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Timing and duration of the Central Atlantic magmatic province in the Newark and Culpeper basins, eastern U.S.A.

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ABSTRACT

New major and trace element data and $^{40}Ar/^{39}Ar$ plateau ages constrain the timing, duration and time-related geochemical evolution of the Central Atlantic magmatic province in the U.S.A. (Newark and Culpeper basins) and refine correlations with basaltic lava flows from other Late Triassic–Early Jurassic circum-Atlantic basins. The precise, statistically robust $^{40}Ar/^{39}Ar$ plateau ages were obtained on biotite and on fresh plagioclase and calculated using the latest ^{40}K decay constants. These ages are supported by a general consistency of the Ca/K calculated from $^{37}Ar/^{39}Ar$ of the plateau steps and the Ca/K obtained by detailed electron microprobe analyses on plagioclase phenocrysts. The ages of five analyzed basalt lava flows, from all three lava flow units in the Newark basins, and the ages of two sill samples are indistinguishable, indicating a brief magmatic peak phase at 201.8 ± 0.7 Ma. Recalibrated $^{40}Ar/^{39}Ar$ plateau ages from the entire province indicate a near-synchronous onset and peak volcanic activity at the Triassic–Jurassic boundary within the circum-Atlantic basins from the U.S.A., Canada and Morocco. The early erupted magmas (Moroccan Lower to Upper basalts, the Fundy basin North Mountain Basalt, and Orange Mountain and equivalent U.S.A. flows) yield an enriched geochemical signature (e.g., with relatively high La/Yb), whereas late magmas in the U.S.A. (Hook Mountain and Hampden basalts) and Morocco (Recurrent basalt) yield relatively depleted geochemical compositions (low La/Yb). A slight, but significant age difference for eruption of Hook Mountain and Hampden basalts (200.3 ± 0.9 Ma) and Recurrent basalts (198.2 ± 1.1 Ma) is interpreted as evidence of a diachronous northward rift–drift transition during break-up of Pangea. Our data indicate also a prolonged intrusive sequence that continued until about 195 Ma at the Palisades sill and is consistent with sporadic late CAMP magmatism for dykes from the south-eastern U.S.A. and for intrusions from Guinea.

1. Introduction: Triassic–Jurassic magmatism in the circum-Atlantic basins

The Central Atlantic magmatic province (CAMP; Fig. 1A) basaltic magmas were erupted in circum-Atlantic basins in Europe, Africa, North and South America over a total surface in excess of 10^7 km^2 (Marzoli et al., 1999; McHone et al., 2005), making this one of the largest known Phanerozoic igneous provinces. Crucial for the definition of the CAMP was recognition of nearly synchronous magmatic activity (mean $^{40}Ar/^{39}Ar$ age ca. 200 Ma) and the largely similar geochemical composition of the magmatic products over the entire province, e.g., from France to Bolivia (Bertrand et al., 2005; Jourdan et al., 2003). Some of the thickest lava piles of the CAMP occur in the once contiguous extensional basins of eastern North America (ENA) and Morocco, where they are interlayered with continental sediments of Triassic–Jurassic age. The North American basins, which probably represent the best-studied continental basins of Late Triassic to Early Jurassic age, contain continuous, or nearly so, accumulations of sediments and volcanics collectively termed the Newark Supergroup. Although the position of the Triassic–Jurassic boundary has long been claimed as occurring below the oldest CAMP flows in the Newark basins (cf. Whiteside et al., 2007), recent research demonstrates that the boundary lies above the oldest CAMP flows (Cirilli et al., 2009; Kozur and Weems, 2010; see below).

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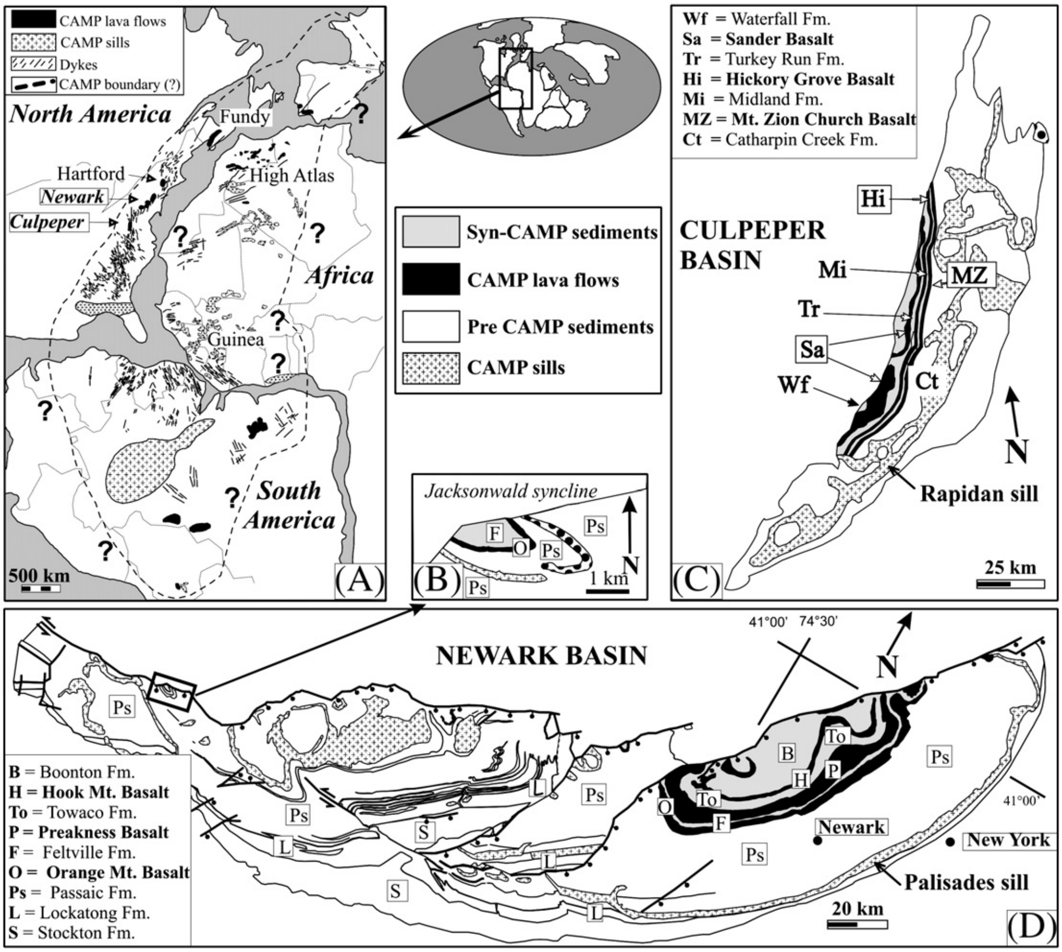

Fig. 1. Schematic map of the CAMP (A) and of Culpeper (C) and Newark (D) basins. Inset B shows the Jacksonwald syncline where Orange Mountain basalt NEW133 was sampled.

The "absolute age anchor" for the Newark sediments is given by the radio-isotopic ages of the CAMP lava flows. As we show below, however, and according to the rigorous data filtering criteria of Baksi (2003) and of Nomade et al. (2007), the previously published isotopic ages for the Newark basaltic flows cannot be considered statistically robust. Precise ages are required also to support bio- and magneto-stratigraphic correlations among the circum-Atlantic basins, notably those from the U.S.A. and Morocco. Therefore, we present here precise ^{40}Ar/^{39}Ar plateau ages for ten Culpeper and Newark basin (U.S.A.; Fig. 1C and D) basaltic lava flows and related sills (Rapidan and Palisades). Combined with new major and trace element geochemical data for the basalts, these ages better constrain inter-basin correlations, the age and duration of the magmatism and its geodynamic significance within the framework of the rifting of Pangea and opening of the Central Atlantic Ocean.

2. CAMP in the eastern U.S.A basins

In ENA, CAMP igneous rocks occur onshore from Newfoundland (Canada) to Florida (U.S.A.), but are exposed at the surface as basaltic lava flows, dykes and sills only in the Newark Supergroup basins from Nova Scotia (Canada) to Virginia (U.S.A. (Fig. 1)). The Triassic–Jurassic basins of the eastern U.S.A. (Massachusetts to Virginia) contain lava piles that are up to 450 m thick and consist of a maximum of three main units (Fig. 2), each comprising multiple flows. In the Newark basin (Fig. 1D) the units are the Orange Mountain (comprising three individual flows), Preakness (five flows) and Hook Mountain basalts (two or three flows; e.g., Puffer and Student, 1992). Based on detailed field-work, biostratigraphic data and basalt geochemistry (e.g., Fowell and Olsen, 1993; Olsen et al., 2002; Tollo and Gottfried, 1992), these three units can be correlated with the basalts from the nearby basins; e.g. in the Hartford basin the correlative units are the Talcott, Holyoke and Hampden basalts, respectively (Fig. 2). In the Culpeper basin (Fig. 1C) also the CAMP lava flows comprise three main units: the Mt. Zion Church (two flows), the Hickory Grove (two flows) and the Sander basalt (at least three flows). The geochemical composition of the Mt. Zion Church basalt is similar to the Orange Mountain and Talcott basalts, whereas the Hickory Grove and Sander basalts (separated locally by more than 100 m of sediments of the Turkey Run formation) resemble the Preakness and Holyoke basalts (Tollo and Gottfried, 1992). Lava flows geochemically similar to the Hook Mountain and Hampden basalts are absent in the Culpeper basin.

Basic rocks in the Culpeper and Newark basins occur also as rather thick, shallow intrusive sills, e.g. the Rapidan and the Palisades sills, respectively. The latter reaches a thickness of about 350 m and is well exposed along the Hudson River in New Jersey, where it intruded conformably within the mainly lacustrine sediments of the Carnian Lockatong Formation. The geochemistry of the Palisades sill exhibits a general trend of upward decreasing MgO and increasing SiO_2, yet significant mineralogical and geochemical fluctuations also occur from base to top (e.g., Gorring and Naslund, 1995; Puffer et al., 2009; Shirley, 1987; Walker, 1969). The most significant variations are associated with the highly mafic olivine-rich layer that occurs at about 10 m above the base of the sill and in the so-called "sandwich horizon," an evolved, granophyre-bearing level near the sill's top. Puffer et al. (2009) have shown general geochemical similarities between the lower part of the Palisades sill and the Orange Mountain basalt, and between the upper half of the sill and the Preakness basalt.

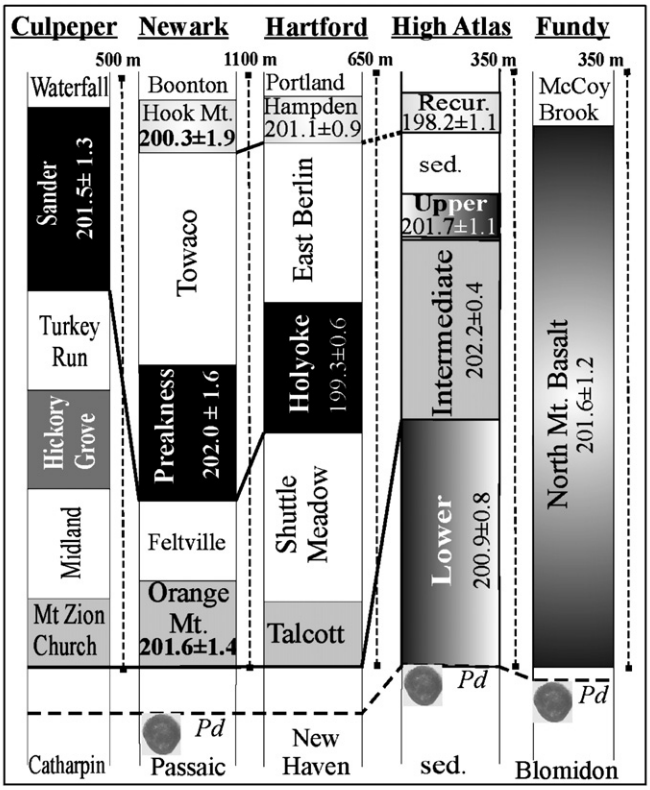

Fig. 2. Schematic logs of Culpeper, Newark, Hartford, Fundy and High Atlas basins. Ages for Newark and Culpeper basins are from present paper (in bold); for Hartford and Fundy basins from Jourdan et al. (2009a); for Morocco, High Atlas, from Sebai et al. (1991), Marzoli et al. (2004), Knight et al. (2004), Verati et al. (2007), and Nomade et al. (2007). Inter- and infra-basaltic sediments (sed.) from Morocco are unnamed. Recur. corresponds to Recurrent basalts. Correlations are based on geochemical data (continuous line) and on biostratigraphic data (last occurrence of *P. densus*; dashed line; Fowell and Olsen, 1993; Fowell and Traverse, 1995; Cirilli et al., 2009). The last occurrence of this sporomorph is observed in sediments up to the first lava flows in Morocco, up to 30 cm from the first flow of the North Mountain Basalt of Nova Scotia, and up to less than 15 m before the first Orange Mountain basalt flow at the Jacksonwald syncline (Fig. 1B).

More specifically, compatible major and trace elements such as MgO or Cr show repeated peaks within the lower half of the sill at heights of about 30, 60 and 100 m above the base, probably reflecting multiple re-injections of less evolved magma.

The ca. 370 m thick Rapidan sill (Fig. 1C), unconformably intruded within the Carnian–Norian Manassas Sandstone and Norian–Rhaetian Balls Bluff Siltstone Member (of the Bull Run Formation) of the Culpeper basin, is less well exposed and thus less studied than the Palisades sill. Available data indicate similar geochemical and mineralogical variations as observed for the Palisades, e.g., a general upward decrease of Cr (ca. 1000 to 400 ppm) and MgO (14 to 9 wt.%; Woodruff et al., 1995).

2.1. Previous ^{40}Ar/^{39}Ar and U/Pb ages on U.S.A. CAMP basalts

There is a large set of radio-isotopic ages available for the CAMP, represented mainly by ^{40}Ar/^{39}Ar dates, but also by some U/Pb ages. However, given the variety of analytical techniques applied and the possible alteration of the rocks that were sampled, careful screening is necessary in order to attain a reliable age for the distribution of CAMP magmatism. Previous studies on CAMP have proposed criteria for a rigorous data filtering (e.g., Baksi, 2003; Nomade et al., 2007). First, whole-rock data should be excluded since they may be affected cryptically by alteration and Ar recoil. This has been discussed largely in connection with other CFB provinces, such as the Deccan and the Karoo (Hofmann et al., 2000; Jourdan et al., 2007a). Also, since ^{40}Ar/^{39}Ar analyses on mineral separates may be affected by alteration and recoil effects, we consider only those ^{40}Ar/^{39}Ar ages with a plateau defined by at least 70% of the total released gas (^{39}Ar), by a high percentage of radiogenic Ar (^{40}Ar*; for our data > 80%), and corresponding to a portion of the ^{37}Ar/^{39}Ar (i.e. Ca/K) spectrum that is concordant and compatible with the analyzed mineral. In order to be mutually comparable, the neutron fluence monitor and its considered age should be available for ^{40}Ar/^{39}Ar ages.

Considering these filtering criteria, a total of 64 ^{40}Ar/^{39}Ar plateau ages can be considered as rigorous, i.e. those selected by Nomade et al. (2007) plus nine recently published plateau ages (Jourdan et al., 2009a; Merle et al., in press). However, these ages were obtained by a long known outdated ^{40}K decay constant (Steiger and Jäger, 1977; in particular the electron capture branch). Recent calibrations of the ^{40}K decay constant and associated international standards based on ^{238}U/^{206}Pb ages (Renne et al., 2010) show that the ages obtained with the previous decay constant were offset by ca. −1% (see discussion in Jourdan et al., 2009a) and needed urgent revision. We therefore recalculated all ages obtained on CAMP using the new set of decay constant and standard ages after Renne et al. (2010). The recalibrated age database (Annex 1 Table) indicates a peak activity for the CAMP at ca. 201 Ma and some minor sporadic late activity continuing to ca. 192 Ma.

Previous ^{40}Ar/^{39}Ar data for the eastern U.S.A. CAMP basalts that meet the filtering criteria include ages for the lava flows from the Newark and Hartford basins, for the dykes from South Carolina, and for the Palisades sill. We note that Hames et al. (2000) and Nomade et al. (2007) report non-plateau ^{40}Ar/^{39}Ar ages (total released ^{39}Ar < 70%) for the Newark Orange Mountain (202.9 ± 2.1 and 200.9 ± 1.6 Ma) and Hook Mountain basalts (200.7 ± 2.0 Ma). Notably, however, the ^{40}Ar/^{39}Ar apparent age for the Hook Mountain basalt of Hames et al. (2000) is concordant over about 68% of the total released ^{39}Ar and thus nearly matches the definition of plateau. Hereafter, it will be referred to as a mini-plateau age. Jourdan et al. (2009a) obtained plateau ages for the alteration phases from the strongly altered Deerfield basalt (201.2 ± 0.6 Ma; Deerfield basin) and Hampden basalt (200.4 ± 1.0 and 201.7 ± 0.6 Ma; Hartford basin) and interpreted them as sub-synchronous with the crystallization age of the lava-flows. ^{40}Ar/^{39}Ar data suggestive of ages close to 200 Ma were obtained for two Culpeper basin sills and for the Gettysburg and Palisades sills (Baksi, 2003; Sutter, 1988), but are either discordant or are based on a neutron fluence monitor (SJ77) that is not intercalibrated with currently used standards (e.g., the Hb3gr hornblende standard employed in this study). Eleven high quality ^{40}Ar/^{39}Ar plateau ages are published for the dykes from North and South Carolina (Beutel et al., 2005; Hames et al., 2000; Nomade et al., 2007). The majority of those (n = 9/11) range from 199.4 ± 1.7 Ma to 201.4 ± 1.5 Ma and correspond to the peak activity of the CAMP, but two dykes yielded significantly younger ages (195.2 ± 2.0 and 196.1 ± 2.2 Ma). Multigrain zircon and baddeleyite U/Pb ages are available for the sandwich layer of the Palisades sill (200.9 ± 1.0 Ma) and for the Gettysburg sill (201.3 ± 1.0 Ma; Dunning and Hodych, 1990) and have been used to extrapolate the age of the volcanic rocks from the Newark basins (e.g., Olsen et al., 2003).

In summary, eleven ^{40}Ar/^{39}Ar plateau ages are available for magmatic minerals of the eastern U.S.A. CAMP, all of which belong to dykes from South and North Carolina. These ages define a peak at 200.6 Ma. Conversely, no ^{40}Ar/^{39}Ar plateau age *sensu stricto* has yet been obtained on CAMP lava flows from the Newark and Culpeper basins, although a Hook Mountain basalt sample yielded a 68% ^{39}Ar released mini-plateau age at 200.7 ± 2.0 Ma.

3. CAMP in other circum-Atlantic regions

As in the Newark and Culpeper basins, the Moroccan lava flows can be subdivided into four geochemically distinct groups, the Lower, Intermediate, Upper and Recurrent basalts (Bertrand et al., 1982; Deenen et al., 2010; Marzoli et al., 2004, 2006; Fig. 2). A total of 21

^{40}Ar/^{39}Ar plateau ages were obtained for the Moroccan CAMP basalts. The Lower to Upper basalts yielded indistinguishable ages (mean age 201.2 ± 0.9 Ma), whereas the Recurrent basalts yielded slightly younger ages, ranging from 199.6 ± 2.3 to 196.3 ± 1.2 Ma (mean age 198.2 ± 1.1 Ma; Knight et al., 2004; Marzoli et al., 2004; Nomade et al., 2007; Sebai et al., 1991; Verati et al., 2007). The Moroccan basalts display an upsection decrease of (most) incompatible element contents (e.g., LREE, Nb) and of ^{87}Sr/^{86}Sr and increase of ^{143}Nd/^{144}Nd (Bertrand et al., 1982; Marzoli et al., 2004, 2006). Such variations are interpreted to reflect a dominantly sub-continental lithospheric mantle source for the Lower to Upper basalts followed by a more significant contribution from a sub-lithospheric source for the Recurrent basalts (Marzoli et al., 2006; Verati et al., 2007; Youbi et al., 2003).

Thick CAMP basalt lava piles outcrop also in the Fundy basin of Nova Scotia, Canada. Based mainly on field and volcanological evidence, the lava sequence (the North Mountain Basalt) has been subdivided into three different units (Kontak, 2008); however, these do not show clear geochemical differences. Eight ^{40}Ar/^{39}Ar plateau ages were obtained by Jourdan et al. (2009a) for the North Mountain basalt, which range from 200.8 ± 0.7 to 202.9 ± 1.4 Ma except for one, possibly intrusive younger sample (192.4 ± 1.0 Ma). A U/Pb age on zircons at 201.31 ± 0.38 Ma has been obtained by Schoene et al. (2010) on a pegmatite level within the lower flow unit.

4. Stratigraphic constraints on the onset of CAMP volcanism and circum-Atlantic correlations

The CAMP lava flows in the Newark Supergroup basins are conformably interlayered with continental sediments, mostly of fluviatile and lacustrine origin. Cyclostratigraphic analysis suggests that the extrusive episodes and intervening periods of sedimentation occupied an interval of about 600 ka (Olsen et al., 1996; Whiteside et al., 2007). The biostratigraphic age of the sediments immediately underlying the basal flows (e.g., Passaic and Catharpin formations in the Newark and Culpeper basins) are constrained by a moderate palynological turnover and by the last occurrence of some species (e.g. *Patinasporites densus*) occurring a few meters below the first CAMP basalt flow (e.g., Fowell and Olsen, 1993). This palynological turnover, closely associated with a moderate Ir anomaly (Olsen et al., 2002) and with a short paleomagnetic reversal (E23r; Kent and Olsen, 1999), long has been interpreted as marking the Triassic–Jurassic boundary (TJb) and has been used to conclude that CAMP volcanism started about 20–40 Ka after the TJb (e.g., Olsen et al., 2003; Whiteside et al., 2007). This interpretation has been challenged recently by Kozur and Weems (2005, 2010) based on conchostracan biostratigraphy and by Cirilli et al. (2009). These latter authors showed that in the Fundy basin of Nova Scotia the last occurrence of *P. densus* (in sedimentary layers about 40 cm below the first basalt flow) does not equate with the TJb because sediments yielding a Rhaetian palynological assemblage were deposited after extrusion of CAMP basalts. Therefore, at least in the Fundy basin, CAMP basalts erupted before the TJb. Since *P. densus* occurs in sediments up to the contact with the lowest CAMP basalts in Morocco, these also are interpreted to have erupted during the latest Triassic (Marzoli et al., 2004).

5. Sampling and petrography of the analyzed rocks

We collected new samples from lava flows and sills of the Newark and Culpeper basins. Details on the sampling sites are given in Table 1.

In the Newark basin, we analyzed seven samples from the Palisades sill and seven samples from lava flows for major and trace elements. Three Palisades sill samples were dated: NEW135, obtained from the bottom of the olivine-rich horizon, at about 10 m above the base of the sill; NEW16, from 30 m above the base; and NEW18, sampled at about 100 m above the base. The Newark lava flows (two Orange Mountain, three Preakness and two Hook Mountain basalts) were sampled in New Jersey, except for the Orange Mountain basalt NEW133, which was sampled in Pennsylvania (Exeter County, Jacksonwald syncline; Fig. 1B) at a stratigraphic position a few meters above the interval where Olsen et al. (2002) interpret the TJb, based on a horizon with a spike in trilete spores (a “fern spike”) and an associated Ir enrichment. The two Hook Mountain basalt samples (NEW73 and NEW74) were obtained from the first and second flows, respectively, at Roseland, New Jersey, where the two lava flows outcrop in direct contact.

The seven lava flows of the Culpeper basin (two of which were dated) that were analyzed for major and trace elements belong to the Mt. Zion Church (two samples), Hickory Grove (two) and Sander basalts (three). Two Rapidan sill samples were analyzed for major and trace element compositions, one of which (CUL8) was dated. Due to the incomplete exposure of the Rapidan sill, we do not know the precise stratigraphic position of the sample, but it belongs to the lower half of the sill, as confirmed by its geochemical and mineralogical composition (cf. Woodruff et al., 1995).

In general, all analyzed rocks show intergranular to subophitic textures. Only the Orange Mountain and Mt. Zion Church basalts are generally fine-grained and micro-porphyritic. The main mineral phases are idiomorphic or sub-idiomorphic plagioclase and augitic clinopyroxene. Plagioclase crystals are optically zoned in the Hook Mountain basalts and are rimmed by alkali feldspar in the Rapidan sill sample CUL8. Rather small, rounded olivine crystals are observed in the Palisades sill (e.g., NEW135; olivine-rich layer of Walker, 1969), in the Rapidan sill (sample CUL8) and, completely or partially altered, in some Orange Mountain and Hook Mountain basalts. Pigeonite is abundant in the Preakness and Sander basalt samples, as in the Palisades and Rapidan samples NEW16, NEW18, CUL9. These sill samples also contain orthopyroxene (also as exsolutions in clinopryroxene). Oxides (magnetite, mostly) are ubiquitous, whereas accessory biotite and rare apatite occur in the sill samples. Quartz-feldspar intergrowths are present in the sills and in the Sander and Preakness lava flows.

6. Analytical techniques

6.1. Whole-rock x-ray fluorescence and ICP-MS analyses

Major elements and compatible trace elements (Ni, Co, Cr, and V) were analyzed by X-ray fluorescence (XRF spectrometer Phillips PW2400) at the University of Padova. Analytical uncertainty ranges from 1 to 2% for major elements and from 10 to 15% for trace elements. Rare Earth elements and other trace elements (Ta, Hf, Th and U, and Rb, Sr, Ba, Y, Zr and Nb) were analyzed by ICP-MS at the ENS-Lyon (France). 200 mg of rock powder was dissolved in a mixture of 3 ml HF and 1 ml HNO_3 during 48 h on a hot plate (130 °C) under a 50 bar pressure. The solutions were evaporated and the residues dissolved in 25 ml HNO_3 (0.5 N) and dried. Analyses were performed with a VG Element plasma quadripole II ICP-MS with electron multiplier. Procedural blank analyses yielded trace elements below the detection limit (<10 ppb). The standard used for all analyses was BHVO-1.

6.2. Electron microprobe analyses

Plagioclase major element compositions were analyzed at IGG-CNR Padova, Italy on a Cameca SX50 electron microprobe (EMP) using ZAF on-line data reduction and matrix correction procedures. At constant accelerating voltage, 15 kV, the beam's current was set at 15 nA. Long counting times (1 min) were adopted for minor element analyses (K and Mg), in order to optimize analytical precision. Repeated analyses of standards indicate relative analytical uncertainties of about 1% for major and 5% for minor elements.

Table 1
Whole-rock major and trace element compositions of Newark and Culpeper basalts.

	Newark basin									Culpeper basin						Hartford basin		
	Palisades sill			Orange Mt.		Preakness		Hook. Mt		Mt. Zion Church	Hickory Grove	Sander		Rapidan sill		Talcott	Holyoke	Hampden
	NEW 135	NEW 16	NEW 18	NEW 69	NEW 133	NEW 50	NEW 52	NEW 73	NEW 74	CUL 6	CUL 13	CUL 25	CUL 28	CUL 8	CUL 9	HB 64	HB 56	HB 29
Locality	Fort Lee, NJ	Englewood, NJ		West Orange, NJ	Jacksonwald PA	Berkeley Heights, NJ		Roseland, NJ		Casanova, VA	Aldie, VA	Casanova, VA		Raccoon Ford, VA		Meriden, CT	Black Pond Lake, CT	East Hampton, MA
Latitude (N)	40°50′47′	40°51′32″	40°53′30′	40°47″35″	40°18′53″	40°40″33″		40°49′03″		38°39′08″	38°54′47″	38°40′15″		38°21′27″		41°33′07″	41°31′40″	42°16′27″
Longitude (W)	73°57′53″	73°57′32″	73°56′28″	74°14′′53″	75°50′53″	74°24′32″		74°19′45″		77°42′17″	77°37′46″	77°43′56″		77°59′12″		72°48′46″	72°44′35″	72°36′16″
XRF																		
SiO_2 (wt%)	48.87	52.87	52.36	52.18	51.31	52.41	52.93	50.23	50.23	52.11	51.66	52.24	52.44	51.40	51.79	49.93	52.12	48.44
TiO_2	0.91	0.91	0.97	1.07	1.14	0.93	0.98	1.44	1.43	1.14	0.73	0.91	1.07	0.82	0.54	1.09	1.07	1.38
Al_2O_3	10.24	12.81	13.81	14.17	14.43	13.41	14.41	13.12	13.16	14.19	15.18	13.65	13.95	12.50	13.79	13.92	13.86	13.46
Fe_2O_3	14.16	10.71	10.51	10.97	11.63	13.72	12.97	16.73	16.69	11.41	11.52	13.82	14.01	11.02	9.16	11.01	13.88	16.54
MnO	0.21	0.17	0.17	0.17	0.19	0.22	0.21	0.24	0.23	0.18	0.19	0.22	0.21	0.17	0.16	0.17	0.22	0.19
MgO	15.77	10.01	8.52	7.91	8.20	6.74	5.53	5.60	5.66	7.65	7.78	5.62	5.59	11.75	10.60	7.88	5.64	5.55
CaO	7.81	10.29	11.20	11.25	11.48	9.60	10.23	9.96	9.94	11.27	11.01	10.20	9.93	10.61	12.60	11.71	9.81	5.91
Na_2O	1.30	1.86	1.90	1.94	1.76	2.59	2.35	2.30	2.25	1.99	2.13	2.19	2.41	1.62	1.48	1.72	2.35	3.62
K_2O	0.65	0.62	0.58	0.28	0.30	0.48	0.55	0.32	0.56	0.19	0.40	0.51	0.61	0.47	0.28	0.46	0.57	1.49
P_2O_5	0.15	0.13	0.13	0.15	0.16	0.13	0.13	0.21	0.20	0.15	0.12	0.11	0.15	0.12	0.08	0.12	0.12	0.16
Tot	100.07	100.38	100.15	100.09	100.60	100.23	100.29	100.15	100.35	100.28	100.72	99.47	100.37	100.48	100.48	98.01	99.64	96.74
L.O.I.	0.39	0.26	0.10	0.32	0.65	0.02	0.03	0.32	0.03	0.66	0.02	0.01	0.06	0.02	0.03	1.55	0.26	2.37
V (ppm)	216	245	268	267	276	345	378	398	396	273	261	330	343	233	226	401	19	57
Cr	416	595	498	406	358	113	42	117	139	361	261	65	68	850	546	46	45	50
Co	87	46	45	43	45	44	44	45	47	40	39	42	42	53	43	103	33	63
Ni	420	133	135	118	157	101	26	78	127	107	89	47	44	213	152	51	52	50
ICP-MS																		
Rb	10.9	20.6	20.6	8.1	3.0	10.1	15.5	20.7	21.8	2.6	7.4	10.5	19.1	18.3	8.8	9.4	16.4	32.0
Sr	143.9	176.3	185.3	172.9	298.5	121.1	152.2	128.5	123.0	187.3	120.4	135.4	174.9	171.3	188.4	180.0	134.3	301.7
Zr	56.3	85.7	89.4	90.5	99.1	76.1	81.7	110.3	114.9	86.9	57.9	69.3	103.4	80.1	41.1	95.8	88.3	111.8
Ba	85.5	147.8	148.5	116.2	113.6	118.4	134.8	156.3	144.2	166.2	93.7	126.9	165.0	128.0	80.6	111.3	135.5	1232.0
Y	12.2	15.3	17.2	15.4	14.0	20.7	19.4	32.3	36.5	13.9	12.3	13.7	25.2	15.4	9.7	20.1	26.9	38.1
Nb	4.01	6.02	5.98	6.27	6.52	3.62	3.85	4.86	4.72	6.39	3.06	3.27	4.68	5.07	2.59	6.81	4.59	5.03
La	5.60	7.94	8.75	8.18	8.24	6.62	7.28	8.35	8.66	8.06	4.27	5.71	8.89	7.80	4.24	10.10	8.61	8.82
Ce	12.26	19.58	19.71	20.66	21.53	15.36	16.61	20.65	19.83	20.52	10.82	14.45	20.63	17.58	9.42	22.20	18.66	20.10
Pr	1.66	2.35	2.56	2.48	2.56	1.96	2.05	2.60	2.68	2.49	1.28	1.66	2.55	2.26	1.24	2.94	2.50	2.80
Nd	7.48	10.62	11.59	11.39	11.54	8.91	9.23	12.18	12.78	11.44	5.88	7.42	11.53	10.10	5.70	12.88	11.03	12.88
Sm	1.99	2.74	2.98	2.98	2.98	2.47	2.50	3.70	3.87	2.96	1.66	1.97	3.14	2.65	1.55	3.27	2.99	3.93
Eu	0.68	0.92	0.97	1.00	0.99	0.87	0.88	1.22	1.29	1.00	0.60	0.78	1.09	0.88	0.65	1.08	1.04	1.44
Gd	2.29	3.11	3.39	3.36	3.27	3.14	3.07	4.84	5.19	3.34	2.10	2.39	4.01	3.03	1.83	3.89	3.89	5.36
Tb	0.38	0.50	0.55	0.55	0.52	0.56	0.54	0.87	0.94	0.53	0.37	0.41	0.70	0.49	0.30	0.61	0.69	0.97
Dy	2.46	3.22	3.57	3.48	3.29	3.89	3.68	6.14	6.56	3.35	2.54	2.82	4.75	3.17	1.98	3.98	4.78	6.73
Ho	0.50	0.63	0.71	0.68	0.63	0.81	0.78	1.29	1.38	0.66	0.52	0.58	1.00	0.61	0.40	0.79	1.03	1.45
Er	1.47	1.84	2.03	1.95	1.83	2.48	2.37	3.97	4.27	1.88	1.58	1.78	3.04	1.83	1.17	2.30	3.22	4.42
Tm	0.21	0.26	0.29	0.27	0.25	0.36	0.35	0.57	0.62	0.26	0.23	0.26	0.45	0.25	0.16	0.31	0.45	0.62
Yb	1.37	1.68	1.90	1.79	1.62	2.45	2.33	3.78	4.15	1.68	1.53	1.75	2.97	1.69	1.10	2.04	3.03	4.20
Lu	0.20	0.24	0.27	0.25	0.23	0.37	0.35	0.56	0.62	0.24	0.22	0.26	0.44	0.25	0.16	0.29	0.46	0.64
Hf	1.48	2.18	2.26	2.22	2.37	1.96	2.07	2.85	3.00	2.08	1.48	1.74	2.61	1.98	1.05	2.60	2.42	3.09
Ta	0.60	1.05	0.92	0.72	0.51	0.52	0.45	0.57	0.56	0.51	0.36	0.34	0.42	0.51	0.33	0.56	0.32	0.47
Pb	2.06	3.19	3.48	2.88	4.97	2.96	3.22	3.46	3.23	3.22	2.49	2.73	4.01	2.53	1.51	4.91	3.84	4.79
Th	1.10	1.68	1.88	1.50	1.44	1.56	1.71	1.98	2.09	1.31	0.90	1.31	2.06	1.61	0.81	1.83	1.87	2.02
U	0.27	0.44	0.44	0.44	1.30	0.50	0.57	0.64	0.59	0.46	0.37	0.49	0.67	0.36	0.19	0.52	0.56	0.76

Major elements and V, Cr, Co, and Ni were analyzed by X-Ray fluorescence; other reported trace elements were analyzed by ICP-MS. L.O.I. = loss on ignition. Compositions of representative samples for the Hartford basin lava flows are reported.

6.3. Ar/Ar geochronology

Plagioclase and biotite were separated using a Frantz magnetic separator and then carefully hand-picked under a binocular microscope. The selected plagioclase grains were further leached in diluted HF for one minute and then thoroughly rinsed with distilled water in an ultrasonic cleaner.

Samples were loaded into large wells of two 1.9 cm diameter and 0.3 cm depth aluminum discs. Each large well was bracketed by three small wells that contained Hb3gr hornblende used as a neutron fluence monitor for which an age of 1074 ± 5 Ma was initially adopted (Jourdan et al., 2006; Turner et al., 1971) and for which good intergrain reproducibility has been demonstrated (Jourdan and Renne, 2007; Jourdan et al., 2006). The discs were Cd-shielded (to minimize undesirable nuclear interference reactions) and irradiated for 25 h in the Hamilton McMaster University nuclear reactor (Canada) in position 5 C. The mean J-values computed from standard grains within the small wells range from 0.0088015 ± 0.0000282 to 0.0087720 ± 0.0000132, determined as the average and standard deviation of J-values of the small wells for each irradiation disc. Mass discrimination was monitored using an automatic air pipette and provided mean values ranging from 1.005296 ± 0.002815 to 1.006490 ± 0.003523 per atomic mass unit. The correction factors for interfering isotopes were $(^{39}Ar/^{37}Ar)_{Ca} = 7.30 \times 10^{-4}$ (±11%), $(^{36}Ar/^{37}Ar)_{Ca} = 2.82 \times 10^{-4}$ (±1%) and $(^{40}Ar/^{39}Ar)_K = 6.76 \times 10^{-4}$ (±32%).

The $^{40}Ar/^{39}Ar$ analyses were performed at the Western Australian Argon Isotope Facility at Curtin University, operated by a consortium consisting of Curtin University and the University of Western Australia. The samples were step-heated using a 110 W Spectron Laser Systems, with a continuous Nd-YAG (IR; 1064 nm) laser rastered during 1 mn over the sample wrapped in 0-blank Nb foil to ensuring a homogenously distributed temperature. The gas was purified in a stainless steel extraction line using three SAES AP10 getters and a liquid nitrogen condensation trap. Ar isotopes were measured in static mode using a MAP 215–50 mass spectrometer (resolution of ~600; sensitivity of 2×10^{-14} mol/V) with a Balzers SEV 217 electron multiplier mostly using 9 to 10 cycles of peak-hopping. The data acquisition was performed with the Argus program written by M.O. McWilliams and was run under a LabView environment. The raw data were processed using ArArCALC software (Koppers, 2002) and the ages were initially calculated using the decay constants recommended by Steiger and Jäger (1977). Raw Ar isotopic data are given in Annex 2. Individual errors in Annex 2 are given at the 1σ level. All the ages reported in the text, figures and summary table were subsequently recalculated after the ^{40}K and standard ages proposed by Renne et al. (2010). Blanks were monitored every 3 to 4 steps, and typical ^{40}Ar blanks range from 1×10^{-16} to 2×10^{-16} mol. Raw Ar isotopic data are given in Annex 2. Individual errors in Annex 2 are given at the 1σ level.

Our criteria for the determination of plateaus are as follows: plateaus must include at least 70% of ^{39}Ar. The plateau should be distributed over a minimum of three consecutive steps agreeing at the 95% confidence level and satisfying a probability of fit (P) of at least 0.05. Plateau ages are given at the 2σ level and are calculated using the mean of all plateau steps, each weighted by the inverse variance of their individual analytical error. Mini-plateaus are defined similarly except that they include between 50% and 70% of ^{39}Ar. Integrated ages (2σ) are calculated using the total gas released for each Ar isotope. Inverse isochrons include the maximum number of steps with a probability of fit ≥0.05, however, in all cases the data cluster near the radiogenic axis have a restricted spreading factor (S≤31%; Jourdan et al., 2009b) preventing a proper use of the isochron technique. Unless otherwise stated, the uncertainties on the $^{40}Ar^*/^{39}Ar$ ratios of the monitors are included in the calculation of the integrated and plateau age uncertainties. However, this does not include the errors on the age of the monitor and on the decay constant (internal errors only, see discussion in Min et al., 2000). External errors (i.e., including uncertainties on the ^{40}K decay constants) were calculated after Renne et al. (2010) and are considered when $^{40}Ar/^{39}Ar$ ages are compared to U/Pb ages and are reported in bracket (e.g. [±0.5] Ma).

7. Results

7.1. Whole-rock compositions of the dated rocks

The compositions of the analyzed ENA CAMP samples (Table 1) are largely consistent with previously published data for those rocks (e.g., Tollo and Gottfried, 1992) and are also broadly similar to CAMP rocks from the entire province (e.g., Bertrand, 1991). Our data confirm the similarity between stratigraphically correlative flows from the Newark and Culpeper (and Hartford) basins as shown in Fig. 2. Therefore, we will refer in the following section to the Newark basin flows, implying also the correlative flows from the other U.S.A. basins.

According to a widely used classification scheme (Weigand and Ragland, 1970), the ENA basalts are divided based on their normative and major element contents. The Orange Mountain (and equivalent) basalts are defined as HTQ (high-Ti, quartz-normative), the Preakness (and equivalent) basalts as LTQ (low-Ti, Q-normative) and as HFQ (high-Fe, Q-normative), and the Hook Mountain (and equivalent) basalts as HFTQ (high-Ti and Fe, Q-normative). All Orange Mountain and Hook Mountain flows are basalts, whereas Preakness lava flows and the Palisades and Rapidan sill samples range from basalts to basaltic andesites (Total Alkali Silica classification; Le Maitre, 2002). Orange Mountain basalts are quite homogeneous as are Hook Mountain basalts (e.g., MgO = 8.1–7.3 and 5.7–5.3 wt.%), whereas Preakness lava flows and in particular the Palisades sill samples show a strongly variable composition (e.g., MgO = 7.2–5.7 and 17.0–6.6 wt.%). These latter as well as the Rapidan sill samples probably do not correspond to magmatic near-liquidus compositions, but are in part cumulitic (cf. Steiner et al., 1992).

Minor and trace element contents and ratios are relatively uniform for each of the magmatic units and define clear differences among them (Fig. 3). The best defined differences are observed for those elements (e.g., TiO_2, REE, Zr, and Nb) that are not significantly affected by alteration and that are strongly incompatible. For example (Fig. 3A), a systematic decrease in La/Yb is evidenced from the Orange Mountain (La/Yb ca. 4.5–5.0) to the Preakness (2.6–3.2) and Hook Mountain basalts (2.1–2.2). While the Orange Mountain basalts yield REE patterns (Fig. 3B) characterized by a smooth decrease from light to heavy REE, Preakness and particularly Hook Mountain basalts yield slightly fractionated light REE (e.g., chondrite-normalized $La/Sm_{CN} = 1.7–1.8$ and 1.4, respectively), but almost flat intermediate to heavy REE ($Sm/Yb_{CN} = 1.1–1.2$ and 1.0–1.1, respectively). Orange Mountain basalts are slightly enriched compared to Preakness and Hook Mountain basalts also in terms of other incompatible elements ratios, such as Nb/La (Fig. 3C). The Palisades and Rapidan sill samples investigated here are rather similar to the Orange Mountain basalts in terms of incompatible trace element ratios and REE pattern.

7.2. Plagioclase compositions

In this section we describe the electron microprobe (EMP) analyses for plagioclase crystals of the dated U.S.A. CAMP basalts (Table 2) and compare these data with the Ca/K calculated for the plagioclase separates from $^{37}Ar/^{39}Ar$ isotopic analyses (cf. next section). Electron microprobe analyses were performed on a few (two to six) plagioclase crystals for each of the dated samples. In order to get a potentially complete set of plagioclase compositions, we analyzed by means of detailed core-rim traverses, selecting rather large crystals, in particular, which showed some optical evidence of zoning (Fig. 4).

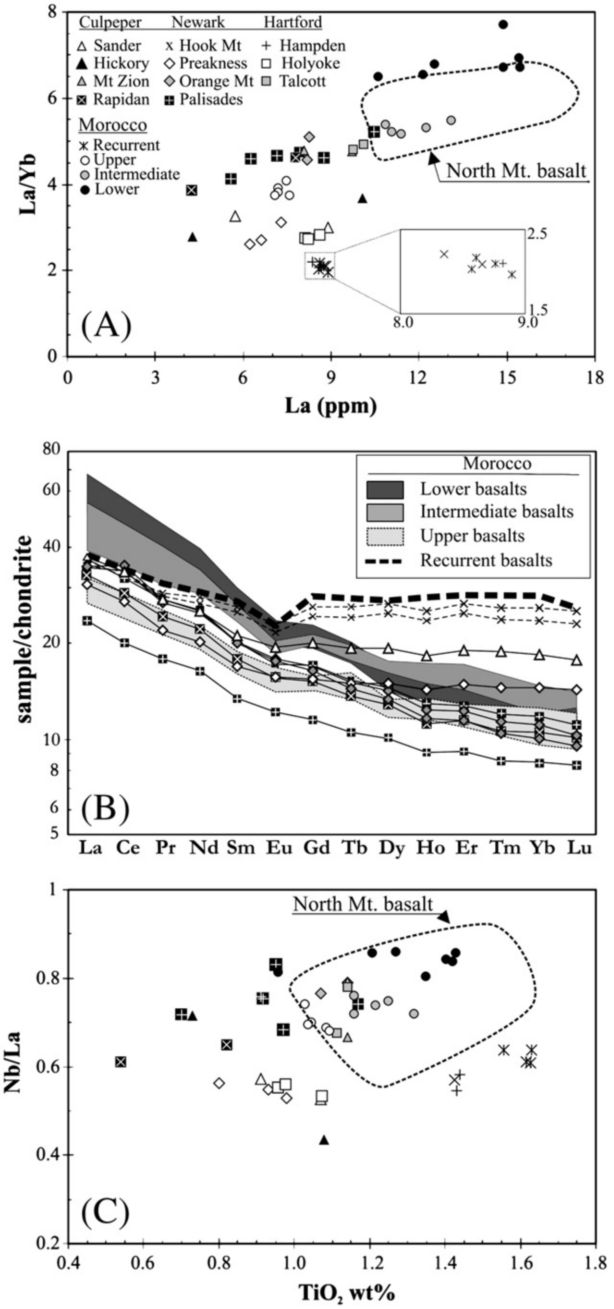

Fig. 3. REE variations for Newark, Culpeper and Hartford basins (Table 1), and from Morocco (data from Marzoli et al., 2004). In A and C, the dashed contour field shows the composition of North Mountain basalt samples, Fundy basin (data sources: Dostal and Greenough, 1992; Greenough et al., 1989). In B, following representative Newark and Culpeper samples are plotted: NEW135 and NEW18 (Palisades); NEW69 and NEW133 (Orange Mountain); NEW52 (Preakness); NEW73 and NEW74 (Hook Mountain); CUL8 (Rapidan); and CUL28 (Sander). Symbols in B are the same as in A and C.

Analyzed plagioclase crystals of most samples are normally zoned, with compositions ranging from about $An_{60–80}$ in the cores to about $An_{40–50}$ at the rims. K_2O is broadly anticorrelated with An and varies from about 0.05 to about 0.40 wt.%, from core to rim, whereas the Ca/K ratio varies between ca. 100 and 20. Significant exceptions are represented by: 1) alkali-feldspar overgrowths on certain plagioclase crystals of sample CUL8 (Rapidan sill; e.g., rim of plg d, Fig. 4); 2) oscillatory zoned plagioclase crystals of NEW18 (Palisades sill); and 3) reverse zoning in some large plagioclase phenocrysts of NEW73 and NEW74 (Hook Mountain basalt flows), with Ca/K varying between about 20 and 40 in the crystal cores and up to about 80 near the crystal rims.

The relative probability distribution of EMP analyses ($[Ca/K]_{EMP}$) of all analyzed plagioclase crystal spots for each rock sample are compared in Fig. 5 to the range of Ca/K calculated from $^{37}Ar/^{39}Ar$ isotopic analyses ($[Ca/K]_{Ar}$) of the plateau steps. In general a good overlap is observed between the two data sets. However, we note some significant exceptions which are:

1) the $[Ca/K]_{EMP}$ for the plagioclase from sample CUL8 (Rapidan sill) and CUL17 (Sander basalt) are significantly higher than their respective $[Ca/K]_{Ar}$. This discrepancy indicates that the dated material does not correspond to the plagioclase analyzed by EMP, suggesting either that the dated mineral separates were altered (by K_2O-rich minerals such as sericite), or that the contribution from alkali-feldspar overgrowths, observed in thin section, but not analyzed by EMP, was significant. Notably, the $^{40}Ar/^{39}Ar$ plateau ages obtained on plagioclase and on biotite for sample CUL8 are indistinguishable suggesting that they reflect a magmatic crystallization age.
2) both Hook Mountain basalt samples yielded apparently higher $[Ca/K]_{Ar}$ than $[Ca/K]_{EMP}$. In this case, the discrepancy is probably due to the reverse zoning of the large plagioclase crystals of the two Hook Mountain samples. Since these large crystals were analyzed mainly by EMP, a bias occurs in the resulting compositions. For Ar isotopic analyses, we separated mostly smaller crystals with a more homogeneous composition, similar to those of the large phenocryst rims, thus obtaining relatively higher $[Ca/K]_{Ar}$.

7.3. New $^{40}Ar/^{39}Ar$ ages

We present twelve new $^{40}Ar/^{39}Ar$ plateau ages obtained on ten intrusive and extrusive Culpeper and Newark basin rocks (Fig. 6; Table 3; the complete isotopic data set is given in the Annex 2 Table). For the volcanic rocks we analyzed plagioclase separates, whereas for the sills we analyzed also biotite where available. In the previous section we have shown that the Ar isotopic data for the plateau steps are generally consistent with the compositions of the analyzed plagioclase samples. We note also that all obtained plateau ages are concordant with the inverse isochron ages, yet the latter are defined by data points clustering near the $^{39}Ar/^{40}Ar$ axis and are thus poorly constrained.

For the Culpeper basin, three basalt samples were analyzed: one from the Rapidan sill and one each from the Hickory Grove and Sander lava flows, respectively. The age spectrum of the Hickory Grove basalt (sample CUL13) is strongly disturbed and did not yield a reliable age. The Sander basalt (CUL17) yielded a plateau age of 201.5 ± 1.3 Ma (all errors at the 2σ level), whereas the Rapidan sill (CUL8) yielded a plateau age of 200.8 ± 1.3 Ma for plagioclase and 201.6 ± 1.5 Ma for biotite. These plateau ages are defined by over 90% of the released ^{39}Ar, are associated with concordant Ca/K spectra, and have $P \geq 0.59$.

For the Newark basin, we analyzed three samples from the Palisades sill and five lava flow samples: two Orange Mountain, one Preakness and two Hook Mountain basalts. All of these samples yielded plateau ages with $P \geq 0.12$. For the Palisades sill, a sample from the olivine-rich level (NEW135, about 10 m above the base of the sill) yielded indistinguishable ages for plagioclase and biotite (202.8 ± 1.8 and 201.7 ± 1.2 Ma, respectively). Plagioclase separates for two samples from within the core of the Palisades sill (NEW16 and NEW18 at about 30 and 100 m above the base, respectively) yielded significantly younger plateau ages (197.5 ± 1.9 and 195.1 ± 2.1 Ma, respectively). All of these plateau ages for the Palisades sill are largely concordant (plateau defined by > 86% of released gas and $P \geq 0.12$) as are the Ca/K spectra.

Samples NEW69 and NEW133 (both from the lowest Orange Mountain lava flow), NEW52 (lowest massive Preakness flow) and NEW74 (second Hook Mountain flow) yielded well defined (>90% of

Table 2
Selected electron microprobe plagioclase analyses for the dated samples.

	Newark								Culpeper	
	NEW135	NEW16	NEW18	NEW69	NEW134	NEW52	NEW73	NEW74	CUL8	CUL17
	Palisades sill			Orange Mountain		Preakness	Hook Mountain		Rapidan sill	Sander
SiO_2 wt.%	50.05	51.85	50.82	50.31	50.65	49.88	54.24	51.11	52.00	53.24
TiO_2	0.02	0.07	0.08	0.06	0.02	0.00	0.06	0.05	0.07	0.06
Al_2O_3	30.42	30.18	30.86	30.60	30.63	30.92	27.67	29.17	29.79	29.49
Fe_2O_3	0.79	0.74	0.54	0.44	0.49	0.68	0.70	2.10	0.59	0.61
MgO	0.08	0.02	0.00	0.25	0.22	0.07	0.08	0.25	0.04	0.08
CaO	14.27	12.74	13.55	14.91	14.84	15.01	11.39	13.09	13.22	12.59
Na_2O	3.44	4.24	3.93	2.86	2.83	2.90	4.85	3.78	3.95	3.99
K_2O	0.20	0.26	0.15	0.10	0.14	0.11	0.41	0.22	0.24	0.18
Total	99.31	100.11	99.93	99.57	99.83	99.57	99.39	99.84	99.92	100.25
Albite %	30.02	37.02	34.13	25.60	25.44	25.75	42.49	33.86	34.63	36.07
Anorthite %	68.81	61.48	65.04	73.79	73.73	73.63	55.17	64.83	64.01	62.86
Orthoclase %	1.17	1.50	0.84	0.61	0.83	0.62	2.34	1.31	1.36	1.07
Ca/K	58.91	40.98	77.74	120.85	88.80	118.83	23.62	49.43	47.05	58.68

the released gas), indistinguishable plateau ages which range from 202.5 ± 2.6 Ma (NEW 133) to 200.3 ± 1.9 Ma (NEW74). These plateau ages ($P = 0.61–0.93$) also are interpreted as crystallization ages, given the overlap with the isochron ages, the atmospheric initial $^{40}Ar/^{36}Ar$ and the concordant Ca/K spectra.

A sample from the first Hook Mountain basalt lava flow (NEW73) yielded a significantly younger plateau age at 191.8 ± 2.5 Ma ($P = 0.17$). Despite the robust plateau, defined by 90% of the released gas, the Ca/K is slightly discordant, yielding a tilde-shaped increasing trend for Ca/K of about 50 to about 90, suggestive of either a slight alteration with sericite (cf. Verati and Féraud, 2003) or magmatic zoning. Notably, this basalt was sampled from just below the second Hook Mountain basalt flow NEW74. These two basalts have almost indistinguishable major and trace element whole-rock composition and contain similar zoned plagioclase crystals (An_{50}–An_{70}). Like for NEW74 (yet at lower absolute values), the $[Ca/K]_{Ar}$ values for NEW73 are consistent with the $[Ca/K]_{EMP}$ of the highest An plagioclase crystal zones. Since there is no field evidence that NEW73 belongs to a sill and considering its significantly higher $^{87}Sr/^{86}Sr$ initial isotopic composition (0.70681 vs. 0.70563), we conclude that the lower $[Ca/K]_{Ar}$ (when compared to NEW74) and the tilde-shaped $[Ca/K]_{Ar}$ spectrum indicate that the young plateau age of NEW73 is most probably related to a late (cryptic) postmagmatic alteration event.

8. Discussion

8.1. Geochemical correlations of circum-Atlantic flows

Incompatible element contents and ratios, particularly when measured with the same instrument, are powerful tools to investigate circum-Atlantic geochemical correlations of CAMP lava flows. Our new ICP-MS trace element data for the U.S.A. CAMP basalts help refine previously proposed correlations between these basalts and those from the Moroccan High Atlas basins (Bertrand and Coffrant, 1977; Deenen et al., 2010; Marzoli et al., 2004). Globally, incompatible element data such as REE show that CAMP basalts from the U.S.A. basins and from the Moroccan High Atlas may be divided into two main groups. One group is characterized by enriched light vs heavy REE (e.g., La/Yb) and by high Nb/La, and defines broadly correlated incompatible element ratios vs incompatible element variations (e.g., La/Yb vs La; Fig. 3A). This "enriched group" is defined by Moroccan Lower, Intermediate and Upper basalts as well as by the Orange Mountain and correlative U.S.A. lava flows and the Palisades and Rapidan sills. Within this group, a clear variation of incompatible element ratios is observed from the Lower Moroccan basalts (e.g., most enriched in La/Yb) to the Palisades sill samples (e.g., less enriched in La/Yb), with the Orange Mountain and equivalent U.S.A. flows plotting between the Moroccan Intermediate and Upper basalts. More problematic are geochemical correlations with the North Mountain basalt of the Fundy basin because the latter, despite being divided into three lava flow units (Kontak, 2008), does not show a clear time-related geochemical evolution. Based on published data (e.g., Dostal and Greenough, 1992; Greenough et al., 1989), the North Mountain basalt samples show relatively large variations. They plot within the "enriched" group overlapping those of the Moroccan Intermediate and partly Lower basalts (e.g., in La/Yb or Nb/La), but do not correlate in any straightforward fashion to any specific U.S.A. or Moroccan CAMP flow unit (Marzoli et al., 2008).

The second depleted group is represented by the Hook Mountain and equivalent flows and by the Moroccan Recurrent basalts. Considering the large set of differentiation processes (e.g., fractional crystallization at various crustal depths, variable degrees of crustal contamination, and variable degrees of mantle melting) possibly experienced by CAMP basalts, a surprisingly good data overlap exists between the Hook Mt., Hampden and the Moroccan Recurrent basalts. They are characterized by almost flat REE patterns (La/Yb ratio ~2), low Nb/La (Fig. 3), and significantly higher Nd and Pb and lower Sr isotopic compositions as compared to the other lava flows from these basins (e.g., Bertrand et al., 1982; Marzoli et al., 2004, 2006; Pegram, 1990; Puffer, 1992; Tollo and Gottfried, 1992). Since there is a general consensus that crustal assimilation did not modify the CAMP magmas significantly (Pegram, 1990; Merle et al., in press), these distinct (enriched vs depleted) geochemical features probably reflect distinct mantle sources for the early (e.g. Orange Mountain) vs the late (e.g., Hook Mountain) CAMP magmas. In general terms, the trace element and isotopic compositions of Hook Mountain and Recurrent basalts trend towards those of Atlantic MORBs (e.g., Janney and Castillo, 2001) whereas the Orange Mountain, the Moroccan Lower to Upper basalts and the Nova Scotia North Mountain basalt (the enriched group) have a dominant sub-continental lithospheric mantle signature (Dostal and Greenough, 1992; Marzoli et al., 2006; Pegram, 1990; Puffer, 1992). Notably, Preakness basalts have trace element and isotopic compositions transitional between the Orange Mountain and the Hook Mountain basalts and cannot be easily correlated with lava flows from the adjacent continent.

8.2. Onset and peak age of Newark and Culpeper CAMP magmatism

Our new $^{40}Ar/^{39}Ar$ plateau age data confirm that CAMP lava flows and related sills were synchronously emplaced in the circum-Atlantic regions. If we consider only the new data for the lava flows from the

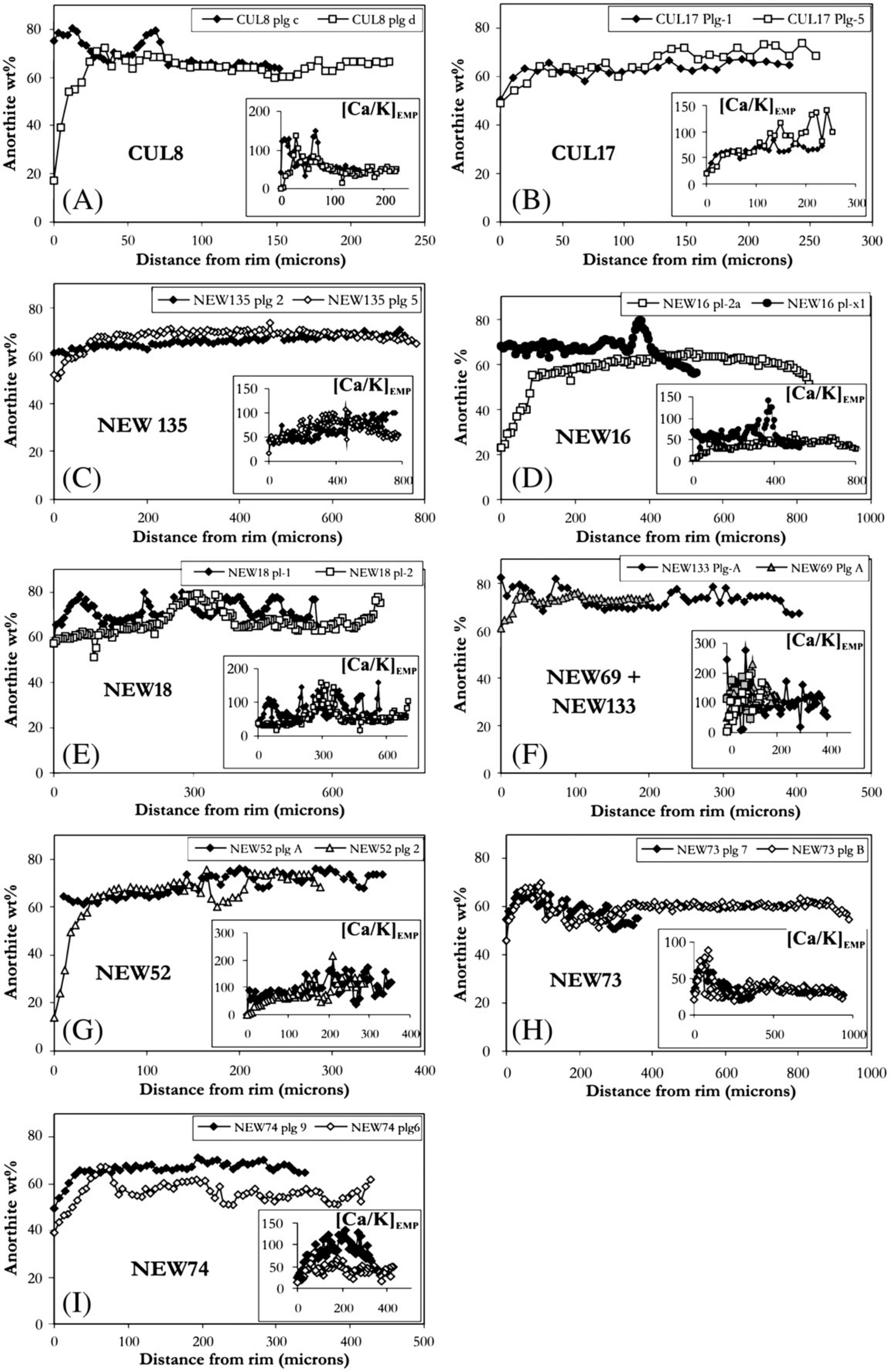

Fig. 4. Anorthite [100 * Ca / (Ca + Na + K)] and Ca/K electron microprobe core–rim traverses for representative plagioclase phenocrysts for the dated Newark and Culpeper basalts.

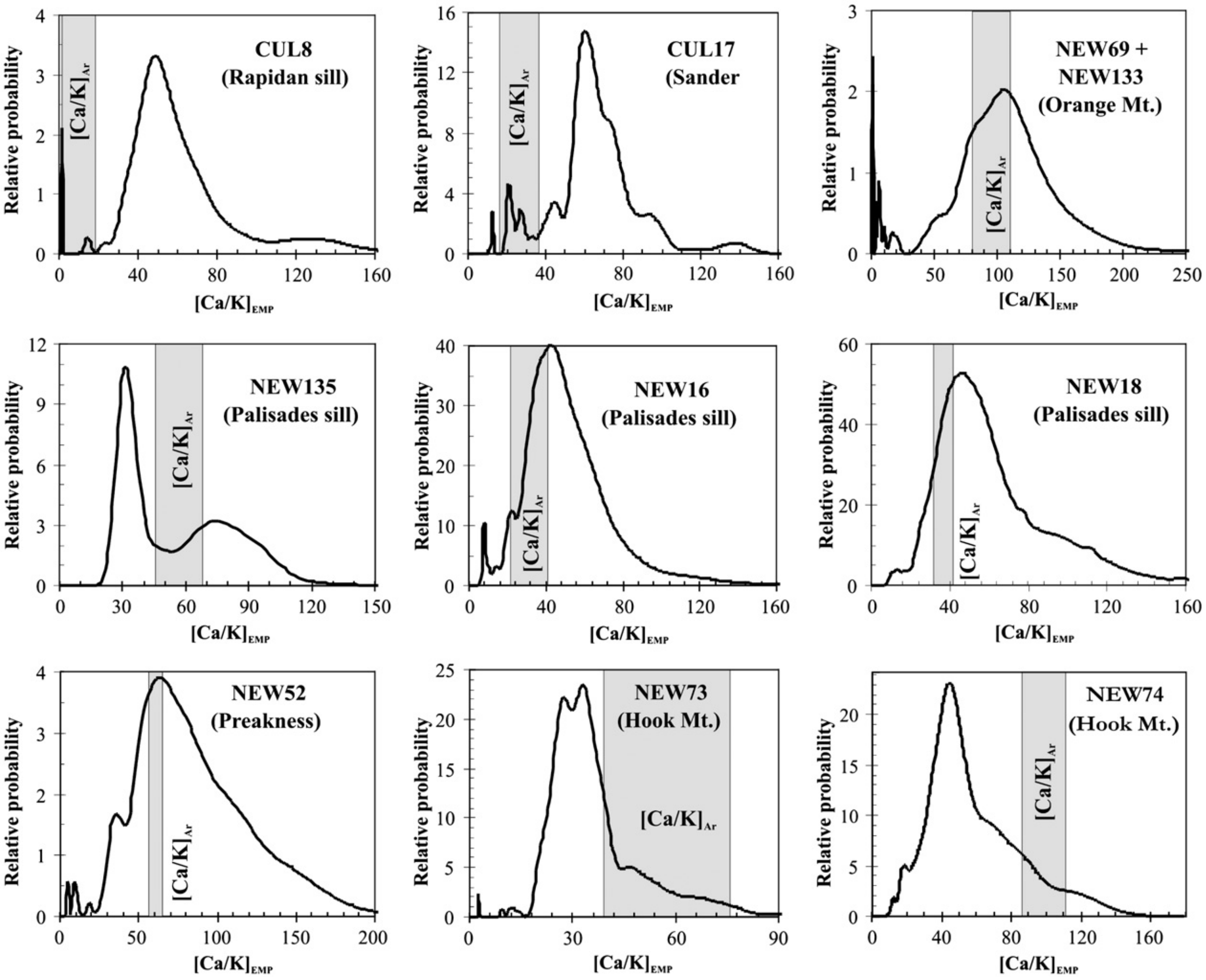

Fig. 5. The probability distribution of electron microprobe $[Ca/K]_{EMP}$ for all analyzed plagioclase phenocrysts of the dated basalts is compared to the range of $[Ca/K]_{Ar}$ calculated from $^{37}Ar/^{39}Ar$ isotopic analyses of $^{40}Ar/^{39}Ar$ plateau steps.

Culpeper and the Newark basins (n = 5 excluding NEW73), which comprise the lowest to highest lava flows (Orange Mountain and Hook Mountain, respectively), these are all indistinguishable in age (weighted mean age: 201.4 ± 0.9 Ma; Fig. 7). Such $^{40}Ar/^{39}Ar$ data are overlapping with the synmagmatic alteration ages of the nearby Hartford basin (Jourdan et al., 2009a) and with previously suggested (mini-plateau) ages for the Orange Mountain and Hook Mountain basalts (Hames et al., 2000). Further, they are consistent with a duration of ca. 0.6 Ma of the volcanic event in the U.S.A. basins as suggested by cyclostratigraphic analyses (Olsen et al., 1996; Whiteside et al., 2007). Except for the two younger Palisades sill samples (NEW16 and NEW18), the dated sills also yield similar ages (weighted mean age including sills and lava flows: 201.8 ± 0.7 Ma).

The mean age and duration of the peak phase of magmatism in the U.S.A. basins is indistinguishable from that of the peak activity in the Fundy basin (201.6 ± 1.1; n = 7; Jourdan et al., 2009a) and from the mean age of Moroccan Lower to Upper basalts (201.2 ± 0.9 Ma; n = 16). This is consistent with bio- and magnetostratigraphic correlations (Cirilli et al., 2009; Deenen et al., 2010; Marzoli et al., 2004). Globally, the occurrence of a similar palynological assemblage comprising *P. densus* up to (Morocco) or almost up to (Fundy and Newark) the first CAMP basalt suggests, but does not prove, a biostratigraphically near-equivalent (i.e. within a time interval of a few tens ka) onset of CAMP volcanism in these circum-Atlantic basins. In detail, Moroccan basalts seem to be the biostratigraphically oldest preserved flows of the circum-Atlantic basins (Fig. 2), given the last occurrence of *P. densus* right up to the first High Atlas flows (Marzoli et al., 2004). Deenen et al. (2010), for example, make a correlation that would indicate the initiation of CAMP volcanism in the Argana basin (Morocco) as preceding that in the Newark basin by 20 ka.

We note also that the $^{40}Ar/^{39}Ar$ ages, when recalculated after Renne et al. (2010), are directly comparable with single-zircon U/Pb ages for CAMP basalts and for the TJb (e.g., Schoene et al., 2006, 2010; Schaltegger et al., 2008). In this sense, the newly recalculated peak activity of CAMP in northern America at 201.54 ± 0.85 [1.38] Ma (Fig. 7; [1.38] denotes all sources of uncertainty) is indistinguishable from the U/Pb age of the TJ-b (201.31 ± [0.43]) and of a Fundy basin CAMP basalts (201.38 ± [0.31] Ma; Schoene et al., 2010).

8.3. Duration of CAMP volcanism in the circum-Atlantic basins

While the onset of CAMP volcanism is near-synchronous in the circum-Atlantic basins, the distinguishably younger Recurrent basalts from Morocco (mean age 198.2 ± 1.1 Ma, P = 0.59; n = 6; Verati et al., 2007) suggest a longer duration for volcanism in Morocco as compared to its North American counterpart. It may be argued that the age difference between the Recurrent and the Hook Mountain basalts is not significant. In fact, the only valid magmatic crystallization age for the Hook Mountain basalt (200.3 ± 1.9 Ma, NEW74) barely overlaps with the weighted mean age of the Recurrent basalts. In addition, the $^{40}Ar/^{39}Ar$ mini-plateau age of 200.7 ± 2.0 Ma obtained by Hames et al. (2000) on a Hook Mountain basalt is consistent with

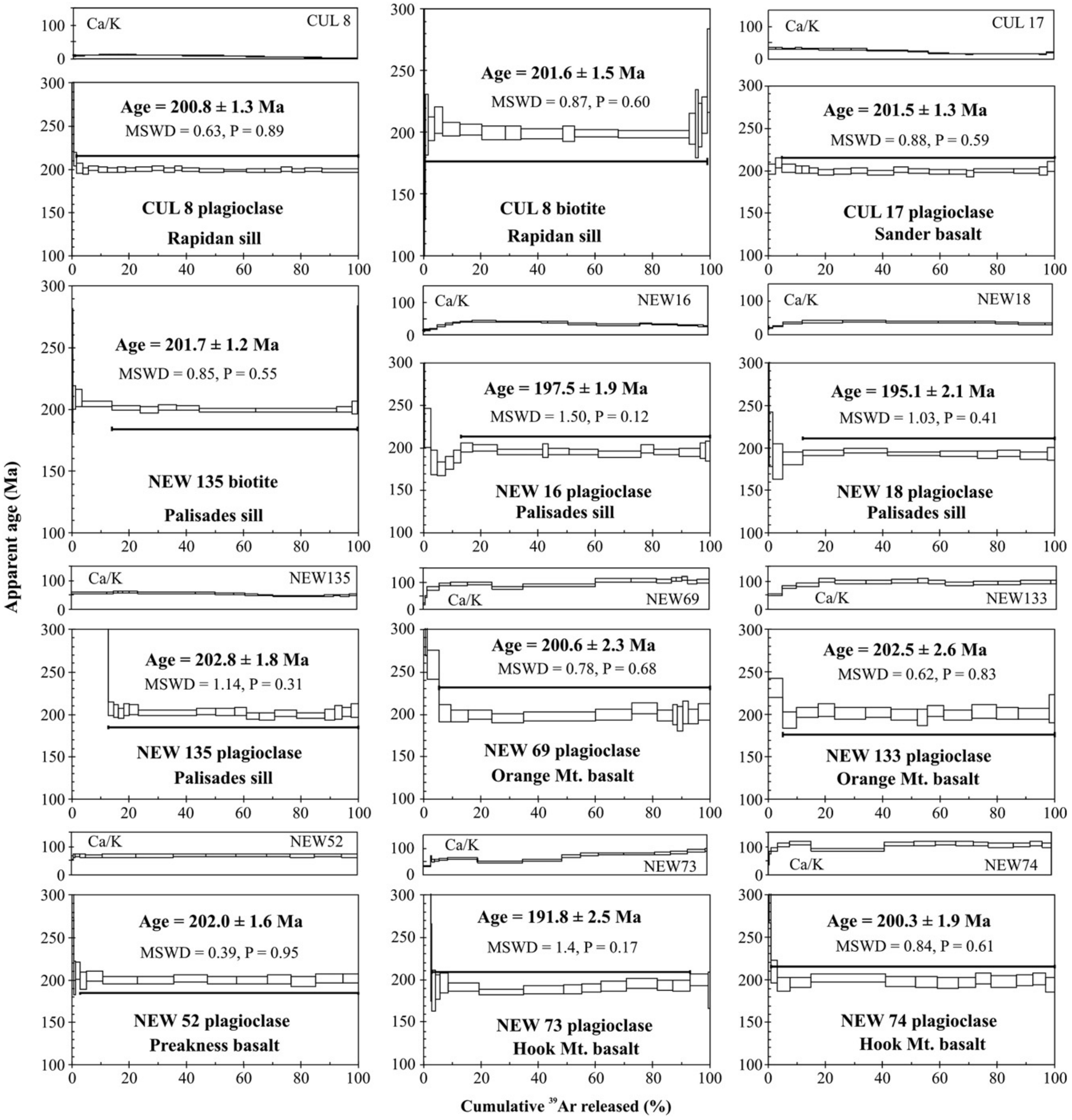

Fig. 6. $^{40}Ar/^{39}Ar$ age and Ca/K (calculated from $^{37}Ar/^{39}Ar$) spectra for Newark and Culpeper rocks. Errors are shown at 2σ level. Bold lines show steps included in plateau age calculations. Hb3gr hornblende is used as a neutron fluence monitor for which an age of 1074 ± 5 Ma was adopted (Jourdan et al., 2006; Turner et al., 1971. The ages were initially measured and calculated using the decay constants recommended by Steiger and Jäger (1977)) and subsequently recalculated using the updated ^{40}K constant and standard age (1080.1 ± 1.1 Ma; Renne et al., 2010) . Isotopic data are given in the Annex 2 Table.

our results. Further support for an age close to ~201 Ma for the Hook Mountain basalt is given by the alteration plateau ages for the nearby chemically and stratigraphically equivalent Hampden basalt (Hartford basin: 201.7 ± 1.1 and 200.4 ± 2.0 Ma; Jourdan et al., 2009a). Such ages were interpreted as syn-crystallization ages and are in any case strict minimum ages for the emplacement of the Hampden basalts. Our new age, together with the mini-plateau age of Hames et al. (2000) and the alteration ages for the Hampden basalts, yield a weighted mean of 200.7 ± 0.7 Ma (P = 0.52). Such a mean age, while statistically indistinguishable from the mean age of the U.S.A. CAMP volcanism and consistent with the short duration established by cyclostratigraphy (Olsen et al., 1996; Whiteside et al., 2007), is nonetheless clearly older than the age of the Recurrent basalt in Morocco.

The Hook Mountain, Hampden, and Moroccan Recurrent basalts define the previously described “depleted” group rocks from the circum-Atlantic basins. As in other continental flood basalt provinces (e.g., Jourdan et al., 2007b; Raposo et al., 1998), late magmas with an E-MORB-like signature such as the Hook Mountain and Recurrent basalts probably document the main phase of continental lithospheric thinning and herald the beginning of oceanization. In this scenario, our age data suggest a migration of the main lithospheric extensional phase from the Newark basin toward the farther northern High Atlas

Table 3
Summary of Ar/Ar age data. Plateau ages are calculated after Renne et al. (2010).

General characteristics					Plateau characteristics						Inverse isochron characteristics				
Sample	Lab N°	Unit	Mineral	Integrated age (Ma, ±2σ)	n	Plateau age (Ma, ±2σ)	Total ^{39}Ar released (%)	Attribute	MSWD	P	Isochron age (Ma, ±2σ)	n	^{40}Ar/^{36}Ar intercept (±2σ)	MSWD	Observation
Newark basin															
NEW73	NEW-73-plagio	Hook Mountain	Plagioclase	195.9 ± 2.5	16	191.80 ± 2.5	90%	Plateau	1.4	0.17	190.0 ± 4.2	12	323 ± 53	1.36	Clustering near ^{39}Ar/^{40}Ar axis
NEW74	NEW-74-plagio	Hook Mountain	Plagioclase	202.1 ± 2.0	15	200.4 ± 1.9	99%	Plateau	0.84	0.61	199.2 ± 3.1	13	314 ± 40	0.83	Clustering near ^{39}Ar/^{40}Ar axis
NEW52	NEW-52-plg2	Preakness	Plagioclase	202.8 ± 1.6	14	202.0 ± 1.6	97%	Plateau	0.39	0.95	201.6 ± 3.5	11	303 ± 68	0.43	Clustering near ^{39}Ar/^{40}Ar axis
NEW69	NEW-69-plagio	Orange Mountain	Plagioclase	206.6 ± 2.5	16	200.6 ± 2.3	94%	Plateau	0.78	0.68	197.4 ± 4.9	13	335 ± 54	0.62	Clustering near ^{39}Ar/^{40}Ar axis
NEW133	NEW-133-plagio	Orange Mountain	Plagioclase	204.0 ± 2.6	14	202.5 ± 0.6	95%	Plateau	0.62	0.83	204.9 ± 5.2	13	279 ± 33	0.59	Clustering near ^{39}Ar/^{40}Ar axis
NEW135	NEW-135-bio	Palisades	Biotite	206.1 ± 0.8	9	202.2 ± 3.1	72%	Plateau	1.06	0.38	200.7 ± 8.2	5	304 ± 44	1.34	Clustering near ^{39}Ar/^{40}Ar axis
NEW135	NEW-135-bio2	Palisades	Biotite (2nd aliquot)	202.5 ± 1.2	14	201.7 ± 1.2	86%	Plateau	0.85	0.55	201.3 ± 1.76	8	319 ± 68	0.91	Clustering near ^{39}Ar/^{40}Ar axis
NEW135	NEW-135-plagio	Palisades	Plagioclase	202.0 ± 3.0	18	202.8 ± 1.8	87%	Plateau	1.14	0.31	202.4 ± 2.2	17	302 ± 19	1.18	Clustering near ^{39}Ar/^{40}Ar axis
NEW16	NEW-16-plagio	Palisades	Plagioclase	197.1 ± 0.74	18	197.5 ± 1.9	87%	Plateau	1.50	0.12	194.6 ± 3.4	12	337 ± 42	1.12	Clustering near ^{39}Ar/^{40}Ar axis
NEW18	NEW-18-plg2	Palisades	Plagioclase	194.8 ± 0.2	12	195.1 ± 2.1	88%	Plateau	1.03	0.41	196.1 ± 3.7	8	285 ± 33	1.14	Clustering near ^{39}Ar/^{40}Ar axis
Culpeper basin															
CUL17	CUL-17-plagio	Sander	Plagioclase	201.9 ± 1.36	19	201.5 ± 1.3	95%	Plateau	0.88	0.59	200.4 ± 1.9	17	310 ± 19	0.75	Clustering near ^{39}Ar/^{40}Ar axis
CUL8	CUL-8-plagio	Rapidan	Plagioclase	201.9 ± 1.3	23	200.8 ± 1.3	98%	Plateau	0.63	0.89	201.5 ± 1.4	20	304 ± 7	0.61	Clustering near ^{39}Ar/^{40}Ar axis
CUL8	CUL-8-bio	Rapidan	Biotite	202.6 ± 1.5	18	201.7 ± 1.5	99%	Plateau	0.87	0.6	201.0 ± 2.4	16	334 ± 44	0.67	Clustering near ^{39}Ar/^{40}Ar axis
CUL13	CUL-13-plg	Hickory Grove	Plagioclase	232.0 ± 2.0	No plateau						No isochron age				

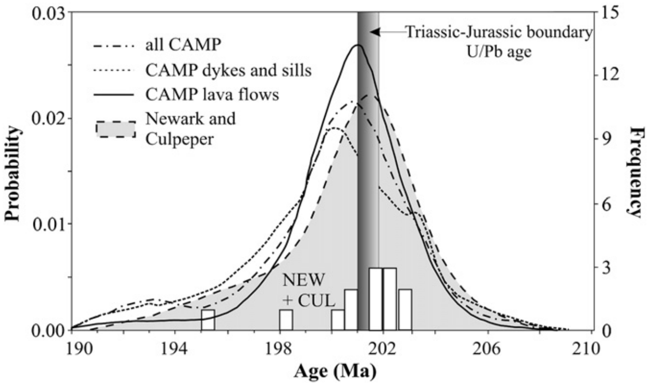

Fig. 7. The probability distribution of ^{40}Ar/^{39}Ar plateau ages for the analyzed Culpeper and Newark samples (gray field, dashed contour) is compared to those of all CAMP basalts (dashed contour), of all CAMP lava flows (continuous line) and of sills and dykes (dotted line). Data references and selection criteria of ^{40}Ar/^{39}Ar plateau ages are given in the text. The white boxes refer to the frequency of the new ^{40}Ar/^{39}Ar plateau ages of Culpeper and Newark samples. The U/Pb age of the Triassic–Jurassic boundary (201.31 ± 0.43 Ma) is after Schoene et al. (2010). ^{40}Ar/^{39}Ar and U/Pb ages include external errors.

basins of Morocco (Fig. 1). This migration is consistent with the diachronous northward rift–drift transition documented by Withjack et al. (1998) and Schlische and Withjack (2003).

8.4. Duration of the Palisades intrusions

Our new age data suggest that intrusive activity in the Palisades sill lasted from 202.8 ± 1.8 Ma to 195.1 ± 2.1 Ma, i.e. much longer than the extrusive activity in the Newark basin (201.3 ± 2.0 Ma; n = 4). Such a scenario, in which peak eruptive activity occurred entirely within a short time span (within analytical error), but intrusive activity in the circum-Atlantic continued for some millions of years, is consistent with ^{40}Ar/^{39}Ar plateau ages for dykes from the Carolinas, which range from 202.1 ± 1.5 Ma to 195.2 ± 2.0 Ma (Beutel et al., 2004; Nomade et al., 2007). Very significantly, ^{40}Ar/^{39}Ar plateau ages for the ca. 1 km thick Kakoulima intrusion and the up to 0.5 km thick Fouta Djalon sills in Guinea (204.7 ± 1.5 to 196.7 ± 2.2 Ma; 203.5 ± 0.2 to 192.3 ± 0.6 Ma, respectively; Deckart et al., 1997) also suggest a similarly prolonged intrusion of CAMP magmas within single intrusive bodies on the African continent. In particular, as for the Palisades sill, the relatively young ages for the Guinean intrusions were obtained on samples from their central portions.

Evidence for multiple magma injection events is provided by multiple geochemical and petrological studies on the Palisades sill even though field evidence for such phenomena is not obvious. In particular, comparison to the geochemically similar erupted basalts and consideration of the cyclostratigraphically derived time constraints of Whiteside et al. (2007) suggested to Puffer et al. (2009) that Palisades magma intrusions through the Fort Lee section occurred as pulses over a period of about 0.3 Ma, with early magmas similar to the Orange Mountain lava flows and late magmas similar to the Preakness basalts. Our new data are not inconsistent with Puffer et al. (2009) because the portion of the Palisades they correlate with the Preakness basalts was not dated by us. The analytically robust younger plateau ages of 197–195 Ma obtained on the samples NEW16 and NEW18 instead document late re-injections of magma within the lower half of the Palisades sill. Notably, these two samples are Cr- (664 and 535 ppm) and pyroxene-rich and were collected at the same level (about 30 and 100 m above the base of the sill) where Shirley (1987) and Gorring and Naslund (1995) observed peaks in Cr and pyroxene contents in their detailed geochemical traverses at Fort Lee. These levels were interpreted as sites of magma re-injections or as the result of normal faulting. Despite the lack of clear field evidence for late intrusions, such as chilled margins (also noted by previous authors, e.g., Gorring and Naslund, 1995; Puffer et al., 2009; Shirley, 1987; Walker, 1969), late magmas may have intruded into very low angle fault plains intersecting the lower Palisades just north of Fort Lee.

9. Conclusions

^{40}Ar/^{39}Ar plateau ages were obtained for ten sill and lava flow samples from the Newark and Culpeper basins. The ^{40}Ar/^{39}Ar plateau ages, recalculated after Renne et al. (2010), were obtained on biotite and on fresh plagioclase and are supported by a general consistency of the $[Ca/K]_{Ar}$ calculated from ^{37}Ar/^{39}Ar of the plateau steps and the $[Ca/K]_{EMP}$ obtained by detailed electron microprobe analyses on plagioclase phenocrysts. Eleven ^{40}Ar/^{39}Ar plateau ages on nine rocks are therefore interpreted as magmatic crystallization ages and show that CAMP magmatism in the Newark and Culpeper basins had a short peak activity at 201.4 ± 0.9 Ma. Overall, the mean ^{40}Ar/^{39}Ar age in North America (201.5 ± 0.9 Ma) is indistinguishable from the U/Pb age of the TJb (201.31 ± 0.43 Ma) and from the mean age of the magmatism from the entire CAMP, and in particular from the other circum-Atlantic basins (High Atlas, Fundy) where CAMP lava flows are preserved. A nearly synchronous onset of CAMP volcanism in all circum-Atlantic basins is consistent with bio-, chemo- and magnetostratigraphic correlations, even if detailed palynological analysis suggests that CAMP volcanism may have started slightly earlier in Morocco than in the Newark and Culpeper basins. Late magmatic activity is represented in the Newark basin by late-intruded portions of the Palisades sill (ca. 197–195 Ma), whereas in Morocco the Recurrent basalts were erupted significantly after eruption of the (preserved) North American basalts (Orange Mountain to Hook Mountain).

Geochemical compositions confirm that eruptions of basaltic magmas with similar composition were nearly synchronous in North America and in Morocco. In particular, the early erupted magmas (Moroccan Lower to Upper basalts, Orange Mountain and equivalent U.S.A. flows, and the Fundy basin North Mountain Basalt) yield an enriched geochemical signature, which, according to previous studies may reflect a dominant lithospheric contribution. Late magmas in the U.S.A. (Hook Mountain and Hampden basalts) and Morocco (Recurrent basalt) yield relatively depleted geochemical compositions, suggesting significant contribution from a MORB-like mantle source, possibly as a result of upwelling of the asthenosphere during the break-up of Pangea (Maillard et al., 2006). Significantly younger ages for the Recurrent basalts in comparison to the Hook Mountain basalts suggest that this upwelling was diachronous, possibly as a result of the northward rift–drift transition documented by Withjack et al. (1998) and Schlische and Withjack (2003).

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