Onset of long-lived silicic and alkaline magmatism in eastern North America preceded Central Atlantic Magmatic Province emplacement

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ABSTRACT

The White Mountain Magma Series (WMMS) is the largest Mesozoic felsic igneous province on the Eastern North American Margin (ENAM). Existing geochronology has suggested that magmatism occurred over 50 Myr with published ages for the oldest units apparently coeval with the ca. 201 Ma Central Atlantic Magmatic Province (CAMP), the flood basalt province associated with the end-Triassic mass extinction and the opening of the Atlantic

Ocean. We use zircon U-Pb geochronology to show that emplacement of WMMS plutons was already underway at 207.5 Ma. The largest volcanic-plutonic complex, the White Mountain Batholith, was emplaced episodically from ca. 198.5 Ma to ca. 180 Ma, ca. 25 Myr older than published ages suggest, and all samples we dated from the Moat Volcanics are between ca. 185 to 180 Ma. This result shows that the Moat Volcanics and the White Mountain Batholith are broadly comagmatic, and it also constrains the age of a key Jurassic paleomagnetic pole. Our data suggest that a regional mantle thermal anomaly in eastern North America developed at least ca. 5 Myr prior to the main stage of CAMP flood basalt volcanism and suggests a geodynamic link between the WMMS and the CAMP.

INTRODUCTION

Despite the long-recognized association of silicic magmatism with continental flood basalts in large igneous provinces, constraints on the relative timing and the geodynamic mechanisms that generate such events remains elusive (e.g., Bryan and Ferrari, 2013). The CAMP, one of the largest continental flood basalt provinces (Marzoli et al., 2018; Marzoli et al., 1999), was emplaced over a very brief time interval (< ca. 1 Myr) beginning at ca. 201.5 Ma and coincided with the end-Triassic mass extinction (e.g., Blackburn et al., 2013; Davies et al., 2017). The WMMS, a predominately silicic igneous province, is situated within the known field of CAMP magmatism (McHone et al., 1987) (Fig. 1) and is the second-largest Mesozoic igneous province in eastern North America. Published constraints based on whole rock and mineral K-Ar, Ar-Ar, or Rb-Sr ages (Armstrong and Stump, 1971; Eby et al., 1992; Foland and Faul, 1977; Foland et al., 1971) indicate an onset of magmatism at ca. 200 Ma, with episodic pulses continuing for ca. 50 Myr. Recent zircon U-Pb studies of limited occurrence of Mesozoic igneous rock (e.g., Eusden et al., 2017) and regional studies of detrital zircons from beach and rivers sands (e.g., Bradley et al., 2015) have yielded no grains that suggest such a protracted duration of magmatism.

Previous workers attributed WMMS magmatism to a variety of causal mechanisms, including mantle plumes (e.g., Morgan, 1983), a long-lived thermal anomaly of unspecified origin (e.g., Eby et al., 1992), and a ‘leaky’ transform fault (e.g., Bédard, 1985). Because the existing chronology for the WMMS does not provide sufficient resolution to fully assess these and other possibilities. We report new zircon U-Pb geochronology to date several WMMS units that together constrain its onset, duration, and temporal relationship with CAMP magmatism.

GEOLOGIC CONTEXT

McHone and Butler (1984) divided all Mesozoic igneous rocks in northeastern North America into four provinces: 1) The Coastal New England (CNE) Province; 2) The Eastern North American Dolerite Province, now known as the CAMP; 3) The WMMS; and 4) The New England Québec (NEQ) Province. The CNE province consists predominantly of basaltic dikes in coastal Maine and has only one reliably dated unit, the intrusive Agamenticus intrusive complex at 238.88 ± 0.11 Ma (Hussey et al., 2016). The NEQ province formed during an Early Cretaceous episode of hotspot magmatism at ca. 125 Ma (Kinney et al., 2021).

The WMMS falls within the region of known CAMP dikes (Fig. 1) and consists of a variety of volcanic and plutonic complexes, predominately ferroan (A_1-type) granites (Eby, 1992; Frost and Frost, 2011) and minor silica-undersaturated intrusions (e.g., Creasy, 1989; Henderson et al., 1989). Published whole rock ages suggest that early WMMS intrusions are coeval with CAMP magmatism and continued until ca. 155 Ma (Table 1). The largest igneous suite in the WMMS is a composite series of intrusions and volcanic rocks forming the White Mountain Batholith (Fig. 2) with an apparent 50-Myr duration of magmatism (e.g., Eby et al., 1992; Foland and Faul, 1977). Within the batholith, the Moat Volcanics unit has provided a key Jurassic paleopole for constraining the apparent polar wander path of North America (Van Fossen and Kent, 1990).

The zircon U-Pb geochronology reported here provides temporal constraints on the relationship between CAMP and WMMS magmatism and specifically tests whether: 1) magmatism in this province can be unambiguously temporally linked to the CAMP within a brief temporal interval; or 2) magmatism is indeed protracted over a long timescale.

METHODS

We dated eleven samples via zircon U-Pb chemical abrasion-isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS) and nine samples via zircon U-Pb laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) (Fig. 2). We selected samples with previously published age constraints to capture the range of apparent magmatism within the batholith. For CA-ID-TIMS measurements, we analyzed samples 2 – 5, where units have published ages from ca. 201 – 195 Ma (Eby et al., 1992; Foland and Faul, 1977). Sample 16 is from the unit (Conway Granite) with the youngest published age of entire province of ca. 155 Ma. We also sampled four units (samples 6, 8, 19, 20) based on published ca. 201 Ma ages (Creasy, 1989; Eby et al., 1992; Foland and Allen, 1991; Henderson et al., 1989). We selected two samples (14 and 15) from the Moat Volcanics at South Moat Mountain, where published ages are between the oldest and youngest dated units within the White Mountain Batholith at ca. 173 – 167 Ma (Eby et al., 1992). Incidentally, these samples provide constraints on an important Jurassic paleomagnetic pole (Van Fossen and Kent, 1990). Finally, we sampled the only proximal zircon-bearing mafic unit (sample 1, 214 ± 9 Ma; Weston Geophysical Corporation, 1976) within the interval of WMMS magmatism. Samples dated via LA-ICP-MS additionally targeted units with observable contact relationships within the Moat Volcanics and western batholith.

Because of the large dispersion relative to analytical precision of single grain U-Pb dates in each sample dated via CA-ID-TIMS, they likely record the timescale of crystallization for zircon within each magmatic system. The calculation of a weighted mean age for such samples requires subjective criteria for grain selection and leads to an age interpretation with ambiguous geologic significance. Instead, we employed a modified Bayesian Markov Chain Monte Carlo (MCMC) model (e.g., Keller et al., 2018; Kinney et al., 2021; Ratschbacher et al., 2018) that more objectively estimates the timing of emplacement based on when the melt reaches rheological lockup. We applied a similar approach to samples dated via LA-ICP-MS and report ages that correspond to the *end* of zircon crystallization.

Sample numbers in the text were changed from field-IDs for brevity and are numbered in order as projected along a W-E transect across the batholith. See Table DR1 and the GSA Data Repository[1] for full sample descriptions, field-IDs, analytical methods, and description of U-Pb age interpretations. Sample 21 is from the Agamenticus complex, dated by Hussey et al. (2016).

RESULTS

Four samples from the WMMS yielded ages from 210 to 200 Ma (Fig. 2), revealing an apparently early episode of magmatism in the region that does not clearly fit into the known ranges of either the CNE or WMMS provinces (Fig. 3). These are the relatively small plutons of West Rattlesnake Mountain (sample 6; 207.24 +0.41/-0.27 Ma), Red Hill (sample 8; 203.86 +0.18/-0.12), Conway Granite at Whaleback (sample 19; 207.41 +0.05/-0.07 Ma), and Rattlesnake Mtn. (sample 20; 200.76 +0.15/-0.08 Ma). These localities have typically been associated with the WMMS based on previously published ages, and our work demonstrates that their emplacement either clearly precedes (samples, 6, 8, 19), or is coincident with, the CAMP (sample 20).

Magmatism within the White Mountain Batholith began no later than 198.56 +0.42/-0.46 Ma (samples 2, 5) and continued until ca. 190 Ma (samples 3, 4, 5, 7) with the emplacement of large bodies of biotite granite that underlie most of the western batholith. In the eastern batholith, the youngest (ca. 155 Ma) biotite granite (Sample 16) according to a previous K-Ar date (Eby et al., 1992) has a U-Pb emplacement age of 182.31 +0.30/-0.29 Ma, which suggests that the duration of magmatism within the White Mountain Batholith may be up to 25 Myr shorter than previously thought. Sample 1, the only known WMMS gabbro with an original K-Ar age of ca. 215 Ma (Weston Geophysical Corporation, 1976), was dated herein via U-Pb at ca. 388.91 ± 4.98 Ma and likely belongs to the older New Hampshire Plutonic Suite (Dorais, 2003)

All the volcanic units (samples 11, 14, 15, 17, 18) from the Moat Volcanics and their intrusive contacts (10, 12, 16), except for an anomalous sample (Sample 13) at 198.410 ± 0.097 Ma, were emplaced between ca. 185 - 180 Ma.

DISCUSSION

Predominately alkaline magmatism in the WMMS began at 207.41 +0.05/-0.07 Ma, ca. 6 Myr prior to the emplacement of the CAMP flood basalts elsewhere in the region. Significant differences between the zircon U-Pb emplacement ages presented here and existing K-Ar and Rb-Sr ages (Fig. 3) are present at many localities, and particularly, in the eastern batholith, suggesting that thermal heating from either the spatially overlapping Cretaceous NEQ province, a magmatic-hydrothermal event of an unknown age, or the effects of alteration or open system behavior affected the minerals used for K-Ar or Rb-Sr dating in previous studies. The good agreement of nearly all samples from the Moat Volcanics and associated intrusions suggest emplacement from 185 – 180 Ma and that the ca. 198 Ma date reflects recycling of an older WMMS xenolith in the system. These data merit closer scrutiny of the Moat Volcanics as a reliable paleopole considering that the magnetizations for this locality are interpreted to be secondary thermochemical remnant magnetizations (Van Fossen and Kent, 1990). Therefore, any emplacement age only provides a maximum estimate for the timing of magnetization.

A similar analogue to our observations of this region on the ENAM is the Paraná-Etendeka (P-E) flood basalt province, where existing geochronologic constraints demonstrate a prolonged duration of intrusive silicic and alkaline magmatism spatially associated with flood basalts (Gomes and Vasconcelos, 2021). In the P-E, small-scale alkaline magmatism both pre-dates the eruption of flood basalts by ca. 4 Myr and post-dates the main phase of flood basalt magmatism by as much as ca. 7 Myr. It is difficult to make direct comparisons to the CAMP and the WMMS without reliable zircon U-Pb age constraints for both the P-E lavas themselves (Rocha et al., 2020) or for the intrusive silicic-alkaline units associated with the P-E province (e.g., the Damaraland Complexes). However, geodynamic models (e.g., Gibson et al., 2006) for P-E magmatism suggest that the early production of silicic and alkaline melts, as well as their duration are consistent with the combined effects of regional extension and the thermal interaction of a plume head with thick, metasomatized continental lithosphere.

Like the P-E, Triassic-Jurassic ENAM magmatism is broadly associated with rifting of a supercontinent, though no consensus exists on the specific geodynamic mechanism. CAMP geochemistry largely points to a depleted upper mantle source for the widespread flood basalt magmatism (e.g., Marzoli et al., 2018), whereas geochemistry from the WMMS (Eby et al., 1992; Foland and Allen, 1991; Foland et al., 1988) suggests a mantle source with variable crustal input but is insufficient to unambiguously characterize the source characteristics or degree of fractionation and assimilation processes. A rift-related mechanism is consistent with the CNE province for which there is evidence of magmatism at ca. 239 Ma (Hussey et al., 2016), approximately coeval with the onset of sedimentation, and therefore extension, in ENAM rift basins. Furthermore, because of the significant offset between zircon U-Pb and vintage K-Ar dates from rocks in this region shown by this study and elsewhere (e.g., Hussey et al., 2016), the only reliable estimate on the timing and duration of the CNE province is the 238.88 ± 0.11 Ma age of the Agamenticus Complex (Sample 21) and there is insufficient evidence to suggest that the ca. 207 Ma plutons dated here are related to this event. It therefore seems more likely that the silicic magmatism at ca. 207 Ma was a precursor to flood basalt volcanism. Because there is no evidence from ENAM rift basins that indicate changes in either regional stress states or extension rates at ca. 207.5 Ma (e.g., Withjack et al., 2013), any proposed causal mechanism for the CAMP should account for localized production of silicic and alkaline melts up to 6 Myr prior to the main phase of flood basalt magmatism

CONCLUSIONS

We demonstrate that small-scale regional silicic and alkaline magmatism associated with the WMMS began at ca. 207.5 Ma, which both post-dates the ca. 239 Ma CNE Province and pre-dates the ca. 201.5 Ma CAMP. Beginning at ca. 198.5 Ma, the main phase of WMMS magmatism, the White Mountain Batholith was episodically emplaced over ca. 20 Myr, significantly shorter than previous estimates of 50 Myr. This discrepancy likely reflects post-emplacement open system behavior in the K-Ar system. Zircon U-Pb age estimates of ca. 185 - 180 Ma for the Moat Volcanics provide a maximum constraint for the Jurassic paleopole derived from this locality. The absence of evidence for any change in regional stress state or extension rate in this segment of the ENAM at ca. 207.5 Ma suggests the development of a regional thermal anomaly ultimately leading to the production of widespread flood basalt magmatism may also be responsible for the onset of the WMMS.

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FIGURES AND CAPTIONS

Figure 1. A) Eastern North American Margin (ENAM) with estimated dike locations from Withjack et al. (2013); study area is within black rectangle B) Study area; province boundaries defined by western-most extent of dikes associated with the Central Atlantic Magmatic Province (CAMP, black) and Coastal New England Province (CNE, Orange) defined by McHone and Butler (1984). Considerable uncertainty is associated with the boundaries of each province because they are defined by dike distributions, many without direct radiometric age constraints. Rift basins containing the record of CAMP lava flows and intrusives on the ENAM and are shown in black. Continental-scale dikes associated with the CAMP (McHone et al., 1987) shown

in blue. NYC – New York City; NB – Newark Basin; HB – Hartford Basin; CAMP – Central Atlantic Magmatic Province; WMMS – White Mountain Magma Series; CNE – Coastal New England; FB – Fundy Basin.

Figure 2. White Mountain Batholith with sample numbers used in text and preferred ages at the 95% credible interval for all CA-ID-TIMS and LA-ICP-MS samples. Superscripts refer to method used: A, MCMC from LA-ICP-MS data; B, MCMC from CA-ID-TIMS data; C, Weighted Mean (WM) from CA-ID-TIMS data. See the GSA Data Repository for sample descriptions, detailed methods, and full model results.

Figure 3. (Top) Summary of preferred ages as shown in Fig. 2, where marker symbols correspond to method and color corresponds to map unit. (Bottom) Kernel density of preferred zircon U-Pb ages produced in this study and all published dates (K-Ar and Rb-Sr) from the White Mountain Batholith and Coastal New England Province plutons (Creasy, 1989; Eby et al., 1992; Foland and Allen, 1991; Foland and Faul, 1977; Henderson et al., 1989). Vertical red bar for CAMP shows age range of all published zircon U-Pb ages (Blackburn et al., 2013; Davies et al., 2017; Heimdal et al., 2018; Marzoli et al., 2019). Horizontal blue bar for CNE province dikes shows approximate range of published K-Ar dates (McHone and Butler, 1984). Sample 21 is Agamenticus Complex with zircon U-Pb date from Hussey et al. (2016).

TABLE CAPTIONS

Table 1. Zircon U-Pb ages showing sample numbers in Fig. 2. Mapped units in New Hampshire from Lyons et al. (1997) and in Maine from Creasy (1989). Both Bayesian MCMC

emplacement/end-crystallization ages and weighted mean calculations are reported for all samples.

[Please include this text at the end of your paper if you are including an item in the Data Repository.]

[1]GSA Data Repository item 201Xxxx, Figures DR1 to DR 49 contain zircon images, Concordia and weighted mean plots and the results of MCMC modeling; Tables DR1 to DR2 contain detailed sample information and detailed methods for LA-ICP-MS analyses; Datasets DR1 to DR3 contain whole rock chemistry and measured isotopic data for all samples, is available online at www.geosociety.org/pubs/ft20XX.htm, or on request from editing@geosociety.org.

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Figure 1

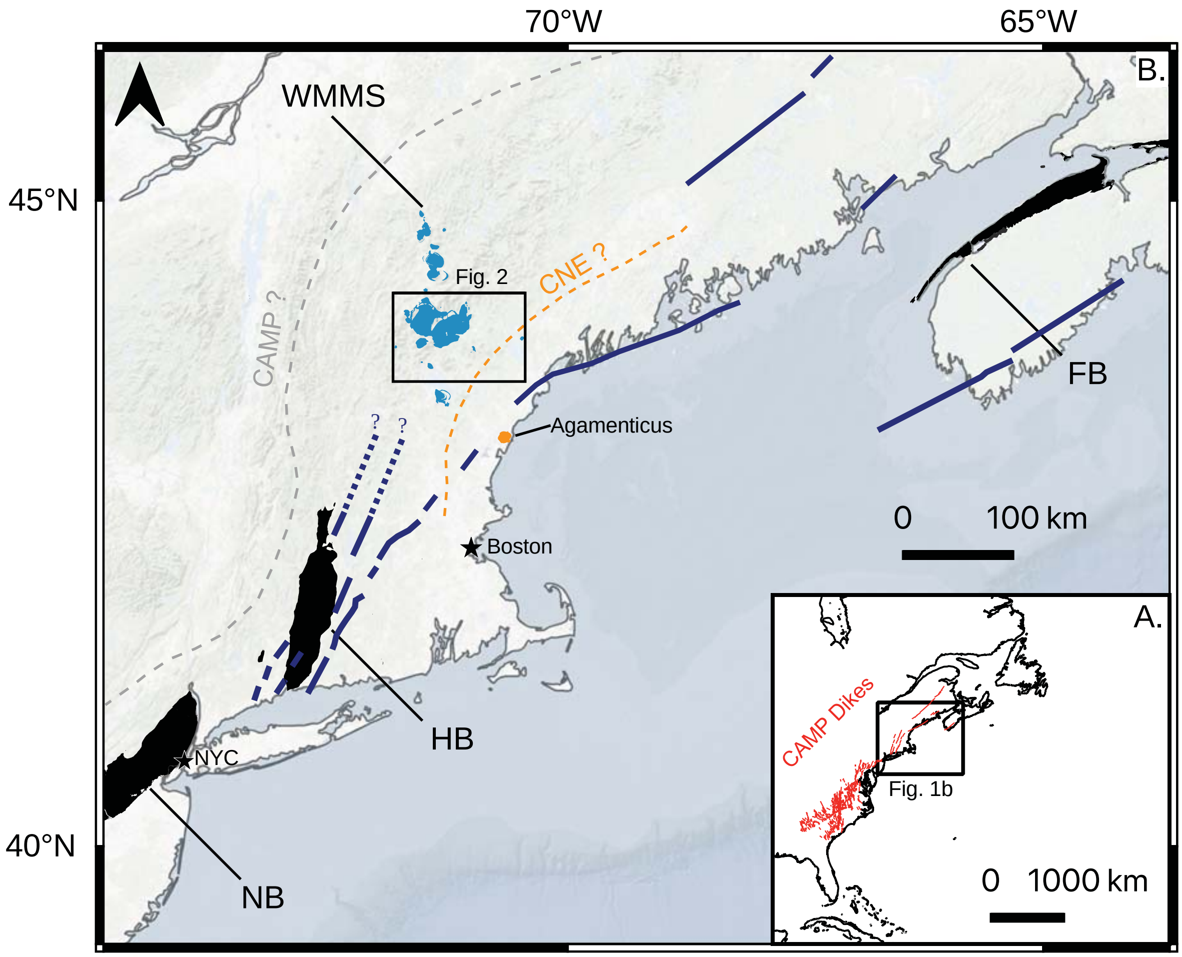
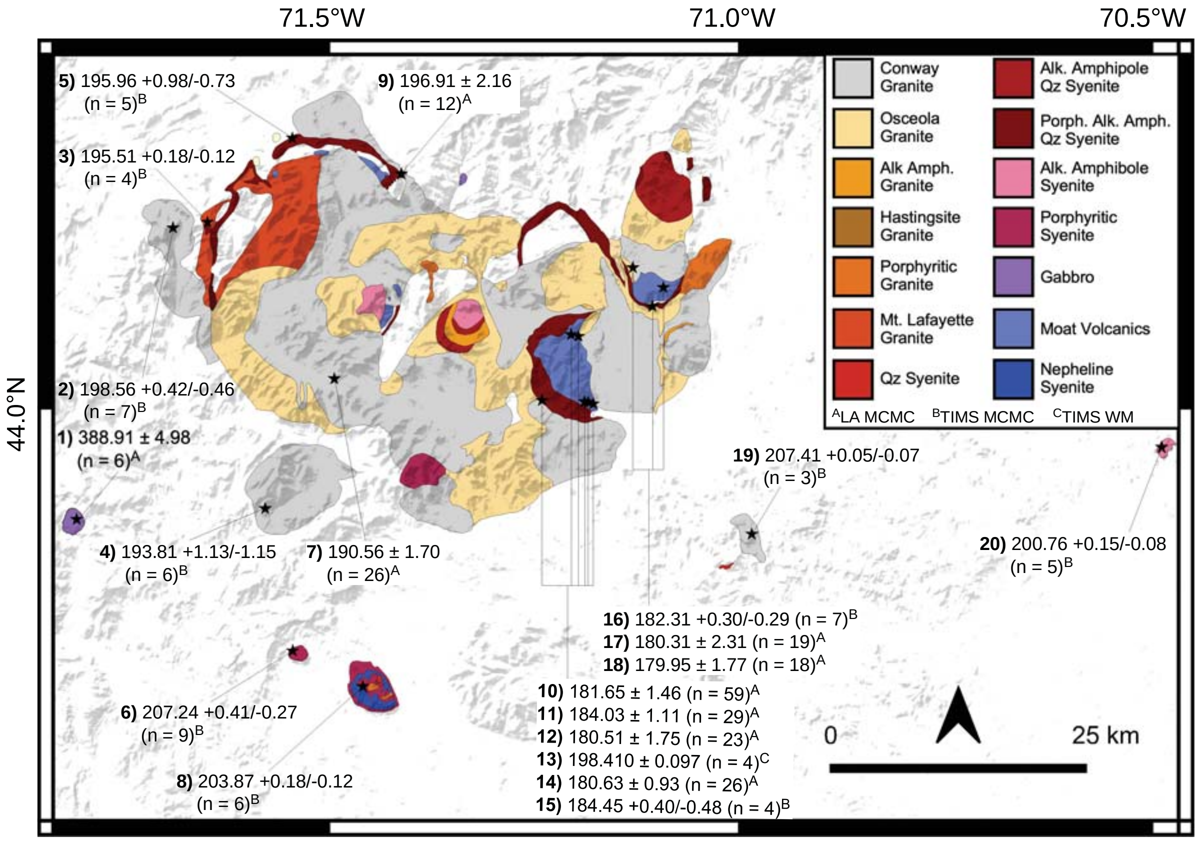
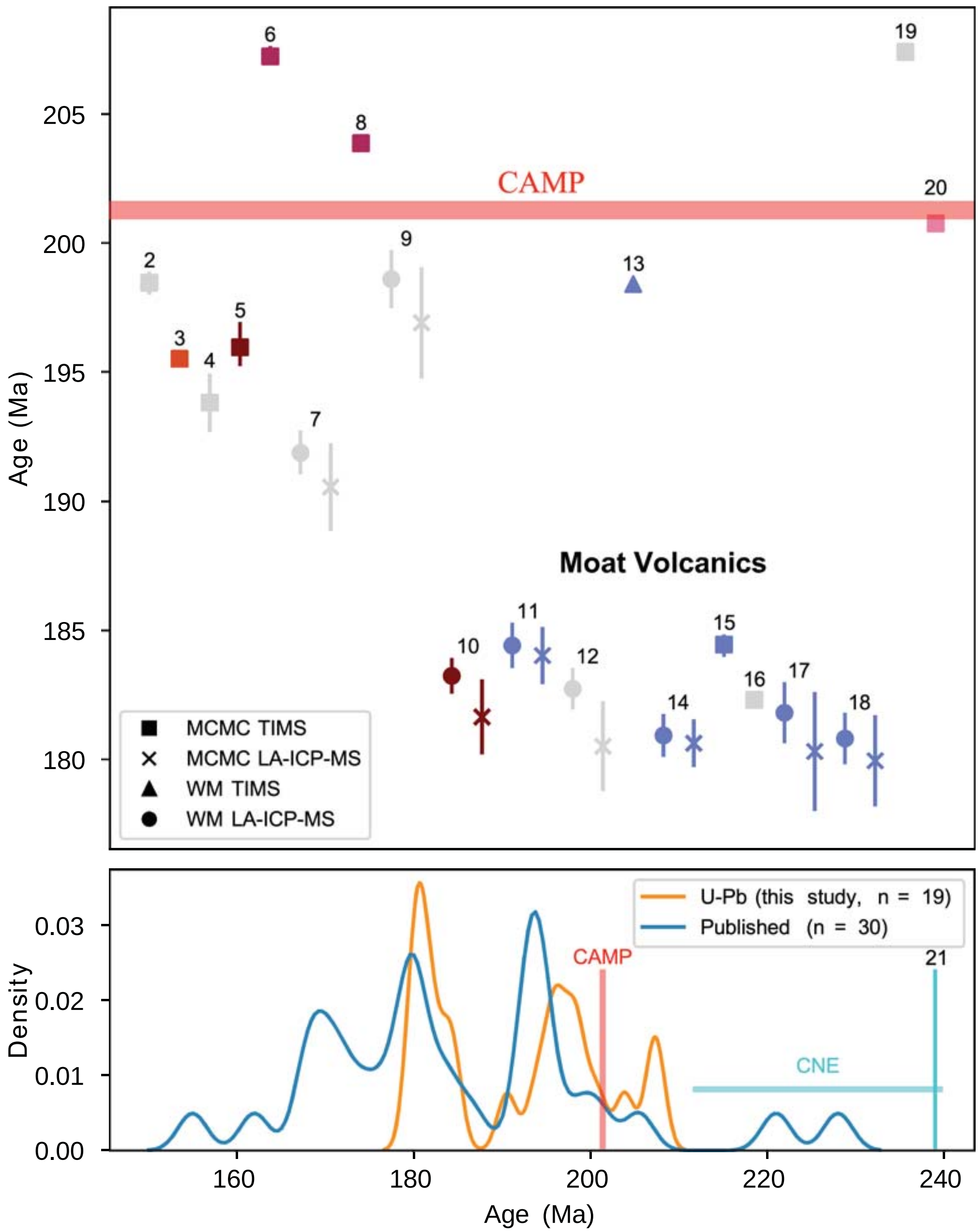

70°W
65°W
45°N
40°N
B.
WMMS
Fig. 2
CNE ?
CAMP ?
Agamenticus
Boston
HB
NYC
NB
FB
0
100 km
A.
CAMP Dikes
Fig. 1b
0
1000 km

Figure 2



71.5°W
71.0°W
70.5°W
44.0°N
Conway Granite
Osceola Granite
Alk Amph. Granite
Hastingsite Granite
Porphyritic Granite
Mt. Lafayette Granite
Qz Syenite
Alk. Amphipole Qz Syenite
Porph. Alk. Amph. Qz Syenite
Alk. Amphibole Syenite
Porphyritic Syenite
Gabbro
Moat Volcanics
Nepheline Syenite
ALA MCMC BTIMS MCMC CTIMS WM
1) 388.91 ± 4.98 (n = 6)A
2) 198.56 +0.42/-0.46 (n = 7)B
3) 195.51 +0.18/-0.12 (n = 4)B
4) 193.81 +1.13/-1.15 (n = 6)B
5) 195.96 +0.98/-0.73 (n = 5)B
6) 207.24 +0.41/-0.27 (n = 9)B
7) 190.56 ± 1.70 (n = 26)A
8) 203.87 +0.18/-0.12 (n = 6)B
9) 196.91 ± 2.16 (n = 12)A
10) 181.65 ± 1.46 (n = 59)A
11) 184.03 ± 1.11 (n = 29)A
12) 180.51 ± 1.75 (n = 23)A
13) 198.410 ± 0.097 (n = 4)C
14) 180.63 ± 0.93 (n = 26)A
15) 184.45 +0.40/-0.48 (n = 4)B
16) 182.31 +0.30/-0.29 (n = 7)B
17) 180.31 ± 2.31 (n = 19)A
18) 179.95 ± 1.77 (n = 18)A
19) 207.41 +0.05/-0.07 (n = 3)B
20) 200.76 +0.15/-0.08 (n = 5)B
0
25 km

Figure 3



CAMP
Moat Volcanics
Age (Ma)
205
200
195
190
185
180
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
MCMC TIMS
MCMC LA-ICP-MS
WM TIMS
WM LA-ICP-MS
U-Pb (this study, n = 19)
Published (n = 30)
CAMP
21
CNE
Density
0.03
0.02
0.01
0.00
160
180
200
220
240
Age (Ma)

TABLE 1. SUMMARY OF ZIRCON U-PB AND PUBLISHED AGES

#	*Zircon U-Pb results* Weighed Mean (Ma)	MCMC (Ma)*	Method	Published Age (Ma)
1	393.55 ± 2.54 (MSWD = 3.42, n = 6)	388.91 ± 4.98	LA	215 ± 7[1]
2	198.55 ± 0.11 (MSWD = 2.2, n = 3)	198.56 +0.42/-0.46	CA	198 ± 4[2]; 194 ± 2[3]
3	195.494 ± 0.105 (MSWD = 0.35, n = 4)	195.51 +0.18/-0.12	CA	195 ± 6[4]
4	193.45 ± 0.11 (MSWD = 1.1, n = 3)	193.81 +1.13/-1.15	CA	186 ±4; 184 ± 4; 193 ± 2
5	-	195.96 +0.98/-0.73	CA	193 ± 6[4]; 201 ± 6[4]
6	206.618 ± 0.033 (MSWD = 1.7, n = 7)	207.24 +0.41/-0.27	CA	198 ± 10[3]
7	191.89 ± 0.84 (MSWD = 1.55, n = 26)	190.56 ± 1.70	LA	184 ± 4[2†]
8	203.733 ± 0.028 (MSWD = 1.2, n = 5)	203.87 +0.18/-0.12	CA	201.93 ± 1.64[6]
9	198.60 ± 1.13 (MSWD = 1.80, n = 12)	196.91 ± 2.16	LA	184 ± 4[2]
10	183.24 ± 0.70 (MSWD = 1.41, n = 59)	181.65 ± 1.46	LA	179 ± 4[4]
11	184.42 ± 0.88 (MSWD = 0.78, n = 29)	184.03 ± 1.11	LA	168.2 ± 1.2[4]
12	182.74 ± 0.81 (MSWD = 1.63, n = 23)	180.51 ± 1.75	LA	172 ± 3[5†]; 180 ± 2[3]
13	198.410 ± 0.097 (MSWD = 1.6, n = 4)	-	CA	173 ± 1.5[4]
14	180.93 ± 0.83 (MSWD = 0.48, n = 26)	180.63 ± 0.93	LA	173 ± 1.5[4]
15	184.29 ± 0.10 (MSWD = 0.32, n = 3)	184.45 +0.40/-0.48	CA	173 ± 1.5[4]
16	182.305 ± 0.089 (MSWD = 1.3, n = 7)	182.31 +0.30/-0.29	CA	155 ± 4[4]
17	181.81 ± 1.19 (MSWD = 1.61, n = 19)	180.31 ± 2.31	LA	173 ± 1.5 - 168.2 ± 1.2[4]
18	180.81 ± 1.00 (MSWD = 1.35, n = 18)	179.95 ± 1.77	LA	173 ± 1.5 - 168.2 ± 1.2[4]
19	207.418 ± 0.044 (MSWD = 0.74, n = 3)	207.41 +0.05/-0.07	CA	189 ± 4[2]
20	200.676 ± 0.021 (MSWD = 1.7, n = 5)	200.76 +0.15/-0.08	CA	205 ± 2[7]
21	238.88 ± 0.11 (MSWD =1.4, n = 4)[8††]	-	CA	228 ± 5[2]

[1]Weston Geophysical. [2]Foland and Faul (1977). [3]Foland and Allen (1991). [4]Eby et al. (1992).
[5]Foland et al. (1971). [6]Henderson et al. (1989). [7]Creasy (1989). [8]Hussey et al. (2016).

*MCMC age calculated using MELTS prior for samples dated via CA-ID-TIMS and using a generic, exponential prior for samples dated via LA-ICP-MS.

††Calculated from Hussey et al. (2016).