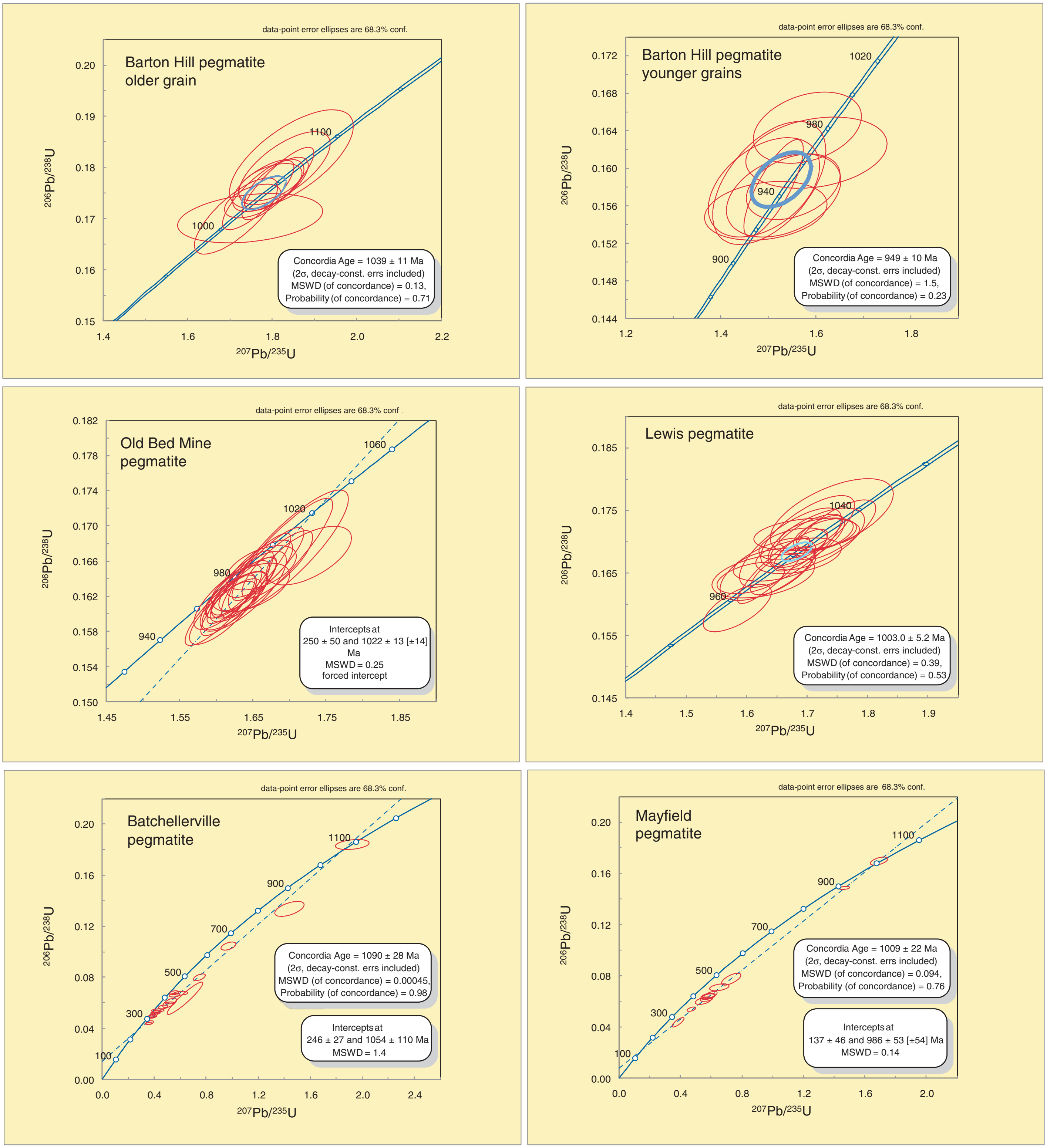

**Figure 6. Concordia diagrams for the Barton Hill, Old Bed Mine, Lewis, Batchellerville, and Mayfield pegmatites. MSWD—mean square of weighted deviates.**

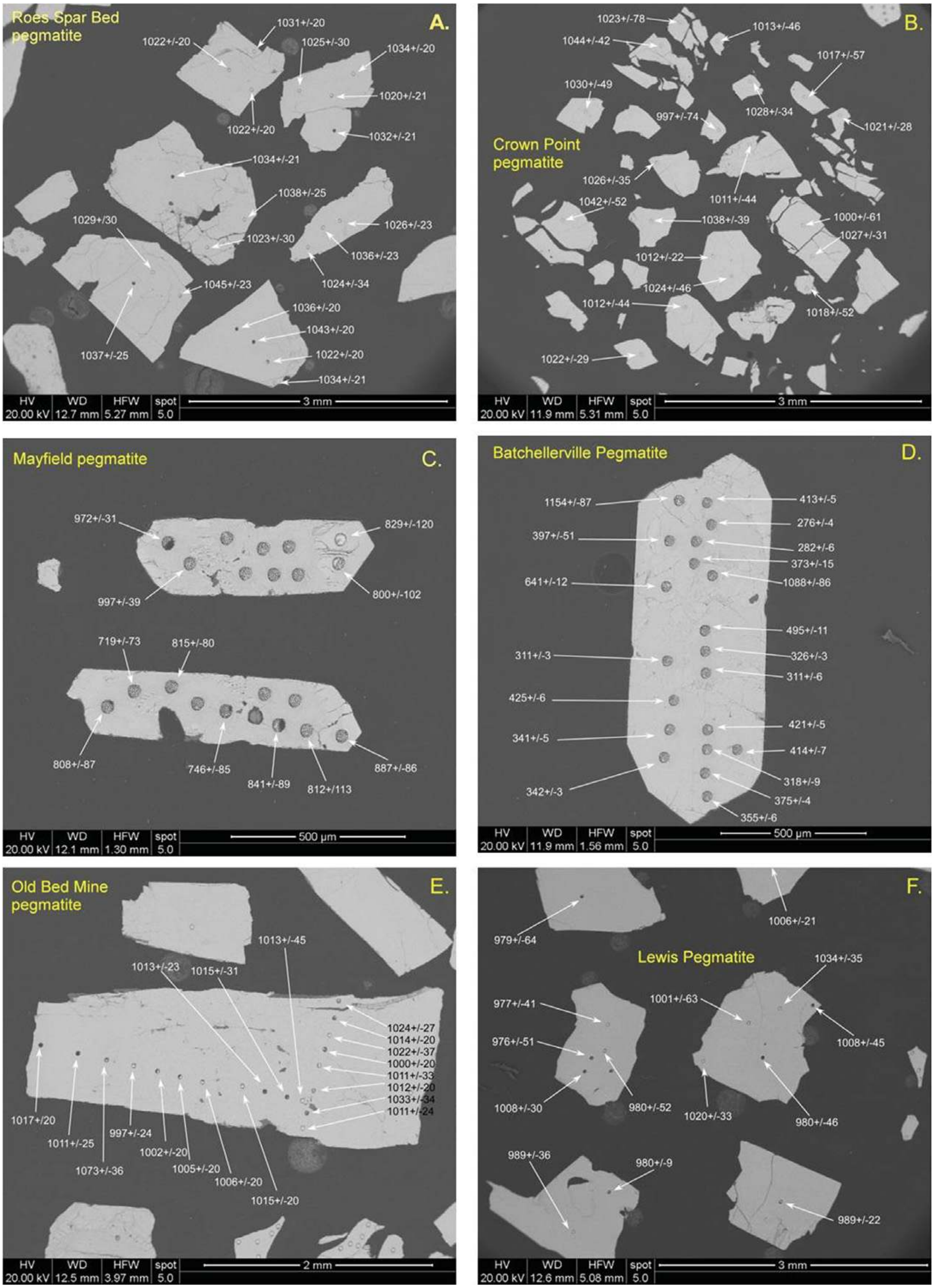

**Figure 7. Photographic plate showing backscatter electron photographs of zircons from pegmatite samples, ablation pits, and ages: (A) Roe's Spar Bed; (B) Crown Point; (C) Mayfield; (D) Batchellerville; (E) Old Bed Mine; and (F) Lewis.**

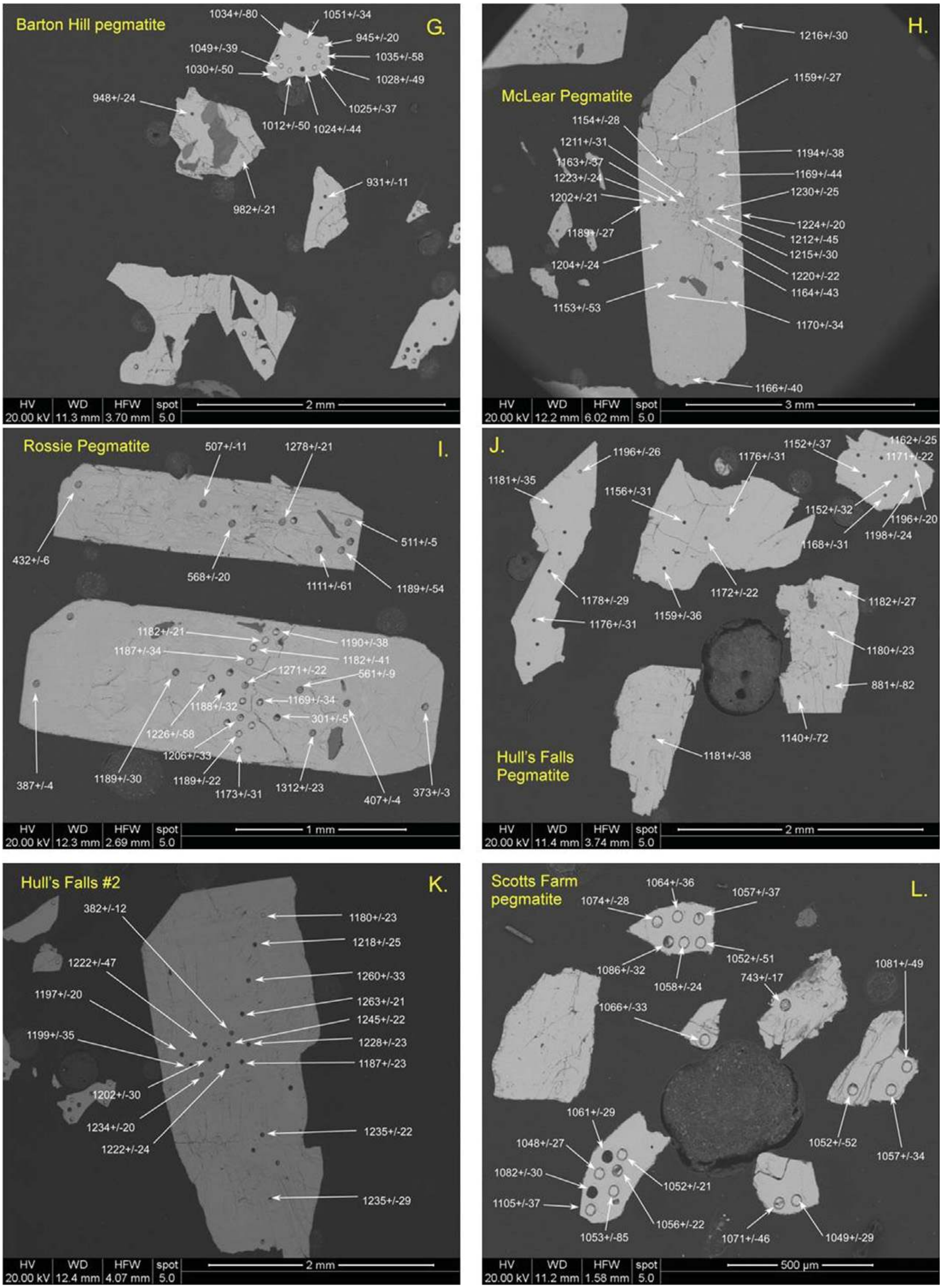

**Figure 8. Photographic plate showing backscatter electron photographs of zircons from pegmatite samples, ablation pits, and ages: (G) Barton Hill; (H) McLear; (I) Rossie; (J) Hulls Falls; (K) Hulls Falls pop. #2; and (L) Scott's Farm.**

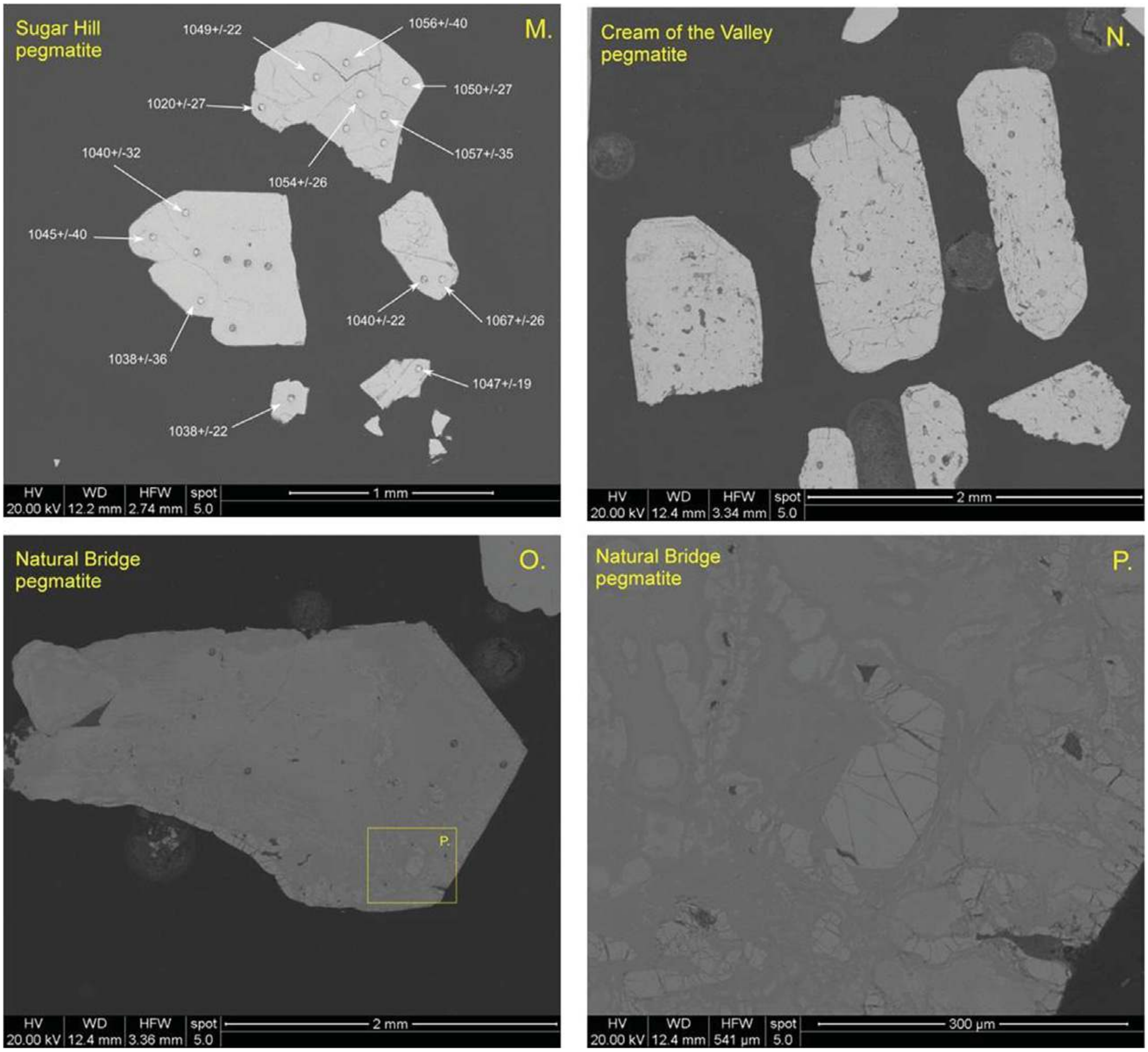

**Figure 9. Photographic plate showing backscatter electron photographs of zircons from pegmatite samples, ablation pits, and ages: (M) Sugar Hill; (N) Cream of the Valley; (O) Natural Bridge; and (P) closeup of Natural Bridge showing metamict regions.**

In addition, a single large (4.5-mm-long), euhedral fractured, dark to light brown grain from the Hulls Falls pegmatite was analyzed. The areas analyzed contained between 901 and 1821 ppm uranium and a mean U/Th ratio of 6.9. The mean $^{206}$Pb/$^{204}$Pb ratio was 45,403. Sixteen analyses, 35 microns in diameter, yield a range of concordancy (51.4% to 101.7%); however, 14 analyses were between 96.6% and 101.7% concordant. With the exception of two discordant analyses, the $^{206}$Pb/$^{207}$Pb ages ranged from 1180 ± 23 to 1263 ± 21 Ma. An upper intercept age of 1222 ± 15 Ma with a lower intercept of 256 ± 50 Ma and a MSWD of 0.85 was obtained. The calculated weighted mean age of the concordant analyses was 1222 ± 12 Ma with a MSWD of 1.09. The age of the upper intercept and the weighted mean age are identical. The crystallization age of the zircon is interpreted to be 1222 ± 12 Ma, as determined by the weighted mean age of the concordant zircon fractions (Fig. 4).

If all the analyses are plotted on a concordia plot, they yield an upper intercept age of 1198 ± 11 Ma, a lower intercept of 273 ± 73 Ma, and a MSWD of 3.6. However, we believe that there are two separate populations of zircon, ~2 mm sub-anhedral grains of 1178 ± 12 and ~4.5 mm euhedral grains of 1222 ± 12 that occur in this pegmatite sample.

***Batchellerville pegmatite (N 43°14′21.2″; W 74°3′34.3″).*** One large (1.50-mm-long), dipyramidal, euhedral, light green, transparent grain from the Batchellerville pegmatite was analyzed. The areas analyzed contained between 1562 and 5204 ppm uranium and had a mean U/Th ratio of 158. The mean $^{206}$Pb/$^{204}$Pb ratio was 16,449. Twenty analyses, 35 microns in diameter, yielded a range of concordancy (39.5% to 100.2%); however, only a single analysis was concordant (100.2%). The $^{206}$Pb/$^{207}$Pb ages ranged from 475 ± 120 to 1154 ± 87 Ma. The oldest $^{206}$Pb/$^{207}$Pb age of 1154 Ma is 70% concordant and is likely inherited. This sample yielded an upper intercept age of 1054 ± 110 Ma, a lower intercept of 246 ± 27 Ma, and a MSWD of 1.4. The crystallization age of the zircon is interpreted to be 1090 ± 28 Ma from the approximate center of the crystal, as determined by the single concordant analysis, which is within analytical error of the concordia upper intercept age (Fig. 6). Given the numerous discordant analyses, the high U content (up to 5204 ppm), and very high U/Th ratios (up to 189), this crystal is likely nearly entirely metamict.

***Scott's Farm pegmatite (N 44°13′36.2″; W 75°06′09.9″).*** Six large (up to 0.5-mm-long), sub-anhedral, fractured, light brown, clear grains from the Scott's Farm pegmatite were analyzed. The areas analyzed contained between 189 and 1525 ppm uranium and had a mean U/Th ratio of 2.9. The mean $^{206}Pb/^{204}Pb$ ratio was 37,541. Twenty analyses, 35 microns in diameter, yielded a range of concordancy (78.5% to 101.5%); however, 19 analyses were between 96.0% and 102.1% concordant. With the exception of one discordant analysis, the $^{206}Pb/^{207}Pb$ ages ranged from 1052 ± 25 to 1105 ± 37 Ma. This sample yielded an upper intercept age of 1063 ± 19 Ma, a lower intercept of 335 ± 280 Ma, and a MSWD of 0.19. The calculated weighted mean age of the concordant analyses was 1062 ± 14 Ma with a MSWD of 0.21. The concordant age was 1064.0 ± 6.5 with a MSWD of 0.12. Because all ages overlap, the crystallization age of the zircon is interpreted to be 1062 ± 14 Ma, as determined by the weighted mean age (Fig. 5).

***Sugar Hill pegmatite (N 43°9′37″; W 73°42′00″).*** Five large (up to 1.05-mm-long), eu-subhedral, fractured, dark brown, opaque grains from the Sugar Hill pegmatite were analyzed. The areas analyzed contained between 1055 and 1850 ppm uranium and had a mean U/Th ratio of 6.3. The mean $^{206}Pb/^{204}Pb$ ratio was 192,319, indicating very low concentrations of common Pb. Thirteen analyses, 35 microns in diameter, yielded a limited range of concordancy (94.0% to 99.6%). With the exception of one discordant analysis, the $^{206}Pb/^{207}Pb$ ages ranged from 1020 ± 27 to 1067 ± 26 Ma. This sample yielded an upper intercept age of 1037 ± 31 Ma, with a lower intercept of –621 ± 3700 Ma, and a MSWD of 0.2. If a 250 Ma lower intercept is forced, an upper intercept age of 1052 ± 18 with a MSWD of 0.20 is calculated. The calculated weighted mean age of the concordant analyses was 1048 ± 14 Ma with a MSWD of 0.23. The concordant age was 1021.7 ± 5.4 with a MSWD of 10.3, because none of the grains were concordant. Both the upper intercept age and the weighted mean age overlap given the analytical uncertainty. The crystallization age of the zircon is interpreted to be 1048 ± 14 Ma, as determined by the weighted mean age (Fig. 5).

***Roe's Spar Bed pegmatite (N 43°58′56.5″; W 73°32′22.1″).*** Seven large (up to 1.85-mm-long), subhedral, fractured, pink, clear grains from the Roe's Spar Bed pegmatite were analyzed. The areas analyzed contained between 371 and 850 ppm uranium and had a mean U/Th ratio of 5.2. The mean $^{206}Pb/^{204}Pb$ ratio was 41,472. Twenty analyses, 35 microns in diameter, yielded a limited range of concordancy (92.6% to 97.8%). The $^{206}Pb/^{207}Pb$ ages ranged from 1020 ± 21 to 1045 ± 23 Ma. This sample yielded an upper intercept age of 1042 ± 42 Ma, with a lower intercept of 248 ± 650 Ma, and a MSWD of 0. 09. The calculated weighted mean age of the concordant analyses was 1030.7 ± 9.9 Ma with a MSWD of 0.11. The crystallization age of the zircon is interpreted to be 1030.7 ± 9.9 Ma, as determined by the weighted mean age (Fig. 5).

***Mineville, Old Bed pegmatite segregation (N 44°05′22.5″; W 73°31′30.5″).*** A single large (up to 3.50-mm-long), subhedral, fractured, rectangular brown, opaque grain from a pegmatite segregation in the magnetite-apatite ore from the Old Bed Mine was analyzed. The areas analyzed contained between 1008 and 1683 ppm uranium and had a mean U/Th ratio of 8.1. The mean $^{206}Pb/^{204}Pb$ ratio was 71,589. Twenty-one analyses, 35 microns in diameter, yielded a limited range of concordancy (92.6% to 97.5%). The $^{207}Pb/^{206}Pb$ ages ranged from 997 ± 24 to 1073 ± 36 Ma. This sample yielded an upper intercept age of 1148 ± 450 Ma, with a lower intercept of 807 ± 470 Ma, and a MSWD of 1.80. If forced through a lower intercept of 250 ± 50 Ma, an age of 1022.4 ± 13 Ma with a MSWD of 0.98 is obtained. The calculated weighted mean age of the concordant analyses was 1013 ± 10 Ma with a MSWD of 0.31. The crystallization age of the zircon is interpreted to be 1022.4 ± 13 Ma, as determined by the upper intercept of the concordia diagram when anchored to 250 Ma (Fig. 6).

***Mineville, Barton Hill Mine pegmatite (N 44°05′34.5″; W 73°32′05.2″).*** Four large (up to 1.65-mm-long), anhedral, fractured, light brown, transparent grains from the Barton Hill Mine pegmatite were analyzed. The areas analyzed contained between 29 and 81 ppm uranium and had a mean U/Th ratio of 6.2. The mean $^{206}Pb/^{204}Pb$ ratio was 4432, likely a reflection of the relatively low uranium and radiogenic lead content. Eighteen analyses, 35 microns (n = 15) and 25 microns (n = 3) in diameter, yielded a range of concordancy (95.9% to 107.2%), with two samples slightly reversely discordant. The $^{206}Pb/^{207}Pb$ ages ranged from 911 ± 34 to 1056 ± 125 Ma. Since the majority of the areas analyzed were concordant but had a large range in $^{207}Pb/^{206}Pb$ ages, no upper intercept was calculated on the concordia diagram. The calculated weighted mean age of the concordant analyses was 1034 ± 29 Ma with a MSWD of 0.08. However, two grains with eight analyses yielded a weighted mean age of 939 ± 18 Ma (MSWD = 0.15), and a single grain with ten analyses yielded a weighted mean age of 1034 ± 29 Ma (MSWD = 0.08). Because the ages of the grains do not overlap, it is concluded that two populations exist. Their weighted mean ages agree with the concordant ages of 949 ± 10 and 1039 ± 11 Ma. The crystallization age of the zircon is interpreted to be 1039 ± 11 Ma and 949 ± 10 Ma, as determined by the concordant ages obtained (Fig. 6).

***Crown Point pegmatite (N 43°55′26.5″; W 73°26′20.7″).*** Eighteen large (up to 1.25-mm-long), eu-subhedral, fractured, light brown, transparent grains from the Crown Point pegmatite were analyzed. The areas analyzed contained between 443 and 1187 ppm uranium and had a mean U/Th ratio of 5.7. The mean $^{206}Pb/^{204}Pb$ ratio was 109,350. Twenty analyses, 35 microns in diameter, yielded a limited range of concordancy (94.7% to 102.7%). The $^{206}Pb/^{207}Pb$ ages ranged from 996 ± 74 to 1044 ± 41 Ma. This sample yielded an upper intercept age of 1023 ± 23 Ma, a lower intercept of 126 ± 1100, and a MSWD of 0.07. The calculated weighted mean age of the concordant analyses was 1022 ± 18 Ma with a MSWD of 0.07. A concordant age of 1024.8 ± 2.8 Ma with a MSWD of 0.07 was obtained. All ages overlap, and the crystallization age of the zircon is interpreted to be 1024.8 ± 2.8 Ma, as determined by the upper intercept of the concordia diagram (Fig. 5).

***Lewis Quarry pegmatite (N 41°17′51.2″; W 74°3′56.1″).*** Six large (up to 2.35-mm-long), sub-anhedral, fractured, pink, clear grains from the Lewis pegmatite were analyzed. The areas analyzed contained between 46 and 102 ppm uranium and had a mean U/Th ratio of 2.6. The mean $^{206}Pb/^{204}Pb$ ratio was 5872, likely a reflection of the relatively low uranium and radiogenic lead content. Twenty analyses, 35 microns in diameter, yielded a limited range of concordancy (96.4% to 103.4%). The $^{207}Pb/^{206}Pb$ ages ranged from 976 ± 51 to 1034 ± 35 Ma. This sample yielded an upper intercept age of 995 ± 3.4 Ma, a lower intercept of 553 ± 860, and a MSWD of 0.17. The concordant analyses yielded a weighted mean $^{206}Pb/^{207}Pb$ age of 991 ± 12 Ma (MSWD of 0.31) and a concordant age of 1003.0 ± 5.2 Ma. All three ages overlap, and the crystallization age of the zircon is interpreted to be 1003.0 ± 5.2 Ma, as determined by the concordant age of the zircon (Fig. 6).

***Mayfield pegmatite (N 43°10′23.6″; W 74°15′28.2″).*** Two large (up to 0.85-mm-long), euhedral, dipyramidal, clear grains from the Mayfield pegmatite were analyzed. The areas analyzed contained between 1148 and 4915 ppm uranium and had a mean U/Th ratio of 60.5.

The mean $^{206}$Pb/$^{204}$Pb ratio was 25,665. Eleven analyses, 35 microns in diameter, yielded a wide range of concordancy (36.9% to 101.2%). The $^{206}$Pb/$^{207}$Pb ages ranged from 719 ± 73 to 997 ± 39 Ma. This sample yielded an upper intercept age of 986 ± 53 Ma, with a lower intercept of 137 ± 46 Ma, and a MSWD of 0.14. A single concordant point yields an age of 1009 ± 22 Ma and MSWD of 0.09. The crystallization age of the zircon is interpreted to be 1009 ± 22 Ma, as determined by the age of a single concordant analysis (Fig. 6).

### U-Pb Monazite Ages

A summary of the monazite Y-U-Th-Pb compositions and chemical ages are presented in Table 2. The complete set of point analyses is available in Table 15 in the Supplemental Table File (see footnote 1).

***Batchellerville (N 43°14′21.2″; W 74°3′34.3″).*** Monazite from the Batchellerville (>1 cm in diameter) is cut by fractures that contain tiny thorite grains. While the examined grain yielded a largely homogenous-looking BSE image, there were small regions with distinctly lower BSE intensity (gray patches). Twenty analyses on the main crystal far from fractures and gray patches yielded an average chemical age of 874 ± 27 Ma. Five points on the fracture revealed stronger heterogeneities, but their average age is 751 ± 71 Ma. The darker areas are heterogeneous and yielded ages from 784 to 943 Ma with an average of 844 ± 33 Ma (Table 2).

***Day (Overlook) pegmatite (N 43°17′40.7″; W 73°56′15.2″).*** The monazite from the Day pegmatite is associated with polycrase-Y, tiny zircon, and thorite crystals. We successfully analyzed 8 points. It is heterogeneous, with uranium levels just above detection limits, producing large counting statistical errors and point-to-point deviations. While this grain is clearly younger than the one from Batchellerville, its exact age is difficult to assess. We report an average age of 297 ± 62 Ma.

## DISCUSSION

### The Use of Pegmatites to Constrain Adirondack Temporal Events

Rocks of the Adirondack Mountains record a variety of tectonic environments and magmatic events (Fig. 3). Three well-documented orogenies, Elzevirian (1245–1225 Ma), Shawinigan (ca. 1190–1140 Ma), Grenvillian orogenies, including the Ottawan (1090–1020 Ma), and a weak Rigolet (1000–980 Ma) pulse are reported (Hudson et al., 2008; Rivers, 2008) in the southern Grenville Province. The effects of the orogenies were not equally intense across the area now exposed in the Adirondacks and, in some regions, the effects of the early events were overlapped and/or erased by subsequent tectonism. The U-Th-Pb ages on zircon separated from different metaigneous suites in the Adirondack region have contributed greatly to our understanding of the temporal evolution of the region and the relationship between deformation and igneous activity (McLelland et al., 1988; McLelland et al., 1996; Wasteneys et al., 1999; McLelland et al., 2004; Heumann et al., 2006).

Pegmatites are commonly associated with economic deposits and often can be used to bracket various deformational, metamorphic, or hydrothermal events. Unfortunately, because of their highly evolved compositions and enrichment in incompatible elements, zircons in pegmatites are often highly enriched in uranium and thorium and are susceptible to metamictization. In addition, inherited zircons are common to pegmatites associated with anatectic processes or derived from supracrustal rocks. The zircons in these pegmatites range in uranium content from several 10s to over 4000 ppm. Most zircons analyzed in this study yielded useful age information, although zircon from the Cream of the Valley and Natural Bridge from the Lowlands were entirely metamict (Fig. 9). Because they yielded geologically unreasonable data, they are not reported here. Other zircons, such as those from the Batchellerville and Mayfield pegmatites, are largely metamict but did have zones that yielded concordant ages. Still others, such as the Crown Point and Lewis pegmatites, yielded entirely concordant points. In general, metamict zircons had high U/Th ratios indicating differential mobility of U and Th during metamictization processes.

### Geochronological Constraints from Pegmatite Ages in the Adirondack Lowlands

In the Adirondack Lowlands, the McLear (1195.1 ± 7.2 Ma) and Rossie (1195.1 ± 8.3 Ma) pegmatites yield ages indicating crystallization during the Shawinigan orogenesis. Although both pegmatites intrude the Lower Marble, the contact of the Rossie pegmatite with the Lower Marble lacks visible metamorphic effects, while the contact of the McLear pegmatite is poorly exposed. Although numerous, exceptionally coarse-grained skarns are developed in the Lowlands adjacent to intrusive bodies, the pegmatites sampled for this study lack the typical calc-silicate mineral assemblages and are considered igneous in origin. They were emplaced within the Lower Marble Formation coincident

TABLE 2. AVERAGED U-TH-PB DATA AND CALCULATED AGES FOR MONAZITES FROM THE BACHELLERVILLE AND DAY PEGMATITES

| | Composition (ppm) | | | | | | | Age (Ma) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Y Sp1 | Pb Sp2 | Pb Sp3 | Pb Sp4 | Pb Sp5 | Th Avg. | U Avg. | Sp2 | Sp3 | Sp4 | Sp5 | Avg. | S.D. |
| Bachellerville | | | | | | | | | | | | | |
| Main crystal (n = 20) | 17,723 | 7745 | 7831 | 8242 | 8264 | 176,059 | 7993 | 841 | 851 | 902 | 851 | 874 | 27 |
| S.D. measured | 531 | 161 | 257 | 193 | 274 | 3196 | 221 | 9 | 15 | 12 | 16 | 10 | |
| S.D. Poisson | 69 | 42.2 | 46 | 54 | 52 | 278 | 97 | 5 | 5 | 6 | 6 | | |
| Fracture rim (n = 5) | 4674 | 1913 | 1973 | 2058 | 2007 | 58,232 | 854 | 704 | 734 | 752 | 736 | 732 | 20 |
| S.D. measured | 887 | 761 | 742 | 872 | 830 | 24,284 | 454 | 70 | 87 | 65 | 74 | 71 | |
| S.D. Poisson | 49 | 30 | 35 | 40 | 39 | 169 | 88 | 12 | 14 | 16 | 16 | | |
| Gray patches (n = 5) | 6840 | 5505 | 5708 | 5950 | 5955 | 142,337 | 2552 | 803 | 834 | 870 | 871 | 844 | 33 |
| S.D. measured | 1924 | 691 | 711 | 724 | 754 | 5107 | 721 | 60 | 64 | 63 | 68 | 64 | |
| S.D. Poisson | 57 | 40 | 45 | 52 | 51 | 255 | 88 | 6 | 7 | 8 | 7 | | |
| Day (Overlook) | | | | | | | | | | | | | |
| (n = 8) | 2419 | 297 | 283 | 353 | 220 | 19,936 | 480 | 308 | 284 | 372 | 223 | 297 | 62 |
| S.D. measured | 715 | 120 | 118 | 112 | 80 | 5052 | 461 | 75 | 54 | 58 | 51 | 41 | |
| S.D. Poisson | 46 | 22 | 24 | 39 | 29 | 111 | 97 | 24 | 26 | 45 | 31 | | |

*Note:* Standard deviation (S.D.) based on counting statistics. Sp—Spectrometer.

with the intrusion of the bimodal calc-alkaline 1207 ± 10 Ma (Wasteneys et al., 1999) or 1203 ± 13.6 Ma Antwerp-Rossie (Chiarenzelli et al., 2010b, this volume) suite. This magmatism was triggered by the impending closure of the Trans-Adirondack backarc basin culminating in the Shawinigan orogeny (Chiarenzelli et al., 2010b, this volume). The age of these two pegmatite bodies, therefore, provides constraints on the nature of Shawinigan magmatism and on the age of the Lower Marble Formation.

Because the Lower Marble is crosscut by these pegmatites, it must be older than ca. 1195 Ma. Barfod et al. (2005) reported a Lu-Hf isochron of 1274 ± 9 Ma and a younger Pb stepwise leaching (PbSL) isochron of 1153 ± 8 Ma on apatite from the Lower Marble Formation. The 1274 ± 9 Ma age has been interpreted as the minimum depositional age of the Lower Marble Formation (Barfod et al., 2005), while the 1153 ± 8 Ma age coincides with the lower limit of Shawinigan metamorphism. Therefore the Rossie and McLear pegmatite bodies intruded well after deposition of the Lower Marble but prior to the culmination of the Shawinigan orogeny. Additionally, widespread anatexis of pelitic gneisses occurred in the Adirondack Lowlands from 1160 to 1180 Ma (Heumann et al., 2006), ~10–15 million years after intrusion of the Rossie and McLear pegmatites. Ages associated with the Grenvillian orogen (Ottawan and Rigolet pulses) were not found, and pegmatites of this age may be absent from the Lowlands or were not sampled in this study.

## Shawinigan Pegmatites in the Highlands?

The Andean-type Shawinigan orogeny (Corrigan, 1995; Rivers, 1997; Wasteneys et al., 1999) was recorded in the Lowlands through the syntectonic emplacement of igneous rocks of the Antwerp-Rossie Granitoids, Hermon and Rockport Granites, and Hyde School Gneiss suites over a 30 million year span from ca. 1207 to 1172 Ma (Heumann et al., 2006; Marcantonio et al., 1990; McLelland et al., 1996; Wasteneys et al., 1999). This intrusive activity was closely followed by the emplacement of AMCG magmatic rocks in the Lowlands and Highlands at ca. 1155 Ma, believed to have been initiated by the delamination of the thickened Shawinigan lithosphere (McLelland et al., 1996; McLelland et al., 2004).

Here, we report the oldest pegmatite age in this study at 1222 ± 12 Ma for a single large grain from the Hulls Falls pegmatite, a small body in the metasedimentary sequence near the eastern border of the Marcy anorthosite (Fig. 2). Unlike the majority of pegmatites sampled, this pegmatite has a simple mineral composition consistent with quartz-feldspar-phlogopite-tourmaline segregation during either the waning stages of the Elzevirian orogeny or early Shawinigan metamorphism. Smaller grains from the same sample yield an age of 1178 ± 12 Ma, which is interpreted as the minimum age of the metamorphism of the host metasedimentary unit. If the Hulls Falls body is an intrusive pegmatite, it is hard to correlate it with any calc-alkaline granitic body in the area, with the exception of slightly older (ca. 1250 Ma) calc-alkaline rocks in the southern Adirondacks (Chiarenzelli and McLelland, 1991). If the older age is inherited, which seems unlikely given the size of the grain, the intrusion of the 1178 Ma pegmatite is consistent with the intraplate pulse model proposed by Corriveau and van Breemen (2000) and Wodicka et al. (2004) for the 1190–1160 Ma interval and corresponds with known Shawinigan magmatic events in the Adirondack Lowlands (e.g., Hyde School Gneiss and Hermon Granitic Gneiss).

## Pegmatites of the Grenvillian Orogeny (Ottawan and Rigolet Pulses)

The collisional Himalayan-type Ottawan orogeny started with the intrusion of the A-type Hawkeye granite at ca. 1090 Ma (McLelland et al., 2001) followed by the ca. 1090–1050 Ma granulite facies metamorphism (McLelland et al., 2001) at temperature ~730°–800 °C and pressure ~5–8 kbar (Spear and Markussen, 1997), and the intrusion of the A-type Lyon Mountain granite at 1070–1040 Ma (McLelland et al., 1996). Most of the pegmatites from the Adirondack Highlands studied in this paper are related to the Ottawan pulse and perhaps early Rigolet pulse of the Grenvillian orogeny and cover an interval of time between 1090 ± 28 Ma (Batchellerville) and 1003 ± 5.2 Ma (Lewis). Heumann et al. (2006) reported ages of 1348 Ma and 1132 ± 20 Ma on zircons separated from the leucosome of a metapelite collected from a location situated at the east end of the Sacandaga Reservoir that is relatively close to the Batchellerville pegmatite. They interpreted the older age as a xenocryst, but the younger one as probably the result of heating at the end of the AMCG suite emplacement.

We analyzed, by electron microprobe, a monazite crystal (>1 cm) with very high amount of Th (up to 17.61 wt%). The U-Th-Pb monazite dating yielded 864 ± 33–888 ± 40 Ma on the large monazite grain and 732 ± 71 Ma on the fracture where Th occurs in thorite. We suggest two scenarios here: (1) the zircon dating represents the age of the pegmatite and the monazite was deposited at ca. 888 ± 40–864 ± 33 Ma by hydrothermal fluids after the intrusion in the southern Adirondack of the 935 ± 9.2 Ma Cathead Mountain leucocratic dike swarm (McLelland et al., 2001) or infiltration of fluids during protracted uplift; or (2) the zircon age represents inheritance, and the chemical age of monazite is the real age of the Batchellerville pegmatite. We consider the first scenario most likely because we obtained similar ages on zircon at 1009 ± 22 Ma for the pegmatite from Mayfield and 1003 ± 5.2 Ma for a tiny pegmatite body crosscutting the wollastonite skarn at the Lewis Quarry. These pegmatites were generated in an extensional setting (Martin and De Vito, 2005) after the Ottawan orogenic collapse.

The Scott's Farm pegmatite from the northwestern Highlands is located in the proximity of the Carthage-Colton Mylonite Zone and yielded an age of 1063 ± 9 Ma. Selleck et al. (2005) documented the intrusion of synextensional, A-type Lyon Mountain granite in the Carthage-Colton Mylonite Zone and interpreted that the crustal extension and orogenic collapse of this part of the Grenville orogen happened at ca. 1045 Ma. The intrusion of the Scott's Farm pegmatite at ca. 1063 ± 9 Ma shows that magmatism associated with orogenic collapse and extension in the northwestern Highlands started earlier than 1045 Ma (Selleck et al., 2005). Deformation associated with granulite facies metamorphism in the Highlands stopped at ca. 1050 Ma because the Lyon Mountain granite largely appears not to display penetrative deformation (McLelland et al., 2001). After 1050 Ma, at least in the eastern part of the Adirondack Highlands, an extensional regime was initiated; the crust was invaded by fluids, and granitic melts of probable anatectic origin were generated in the supracrustal units metamorphosed to granulite facies.

These fluids could also be, at least, partially responsible for the mobilization and deposition of the magnetite ores mined in this region (Foose and McLelland, 1995; McLelland et al., 2002; Valley et al., 2009). We suggest that the Sugar Hill (1048 ± 14 Ma), Roe's Spar Bed (1038 ± 9.9 Ma), Barton Hill (1039 ± 11 Ma), and Crown Point (1024.8 ± 2.8 Ma) pegmatites represent granitic melts produced during the cessation stage of the Ottawan Pulse of the Grenvillian orogeny. They are NYF-type pegmatites and may be generated in the metasedimentary units that have been metasomatized by an earlier $H_2O$- and $CO_2$-rich fluid that was probably released from the mantle (Martin and De Vito, 2005).

The zircon crystals sampled from within a pegmatite-like separation in the magnetite-apatite ore from the Old Bed layer from the Mineville iron ore mining district yielded an age of 1022.4 ± 13 Ma. We determined an age of 1039 ± 11 and a rim age of 949 ± 10 Ma on zircon crystals from a pegmatite body crosscutting the ore at the Barton Hill Mine in the Mineville iron ore mining district. The difference in age could be related to the difference in the degree of metamictization of the zircons followed by variable amounts of Pb loss. Valley et al. (2009) interpreted their 1020 ± 11 Ma age as a minimum age; we suggest that the minimum age for the zircons from the Old Bed is 1022.4 ± 13 Ma (probably the same age of the Lyon Mountain granite), and the younger ages are the result of the zircon growth from alkalic fluids during the extensional environment created during the waning stages of the Ottawan or Rigolet event.

### Late Acadian Events

We obtained an electron microprobe chemical age of 297 ± 62 Ma on a monazite crystal from the Day (Overlook) pegmatite (Table 2) located at ~9.6 km northeast from the Batchellerville pegmatite. The monazite crystal is intimately associated with tiny zircon, thorite, and polycrase-Y; the last mineral displays strong chemical heterogeneities probably caused by late hydrothermal fluids. Although the error on this estimate is large, its U-Th-Pb composition clearly indicates that it is much younger than the events that produced the region's pegmatites. This very young age is supported by other findings in the southern Adirondack Highlands. Ages of 395–505 Ma were reported by Storm and Spear (2002a, 2002b) on rims on monazite from the southern Adirondack Highlands metapelites; they suggested that these ages coincide with the timing of metamorphism to the east of the northern Appalachians. Alteration rims of Th-rich allanite on monazite from the same region yielded 353 Ma and could be related to the hydrothermal fluids released in the waning stages of the Acadian orogeny (Storm and Spear, 2002a). We suggest that the formation of monazite from the Day (Outlook) pegmatite was probably related to the hydrothermal fluids that were released during the late Acadian events, like those seen in the rocks east of the Adirondack Mountains.

## CONCLUSIONS

(1) The pegmatites from the Adirondack Mountains are predominantly granitic NYF-type pegmatites.

(2) Zircon from these pegmatites has been dated by LA-MC-ICP-MS methods utilizing multiple analyses on a single large crystal or several crystals. High uranium areas, which often show a cloudy or nebulous structure, are severely metamict. However, even some high uranium and largely metamict crystals have areas that retain concordancy.

(3) They were generated and emplaced during the Elzevirian (or very early Shawinigan), Shawinigan, Grenvillian (Ottawan and Rigolet pulses) of the Grenville Orogenic Cycle. The oldest pegmatite ages reported from the Lowlands include the McLear (1195 ± 7.2 Ma) and Rossie (1195 ± 8.3 Ma) pegmatites; the youngest pegmatite crystallization ages were determined from the Highlands at Lewis (1003 ± 5.2 Ma) and Mayfield (1009 ± 22 Ma).

(4) The pegmatites from the Lowlands were emplaced into the Lower Marble Formation probably during the early stages of the Shawinigan orogeny; they display older ages from zircon cores (inheritance), and post-emplacement deformation (associated with Shawinigan deformation). A core within the Rossie pegmatite zircon yields a maximum age of 1312 ± 22 Ma.

(5) The Hulls Falls pegmatite in the Highlands was likely emplaced at 1222 ± 12 Ma during the late Elzevirian or early Shawinigan orogenic event well before the intrusion of the AMCG suite. A younger age of 1178 ± 9 from smaller grains recovered from the same pegmatite may record the timing of Shawinigan metamorphism in the eastern Highlands.

(6) Most of the pegmatites from the Highlands were generated between ca. 1065 and 1000 Ma in extensional environments following the Ottawan granulite-facies metamorphism, probably from anatectic melts in metasedimentary units metasomatized by $H_2O$- and $CO_2$-rich fluids probably of mantle derivation.

(7) We suggest that the formation of pegmatites including zircon 949 ± 10 Ma in the Barton Hill pegmatite and monazite (874 ± 27 Ma) from the Batchellerville pegmatite could be related to the same event that generated the Cathead Mountain dike swarm or the infiltration of hydrothermal fluids following uplift. These ages are younger than those associated with the Grenville Orogenic Cycle and provide information on events that followed the orogeny.

(8) We suggest that the 297 ± 62 Ma upper Paleozoic age for the monazite from the Day (Overlook) pegmatite is related to the infiltration of hydrothermal fluids associated with the late Acadian events. Numerous pegmatite samples have lower intercept ages around 250 Ma in concert with this finding.

(9) All except two pegmatite zircon separates yielded useful geochronological information broadening the range of available targets to constrain magmatic and orogenic events. While metamictization and inheritance are potential problems, even large, dark, and intensely fractured grains may yield useful information.

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