The Central Atlantic Magmatic Province (CAMP) in Morocco

MARZOLI, Andrea, et al.

Abstract

The Central Atlantic Magmatic Province (CAMP) is a large igneous province (LIP) composed of basic dykes, sills, layered intrusions and lava flows emplaced before Pangea break-up and currently distributed on the four continents surrounding the Atlantic Ocean. One of the oldest, best preserved and most complete sub-provinces of the CAMP is located in Morocco. Geochemical, geochronologic, petrographic and magnetostratigraphic data obtained in previous studies allowed identification of four strato-chemical magmatic units, i.e. the Lower, Intermediate, Upper and Recurrent units. For this study, we completed a detailed sampling of the CAMP in Morocco, from the Anti Atlas in the south to the Meseta in the north. We provide a complete mineralogical, petrologic (major and trace elements on whole-rocks and minerals), geochronologic (40Ar/39Ar and U–Pb ages) and geochemical set of data (including Sr–Nd–Pb–Os isotope systematics) for basaltic and basaltic–andesitic lava flow piles and for their presumed feeder dykes and sills. Combined with field observations, these data suggest a very rapid

Reference


DOI : 10.1093/petrology/egz021

Available at:
http://archive-ouverte.unige.ch/unige:127436

Disclaimer: layout of this document may differ from the published version.
The Central Atlantic Magmatic Province (CAMP) in Morocco

Andrea Marzoli1*, Hervé Bertrand2, Nasrddine Youbi3,4, Sara Callegaro5, Renaud Merle6, Laurie Reisberg7, Massimo Chiaradia8, Sarah I. Brownlee9, Fred Jourdan10, Alberto Zanetti11, Joshua H.F.L. Davies6†, Tiberio Cuppone1, Abdelkader Mahmoudi12, Fida Medina13, Paul R. Renne14,15, Giuliano Bellieni1, Stefano Crivellari16, Hind El Hachimi17, Mohamed Khalil Bensalah3,4, Christine M. Meyzen1 and Christian Tegner18

1Geoscience Department, Padova University and IGG-CNR, Padova, Italy; 2Laboratoire de Géologie de Lyon, Université Lyon 1, CNRS UMR 5276, Université de Lyon, Lyon, France; 3Department of Geology, Faculty of Sciences-Semlalia, Cadi Ayyad University, Marrakech, Morocco; 4Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal; 5Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Oslo, Norway; 6Department of Geosciences, Swedish Museum of Natural History, Stockholm SE-104 05, Sweden; 7Centre de Recherches Pétrographiques et Géochimiques, UMR 7358 CNRS-Université de Lorraine, France; 8Department of Earth Sciences, University of Geneva, Genève, Switzerland; 9Department of Geology, Wayne State University, Detroit, USA; 10Department of Applied Geology, Curtin University, Bentley, Australia; 11IGG-CNR, Pavia, Italy; 12Département de Géologie, Université Moulay-Ismail, Meknes, Morocco; 13Moroccan Association of Geosciences, Rabat, Morocco; 14Berkeley Geochronology Center, Berkeley, USA; 15Department of Earth and Planetary Science, University of California, USA; 16Instituto de Geociencias, University of São Paulo, São Paulo, Brazil; 17Department of Geology, Faculty of Sciences, Chouaib Doukkali University, El Jadida, Morocco; 18Centre of Earth System Petrology (ESP), Department of Geoscience, Aarhus University, Denmark

*Corresponding author. E-mail: andrea.marzoli@unipd.it
†Present address: Département des sciences de la Terre et de l'atmosphère, Université du Québec à Montréal, 201, avenue du Président-Kennedy, Montréal, Québec, H2X 3Y7, Canada

Received June 5, 2018; Accepted April 1, 2019

ABSTRACT

The Central Atlantic Magmatic Province (CAMP) is a large igneous province (LIP) composed of basic dykes, sills, layered intrusions and lava flows emplaced before Pangea break-up and currently distributed on the four continents surrounding the Atlantic Ocean. One of the oldest, best preserved and most complete sub-provinces of the CAMP is located in Morocco. Geochemical, geochronologic, petrographic and magnetostatigraphic data obtained in previous studies allowed identification of four strato-chemical magmatic units, i.e. the Lower, Intermediate, Upper and Recurrent units. For this study, we completed a detailed sampling of the CAMP in Morocco, from the Anti Atlas in the south to the Meseta in the north. We provide a complete mineralogical, petrologic (major and trace elements on whole-rocks and minerals), geochronologic (40Ar/39Ar and U–Pb ages) and geochemical set of data (including Sr–Nd–Pb–Os isotope systematics) for basaltic and basaltic–andesitic lava flow piles and for their presumed feeder dykes and sills. Combined with field observations, these data suggest a very rapid (<0.3 Ma) emplacement of over 95% of the preserved magmatic rocks. In particular, new and previously published data for the Lower to Upper unit samples yielded indistinguishable 40Ar/39Ar (mean age = 201 ± 0.8 Ma) and U–Pb ages (201.5 ± 0.04 Ma), suggesting emplacement
coincident with the main phase of the end-Triassic biotic turnover (c.201.5 to 201.3 Ma). Eruptions are suggested to have been pulsed with rates in excess of 10 km³/year during five main volcanic pulses, each pulse possibly lasting only a few centuries. Such high eruption rates reinforce the likelihood that CAMP magmatism triggered the end-Triassic climate change and mass extinction. Only the Recurrent unit may have been younger but by no more than 1 Ma. Whole-rock and mineral geochemistry constrain the petrogenesis of the CAMP basalts. The Moroccan magmas evolved in mid-crustal reservoirs (7–20 km deep) where most of the differentiation occurred. However, a previous stage of crystallization probably occurred at even greater depths. The four units cannot be linked by closed-system fractional crystallization processes, but require distinct parental magmas and/or distinct crustal assimilation processes. EC-AFC modeling shows that limited crustal assimilation (maximum 5–8% assimilation of e.g. Eburnean or Pan-African granites) could explain some, but not all the observed geochemical variations. Intermediate unit magmas are apparently the most contaminated and may have been derived from parental magmas similar to the Upper basalts (as attested by indistinguishable trace element contents in the augites analysed for these units). Chemical differences between Central High Atlas and Middle Atlas samples in the Intermediate unit could be explained by distinct crustal contaminants (lower crustal rocks or Pan-African granites for the former and Eburnean granites for the latter). The CAMP units in Morocco are likely derived from 5–10% melting of enriched peridotite sources. The differences observed in REE ratios for the four units are attributed to variations in both source mineralogy and melting degree. In particular, the Lower basalts require a garnet peridotite source, while the Upper basalts were probably formed from a shallower melting region straddling the garnet-spinel transition. Recurrent basalts instead are relatively shallow-level melts generated mainly from spinel peridotites. Sr–Nd–Pb–Os isotopic ratios in the CAMP units from Morocco are similar to those of other CAMP sub-provinces and suggest a significant enrichment of the mantle-source regions by subducted crustal components. The enriched signature is attributed to involvement of about 5–10% recycled crustal materials introduced into an ambient depleted or PREMA-type mantle, while involvement of mantle-plume components like those sampled by present-day Central Atlantic Ocean Island Basalts (OIB, e.g. Cape Verde and Canary Islands) is not supported by the observed compositions. Only Recurrent basalts may possibly reflect a Central Atlantic plume-like signature similar to the Common or FOZO components.

**Key words:** Central Atlantic Magmatic Province (CAMP); large igneous province (LIP); geochronology; basalt petrogenesis; crustal contamination; Morocco

### INTRODUCTION

The Central Atlantic magmatic province (CAMP) is a large igneous province (LIP) composed almost exclusively of basic rocks (Marzoli et al., 1999, 2018). These crop out as dykes, sills, a few layered intrusions and lava flows in the four continents surrounding the Atlantic Ocean (Fig. 1a) spanning an inferred original total surface area exceeding 10 million km², with an estimated total volume of more than 3 million km³ (Marzoli et al., 2018). Emplacement of the CAMP occurred in an extensional tectonic setting, heralding break-up of the mega-continent Pangaea and opening of the Central Atlantic Ocean (Sahabi et al., 2004; Labails et al., 2010). CAMP magmatism was synchronous with one of the most severe environmental and biotic crises in Earth's history, which occurred during the latest Triassic (Hesselbo et al., 2002; Marzoli et al., 2004, 2008, 2011; Blackburn et al., 2013; Davies et al., 2017). CAMP is, therefore, one of the biggest LIP events ever recorded and its emplacement influenced the tectonics of Earth's continental plates and the evolution of life on our planet.

One of the oldest sub-provinces of the CAMP is located in Morocco where c.201 Ma volcanic and intrusive basaltic rocks are widespread and well exposed. Indeed, the first studies that recognized the existence and importance of a circum-Atlantic Triassic–Jurassic tholeiitic magmatic province were conducted in Morocco and in the once contiguous regions of North America (e.g. Manspeizer et al., 1978; Bertrand et al., 1982). Various aspects of the CAMP event in Morocco, including time-related evolution of the basaltic lavas, their age and their bearing on the end-Triassic mass extinction event have been investigated in the past (e.g. Bertrand et al., 1982; Sebai et al., 1991; Youbi et al., 2003; Knight et al., 2004; Marzoli et al., 2004; Nomade et al., 2007; Verati et al., 2007; Deenen et al., 2010; Dal Corso et al., 2014). However, a comprehensive geochemical-petrologic-geochronologic study of CAMP magmatism from throughout Morocco has never been published. Here, we intend to fill this gap by providing and discussing a large number of mineralogical (including mineral trace elements), geochemical (including Sr–Nd–Pb–Os isotopes) and geochronologic data (including ⁴⁰Ar/³⁹Ar and U–Pb ages) for both intrusive and effusive mafic rocks from throughout Morocco to decipher their eruption mechanism and rate, mantle
source and any temporal evolution. This work aims to improve our understanding of the global geodynamic and environmental consequence of CAMP magmatism in particular and potentially for LIPs in general. A companion paper (Tegner et al. in press) focuses on mantle dynamics of the Moroccan CAMP as constrained by their Platinum Group Element geochemistry.

Overview of CAMP magmatism

The CAMP shares common aspects with other continental LIPs, such as the Karoo, the Paraná-–Etendeka, the Deccan, the Ethiopian Traps and the North Atlantic Igneous Province (Hofmann et al., 1997; Peate, 1997; Tegner et al., 1998; Melluso et al., 2006; Jourdan et al., 2007; Heinonen et al., 2016; Parisio et al., 2016; De Min et al., 2018). Common features of these LIPs include the association with continental break-up events, the brief duration of the magmatism and the huge volume of magmatic rocks emplaced at high eruption rates. However, unlike the other cited LIPs, the CAMP lacks alkaline and silicic magmatism, with almost all the rocks analysed so far being basalts or basaltic andesites (and intrusive equivalents). On the other hand, near-primary magmatic compositions (e.g. picrites) are also virtually absent in the CAMP, with the exception of a few primitive basaltic dykes sampled in North Carolina (Callegaro et al., 2013). A further significant peculiar feature of the CAMP is the abundance of shallow intrusive rocks (e.g. huge sill complexes in Brazil, Mali, Guinea, and prominent dyke swarms in Morocco, Spain, Mali, Liberia, Brazil, Guyana, USA; Fig. 1) compared to the relatively thin and dispersed volcanic successions. The best exposures of CAMP lava flows and the thickest lava piles have been observed in Canada, USA, Morocco and Brazil, but the preserved lava pile thickness never exceeds 400 m (e.g. Kontak, 2008), contrasting with thicknesses of a few kilometres observed in the other LIPs cited above. Lava piles in Portugal, Bolivia and Algeria are even thinner (<100 m; Martins et al., 2008; Bertrand et al., 2014; Callegaro et al., 2014a; Meddah et al., 2017).

CAMP magmatism was synchronous with the end-Triassic mass extinction event and probably triggered it (Marzoli et al., 1999, 2004; Blackburn et al., 2013; Callegaro et al., 2014b; Davies et al., 2017). CAMP magmatism may also have triggered widespread seismic activity recorded in seismites from northern Europe (Lindström et al., 2015). The peak magmatic activity occurred between about 201.6 and 201.3 Ma throughout CAMP (Blackburn et al., 2013; Davies et al., 2017), but after this main event, discontinuous magmatism lasted possibly until ~196 Ma (Sinemurian), for example in Brazil, USA and Morocco (Marzoli et al., 1999; 2011; Ruhl et al., 2016).

CAMP basalts are represented by low-Ti and high-Ti tholeites (below and above 2.0 wt % TiO₂, respectively; e.g. Merle et al., 2011). Low-Ti basalts are largely

![Fig. 1. (a) Schematic map of the western Pangea supercontinent at about 201 Ma showing the location of CAMP lava flows, sills and dykes. The dashed line shows the estimated global surface area of the CAMP. The pink areas indicate the approximate location of the West African craton (WAC), the Amazonian craton (AC) and the Sao Francisco craton (SFC). (b) Schematic geologic map of Morocco (for the area shown by the rectangle in Fig. 1a). The main sampling sites are shown by stars. Ag, Agouim; EC, Ec Cour; OL, Oued Lahr; JI, Jebel Imizar; AO, Ait Ourir; Aj. Fn., Ajoundou F’nouss. The thick dashed line represents the area probably covered by CAMP lava flows.](https://academic.oup.com/petrology/article-abstract/60/5/945/5475177)
dominant in volume and crop out all over the province, while high-Ti ones are limited to a relatively small area comprising northeastern Brazil, Guyana and the once contiguous Sierra Leone and Liberia. Major and trace elements and Sr–Nd–Pb–Os isotopic compositions indicate that the basaltic magmas had an enriched composition compared to those of Mid-Ocean Ridge basalts and yet differed in composition from Atlantic Ocean Island basalts, for example in terms of incompatible trace elements such as Nb, Ti, Rb, Ba. The enriched composition of CAMP basalts is only in part attributable to crustal contamination (Marzoli et al., 2014). High-Ti basalts were probably contaminated by metasomatic veins present in the continental lithospheric mantle of the Man and Amazonian cratons (e.g. Dupuy et al., 1988; Deckart et al., 2005; Merle et al., 2011; Klein et al., 2013; Callegaro et al., 2017). On the contrary, the enriched signature of the low-Ti CAMP basalts is attributed to recycling of subducted continental crustal material that enriched the shallow upper mantle under the Pangea supercontinent (Callegaro et al., 2013, 2014a; Merle et al., 2014; Whalen et al., 2015).

The origin of the CAMP remains controversial. Several authors (e.g. May, 1971; Hill, 1991; Oyarzun et al., 1997; Ruiz-Martinez et al., 2012) proposed a mantle-plume origin. However, geochemical and thermometric data (e.g. relatively low mantle potential temperatures; Herzberg & Gazel, 2009; Callegaro et al., 2013, Whalen et al., 2015) do not support this scenario. Moreover, the size and shape of the CAMP as well as the lack of any clear hot-spot track argue against a classical mantle-plume origin. Therefore, McHone (2000) and Coltice et al. (2007) proposed alternative scenarios based on continental thermal insulation under the Pangea super-continent to explain the near-synchronous melting over the entire province. Alternatively, a mantle-plume rising under a plate, which is already undergoing extension (Burov & Gerya, 2014), as was Pangea during the Triassic, would lead to an asymmetric distribution of magmatic rifts and magmatic horst structures, consistent with the patterns in the CAMP in general. Delamination of the lithospheric keel would favor the rise and decompression melting of the mantle (e.g. Elkins-Tanton, 2005; Dinesen Petersen et al., 2018). Paleomagnetic reconstructions support this model, since Morocco at 201 Ma was located above the margin of the African Large Low Shear Velocity Province (LLSVP), considered a plume-generation zone (Ruiz-Martinez et al., 2012).

THE CAMP IN MOROCCO

Brief outline of the geology of Morocco

The geology of Morocco is characterized by three main orogenic cycles, the Eburnean (c.2 Ga), the Pan-African (c.0-6 Ga) and the Hercynian (c.0-3 Ga). These compressional events were intercalated with extensional phases, e.g. Triassic–Jurassic sedimentary rift-basin formation in the High and Middle Atlas regions associated with the CAMP.

The Anti Atlas in southern Morocco (Fig. 1b) formed at the northern margin of the West African Craton (WAC) chiefly during the Eburnean (c. 2.0 Ga; e.g. Abouchami et al., 1990) and the Pan-African (c. 0.6 Ga; e.g. Gasquet et al., 2005, 2008; Youbi et al., 2013) orogenic events. Eburnean and Pan-African rocks are represented mainly by silicic intrusions. Most Eburnean granites crop out south of the Anti Atlas Major Fault, i.e. in the southern Anti Atlas. The northern border of the Pan-African belt occurs presently along the South Atlas Fault (the fault marking the southern limit of the Atlas mountain range). This boundary is also interpreted by some authors as being the northern border of WAC rocks at depth (Enniih & Liégeois, 2001). An oceanic magmatic belt (ophiolites) was accreted at about 0.7–0.8 Ga (Thomas et al., 2002) and presently outcrops near Bou Azzer, Anti Atlas. After the Pan-African orogeny, during the Late Ediacaran and Paleozoic, the Anti Atlas experienced a period of subsidence with deposition of thick volcano-sedimentary sequences of Neoproterozoic–Cambrian to Carboniferous age (mainly represented by Ediacaran volcanics and Cambrian to Ordovician sandstones).

The basement of central-northern Morocco (Western and Eastern Meseta; Fig. 1b) is formed chiefly by Hercynian (Carboniferous to early Permian) granites, metamorphic rocks and quite rare basic intrusions. Post-orogenic alkaline rocks (lamprophyres) were intruded during the Permian west of Marrakech (Jbiels area). These lamprophyres host crustal xenocrysts dated at 0.3–2.0 Ga (Dostal et al., 2005). Sparse Proterozoic gabbrons and granites have been discovered in Central Morocco, north of the High Atlas (Baudin et al., 2003; Pereira et al., 2015), testifying to the existence of possible pre-Hercynian crustal roots also in this region.

From the Permian, sedimentary basins began developing in the Argana Valley (western High Atlas; Medina, 1991) and progressively expanded east and northwards into the present-day Central High Atlas and Middle Atlas regions. Triassic clastic sedimentary rocks in these basins are exclusively continental or lagoonal and were mainly derived from Pan-African and minor Eburnean source rocks (Marzoli et al., 2017). Carbonate platforms formed after emplacement of the CAMP during the Early Jurassic.

Morocco experienced several episodes of anorogenic continental magmatism during the Proterozoic. Indeed, sparse basic dykes (c.1.8–1.4 Ga) were recently discovered in the Anti Atlas and attributed to Paleo- and Meso-Proterozoic LIPs (e.g. Youbi et al., 2013). Post-CAMP Mesozoic and Cenozoic magmatism includes late-Jurassic to early Cretaceous transitional basalt flows from the Central High Atlas (Bensalah et al., 2013), sparse Cenozoic lamproites and carbonatites (e.g. carbonatites of Taourirt, northeastern Morocco and Tamazert, High Atlas near Midelt; Wagner et al., 2003;
Bouabdellah et al., 2010). The most recent magmatic activity in Morocco took place during the Miocene to Quaternary, when alkaline (basalt to trachyte and phonolite) lava flows were emplaced in the Anti Atlas and Middle Atlas regions (e.g. El Azzouzi et al., 2010; Berger et al., 2014; Bosch et al., 2014). The origin of this recent alkaline magmatism has been attributed to hotspot activity by some authors (e.g. Duggen et al., 2009), although this interpretation is debated (e.g. Berger et al., 2010).

The CAMP in Morocco: previous geochemical, geochronologic and biostratigraphic studies

The CAMP products are well exposed in Morocco (Bertrand et al., 1982; Youbi et al., 2003; Mahmoudi & Bertrand, 2007; Benzalah et al., 2011) and include lava flow piles in the centre and north of the country in the High and Middle Atlas, as well as in the Eastern and Western Meseta (Fig. 1b). Intrusive CAMP rocks are mostly limited to southern Morocco, i.e. the Anti Atlas.

The pioneering work of Bertrand et al. (1982) recognized systematic stratigraphic geochemical changes of the Moroccan CAMP lava piles. Based on major and trace element analyses and on field-work observations, Bertrand et al. (1982) subdivided the lava piles into four units, the Lower, Intermediate, Upper and Recurrent lava flows. Lower to Upper units show an enriched geochemical character compared to Mid-Ocean-Ridge (MORB), but the extent of this enrichment varies with stratigraphic height, a secular, up-section depletion of incompatible major (e.g. TiO₂) and trace elements being observed. The latest lava flows were named Recurrent basalts and crop out only locally in the Central High Atlas. Recurrent basalts were distinguished in particular by their low La/Yb. Bertrand et al. (1982) also highlighted the similarity of Moroccan CAMP flows in terms of major and trace element chemistry with those from the Newark Basin in eastern North America, proposing that these were related to the same LIP.

Geochronology (40Ar/39Ar and U–Pb), palaeomagnetism and biostratigraphy have constrained the age of the magmatism from the High Atlas and suggest pulsed emplacement mechanisms (Sebai et al., 1991; Knight et al., 2004; Marzoli et al., 2004; Nomade et al., 2007; Verati et al., 2007; Palencia Ortas et al., 2011; Blackburn et al., 2013). A total of 22 40Ar/39Ar plateau ages on plagioclase have been previously published for Moroccan CAMP volcanic rocks and comprise data for all four lava flow units. However, except for one sample from eastern Morocco (Oujda, Eastern Meseta) age data are limited to samples from the Central High Atlas (Sebai et al., 1991; Knight et al., 2004; Marzoli et al., 2004; Nomade et al., 2007; Verati et al., 2007). The ages recalculated after Renne et al. (2011) are summarised in Marzoli et al. (2011). Even if cryptic alteration or excess 40Ar may have affected some of the published data, for the Lower, Intermediate and Upper basalts 40Ar/39Ar plateau ages range from 202.7 ± 1.6 to 199.3 ± 0.6 Ma and are generally indistinguishable for these three units, defining a clear age peak at 201.3 Ma (Fig. 2). This is also supported by the U–Pb zircon age (201.56 ± 0.05 Ma) obtained by Blackburn et al. (2013) for a sample from the Amelal sill, Argana Valley. This U–Pb dated sample is chemically correlated with the Intermediate unit basalts (Blackburn et al., 2013). In contrast, Recurrent basalts yielded generally distinguishably younger 40Ar/39Ar plateau ages (196.6 ± 2.3 Ma to 196.3 ± 2.4 Ma; Verati et al., 2007) and define an age peak at c. 199 Ma. A significant eruption gap between Upper and Recurrent basalts is consistent with field evidence for deposition of 30–50 m thick sedimentary strata between these two basaltic units in the Central High Atlas.

The intrusive rocks of the Anti Atlas are poorly dated (unreliable K–Ar ages and one disturbed 40Ar/39Ar age spectrum; Sebai et al., 1991; Youbi et al., 2003 and references therein), but paleomagnetic studies support a c. 200 Ma intrusion age for the Foum Zguid dyke (Silva et al., 2006; Palencia Ortas et al., 2011). An attempt to date the Bas Draa sills (Anti Atlas near Foum Zguid village) by the 40Ar/39Ar method yielded disturbed age spectra, which are generally consistent with a CAMP-like age (Renne & Callegaro, unpublished data). More recently, Davies et al. (2017) obtained a zircon U–Pb age for a differentiated portion of the Foum Zguid sample AN733 (201.11 ± 0.07 Ma), confirming that this dyke was emplaced during the CAMP peak activity.

Further constraints on the duration of the CAMP event in Morocco are given by magnetostratigraphic studies (Knight et al., 2004; Marzoli et al., 2004) of the Tiourjdal and Oued Lahr volcanic piles, showing that basaltic eruptions occurred in a series of five pulses, each of which lasted less than a secular variation cycle (about 450 years by analogy with the duration of these cycles in the Holocene; Schnepf et al., 2003). The number of pulses calculated by Knight et al. (2004) was also based on the presence of a brief reversal event apparently recorded within a sedimentary interlayer. These authors estimated the duration of the Lower to Upper volcanism to be about 0.1 Ma, including the magnetic reversal event. Font et al. (2011) showed that this magnetic reversal event is probably not primary, but was induced by a much later overprint. Thus, if we exclude the magnetic reversal, the duration of volcanic activity at Tiourjdal may have been shorter than estimated by Knight et al. (2004) and the number of eruption pulses reduces from five to four. Therefore, the pulses were two for the Lower unit flows, one for the base of the Intermediate unit and one including the top of the Intermediate unit and all Upper flows. This suggests high eruption rates and has important consequences for the environmental impact of the volcanism, as well as for the formation and differentiation mechanisms of the basaltic magmas.

Biostratigraphic data indicate that the onset of CAMP volcanism and eruption of Lower to Upper basalts in
Morocco occurred within the Rhaetian, the last stage of the Triassic. Such evidence is provided mainly by palynological data (Manspeizer et al., 1978; Marzoli et al., 2004; Nomade et al., 2007; Verati et al., 2007; all previous ages filtered after Marzoli et al. (2011) and recalculated after Renne et al. (2011)) and the U–Pb ages for the Amelal sill from Blackburn et al. (2013) and from this study. Ages are in millions of years, Ma. The vertical bars represent 2 sigma analytical uncertainties. Previous data are shown by open symbols, new data from this study are shown by filled symbols. The apparently slightly older ages for some Intermediate vs some Lower flows is most probably due to the effects of cryptic alteration or excess ⁴⁰Ar. (b) The inset shows a relative age probability plot for all available ⁴⁰Ar/³⁹Ar plateau ages for the four lava flow units and the two U–Pb ages.

FIELD EVIDENCE AND SAMPLING

A total of about 200 samples from 14 lava piles, two main dykes and six sills was collected. Sampling sites are widespread in the High and Middle Atlas, the Western and Eastern Meseta, and the Anti Atlas (Fig. 1b). For each of the tectonically undisturbed volcanic sections, all fresh lava flows were sampled. For three sections from the Central High Atlas (Oued Lahr, Telouet and Tiourjdal) the samples collected for the magnetostratigraphic study of Knight et al. (2004) were used here for geochemical analysis. Coordinates of the main sampling sites are reported in Supplementary Data Electronic Appendix Table S1; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org.

Lava sequences

As already mentioned, the striking feature of the CAMP event in Morocco is the occurrence of four stratigraphically sequenced lava flow units, the Lower, Intermediate, Upper and Recurrent flows, which are defined based on
field, petrographic and geochemical criteria (Bertrand et al., 1982; Bertrand, 1991; Youbi et al., 2003; Knight et al., 2004; Marzoli et al., 2004; Deenen et al., 2010). Based on field observations alone, the relatively coarse-grained doleritic Lower and Intermediate compound pahoehoe lava flows are easily distinguishable from the slightly porphyric massive Upper and Recurrent sheet flows. Pillow lavas are quite abundant within the lower half of the Intermediate unit throughout Morocco, but are absent or very rare in the other units. Upper flows are the only ones characterized by well-developed columnar jointing the thin columns are probably indicative of sub-aqueous emplacement (Jerram et al., 2016). Everywhere it crops out, the Recurrent basalt is a single massive simple sheet flow reaching up to 15 m in thickness locally. The Recurrent flow was emplaced on top of wet siltstones, which show signs of deformation (load casts) in response to the load imposed by the lava flow.

A total of 13 lava piles from the High Atlas, Middle Atlas and Western Meseta have been sampled in detail (Fig. 3). The sampled sections display several common features as well as some site-specific peculiarities (Fig. 4a–f). Generally, the lava piles are sub-horizontal or slightly tilted (10–30°) and tectonically undisturbed. The thickest lava pile is preserved at Tsiourjal (Central High Atlas, c.300 m), while at most other sites the total lava thickness ranges from 100 to 150 m. Except at a few sites where the base of the lava piles does not crop out, the first lava flows are emplaced on grey, black and red continental siltstones of latest Rhaetian age (Panfili et al., 2019). These basal lava flows always belong to the Lower unit, except at the Middle Atlas section of Agourai, where the first lava flows belong to the Intermediate unit. Lower and Intermediate lava flows are present at all localities. The Lower flows make up c.30–50% of the total preserved lava thickness in the Central High Atlas, Argana and at Midelt, while they represent <10% of the total thickness in the Middle Atlas and Western Meseta. On the contrary, Intermediate flows are less abundant in central compared to northern Morocco (i.e. c.30 vol.% in the Central High Atlas and Argana vs > 90 vol.% in the Middle Atlas and Western Meseta).
Upper flows are also quite widespread over Morocco (except at Argana and in the Western Meseta), but their volume never exceeds 10% of the preserved lava piles. The Recurrent unit is limited to the Central High Atlas lava piles and is absent in northern Morocco and at Argana.

Sedimentary interlayers are rare and thin from the base of the lava section to the top of the Upper unit. The nature of the sedimentary interlayers varies considerably. Sedimentary interlayers within the Lower and Intermediate units and between these units are very thin (<20 cm). Slightly thicker (up to 2–3 m) carbonate layers are for example observed between the Intermediate and Upper flows in the Central High Atlas. The most prominent carbonate and terrigenous sedimentary interlayers occur between the Upper and the Recurrent flows, where these flows are present (Central High Atlas). Sedimentary strata on top of the Upper unit are thin and rare.
flows are still of Rhaetian age (Panfili et al., 2019). On top of the Recurrent basalt quite thick (up to 60 m) red siltstones are followed by carbonates of Sinemurian age (Courtinat & Algouti, 1985). Further details on the sampled sections are given in the (Supplementary Data Electronic Appendix 1; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org).

Intrusive rocks
Intrusive CAMP rocks are quite rare in Morocco (as opposed to North and South America or to other areas of northwest Africa, e.g. Mali, Mauritania). In particular, dykes and sills are absent (to our knowledge) in the Middle Atlas and in the Central High Atlas, while one small and fairly shallow level sill (the Amelal sill) occurs in the Argana Valley. The Amelal sill is about 80 metres thick and crops out over a distance of about 5 km. It intrudes Late Triassic lacustrine sediments (red siltstones), forming a small contact aureole at the base of the sill (Fig. 4g). The depth of intrusion of the sill was probably very shallow (about 0.5 km), as it is separated from the overlying lava flows by only a few hundred metres of siltstones. The basalt at the contact with the sediments is fine-grained, while the inner portions of the sill are coarse-grained and occasionally show granophyric textures. Alteration is pervasive throughout the sill and hinders recognition of intrusive structures and of possible multiple magma injections. Nevertheless, it can be observed that inner portions of the sill are fairly coarse-grained and feldspar-rich. The sample LV34, which yielded the U–Pb age (see below) was collected from this level. Alteration also hinders straightforward comparison of the geochemical composition of the eight analysed sill samples with that of the lava flows.

One dyke and one sill were sampled in the Jbilet Massif, northeast of Argana (Fig. 1b). Here, the intrusive rocks intrude the Paleozoic basement. The geometry of the outcrops in the rather flat Jbilet hills hinders definition of the morphological features of these intrusive rocks. However, aeromagnetic data suggest that the Jbilet dyke has a length of several tens of km and trends towards the Argana Valley where it may have fed the lava flows (Huvelin, 1971; Youbi et al., 2003).

The most abundant outcrops of CAMP intrusive rocks occur in the Anti Atlas, southern Morocco (Bertrand et al., 1982; Youbi et al., 2003 and references therein). The most striking feature is the c. 200 km long and up to about 200 m thick, NE–SW trending Foum Zguid dyke (Silva et al., 2006; Bouflaine et al., 2017). The dyke intrudes Neoproterozoic to Paleozoic sedimentary sequences and locally splits into multiple branches. We collected 16 samples from the dyke, from NE (Imiter) to SW (Bas Draa valley, near Foum Zguid village; Fig. 4h). Southeast of Foum Zguid village, we sampled small dykes approximately parallel to the main Foum Zguid dyke. In the same area, i.e. the Bas Draa valley, CAMP magmas intruded the lower Paleozoic sediments as sills, four of which have been sampled. The sills are up to about 50 m thick and are sometimes connected by small dykes. Further outcrops of probable CAMP sills occur towards and across the Algerian–Moroccan border, but are not accessible. On the contrary, the Ighrem dyke which is parallel to the Foum Zguid dyke and was tentatively attributed to the CAMP (e.g. Silva et al., 2006; Palencia Ortas et al., 2011), is composed of rocks, which are petrographically and geochemically clearly different from any known CAMP rock. Unlike most CAMP rocks, the Ighrem dyke rocks are moderately alkaline (i.e. most samples classify as trachybasalt or trachyandesite), yielding higher K than Na and are in general enriched in all incompatible trace elements (e.g. Nb > 15 ppm, Zr > 170 ppm; La > 28 ppm) compared to any previously analysed CAMP rock. We also note that the paleomagnetic pole of the Ighrem dyke (Palencia Ortas et al., 2011) is significantly displaced towards the north compared to that of the Foum Zguid dyke, arguing against a synchronous emplacement of these two dykes. Therefore, we conclude that the Ighrem dyke is not part of the CAMP and do not consider it further in this study.

The depth of intrusion of the sills and dykes in the Anti Atlas was probably 4–5 km below the surface, considering the thickness of the Proterozoic to Carboniferous sedimentary cover (Michard et al., 2008). We also note that in the Newark basins, CAMP sills typically intruded at similar depths of about 5 km, below continental lacustrine-fluvialite sediments (e.g. Puffer et al., 2009).

ANALYTICAL METHODS
The main features of the analytical methods are described here in summary. The complete description can be found in the (Supplementary Data Electronic Appendix 1; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org).

Whole-rock major element and selected trace element contents were determined by X-ray fluorescence (XRF) at the University of Padova with a Philips PW2400 spectrometer, following methods described in Callegaro et al. (2013). Trace elements were also analysed by Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) at the University of Bretagne Occidentale, Brest (France), following analytical protocols described in Barrat et al. (1996). Analytical uncertainties are estimated at less than 5%.

Sr–Nd–Pb radiogenic isotope ratios were measured at the Department of Earth Sciences, University of Geneva (Switzerland) using a Thermo Neptune PLUS Multi-Collector ICP-MS. The method is described in detail in Chiaradia et al. (2011) and Béguelin et al. (2015).

Chemistry and mass spectrometry for Re–Os isotopic analyses were performed at the Centre de Recherches Pétrographiques et Géochimiques (CRPG-
Argon geochronological analyses were carried out at the Western Australian Argon Isotope Facility (WAAIF) of the John de Laeter Centre, Curtin University (Perth, Australia) and at the Berkeley Geochronology Center (Berkeley, USA). Plagioclase separated from samples AN16, AN49, AN24, AN160, AN50, AN530, AN540 were analysed at Curtin, while plagioclase separates from samples AN216, AN219, AN504, AN525b, AN530, AN539, AN540 were analysed at Berkeley. GA1550 and FCs were used as neutron fluence monitors, adopting ages of 9.93 to 0.100 Ma and 28.294 ± 0.036 Ma (1σ), respectively (Renne et al., 2011). More details on the Ar analyses are reported in Renne et al. (1998) and Jourdan et al. (2009).

U–Pb geochronology was performed at the Department of Earth Sciences, University of Geneva (Switzerland). Zircon crystals from sample LV34 of the Amelal sill were extracted and analysed following a procedure similar to that of Davies et al. (2017).

Paleomagnetic analysis were performed at the Berkeley Geochronology Center (Berkeley, U.S.A.) following methods outlined in Knight et al. (2004).

RESULTS

40Ar/39Ar and U–Pb geochronology

Nine new 40Ar/39Ar ages are presented in Fig. 5 and Table 1 (the complete data set is reported in the Supplementary Data Electronic Appendix Table S2; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org). Seven of these are 40Ar/39Ar plateau ages, while two samples (AN504 and AN24) yielded mini-plateau ages defined by 67% and 55% of the released argon, respectively. The plateau ages are statistically quite robust (MSWD in the range of 0.5–1.8, probability 0–93%). The Ca/K of the plateau steps (c.40–120), calculated from the 39Ar/39Ar isotope ratios, is generally consistent with the Ca/K measured by electron microprobe analysis (see below). Inverse isochron ages generally overlap the plateau and mini-plateau ages and yield initial 40Ar/39Ar values (252 ± 25 to 305 ± 25) overlapping or approaching atmospheric values (298–56). The only exception is sample AN525b, which yields an initial 40Ar/39Ar value (162 ± 9) implausibly below the atmospheric value. Therefore, we consider the apparent age of sample AN525b to be affected by post-eruption alteration and do not consider it as a valid crystallization age. Samples AN530 and AN510 were analysed both at Curtin University and at the BGC and yielded indistinguishable ages. The ages obtained at Curtin are slightly more precise (lower uncertainty) and are here retained. Furthermore, three more samples (AN216, AN219, AN540) were analysed, but did not provide plateau or isochron ages.

The seven retained 40Ar/39Ar plateau ages and the mini-plateau age (AN24) range from 200.10 ± 2.04 Ma to 203.10 ± 1.40 Ma. Three dated samples belong to the Lower unit from the Central High Atlas (AN16, AN49) and from the Western Meseta (AN504, mini-plateau age), while four belong to the Intermediate unit from the Central High Atlas (AN160), the Middle Atlas (AN530, AN539) and the Western Meseta (AN510). The only dated Recurrent basalt (AN24) yields a mini-plateau (201.15 ± 0.70 Ma). The new ages for Lower and Intermediate basalts from the Central High Atlas, Middle Atlas and Western Meseta lava flows and previously published ones for the Central High Atlas and Eastern Meseta are near-synchronous, supporting a similar eruption age for CAMP basalts in all regions of Morocco. The Upper basalt previously dated (201.7 ± 2.1 Ma, Sebai et al., 1991, age recalculated in Marzoli et al., 2011) overlaps in age with the Lower and Intermediate lava flows. The only analysed Recurrent basalt (AN24) yielded a mini-plateau age (201.15 ± 0.70 Ma) that is indistinguishable from those of the other lava flow units. This value contrasts with previous studies that found younger 40Ar/39Ar ages for Recurrent basalts (196.3 ± 2.4 to 199.6 ± 2.3 Ma; Verati et al., 2007; recalculated in Marzoli et al., 2011). Our new age overlaps with the 40Ar/39Ar age for the Hook Mt. flows (200.3 ± 1.9 Ma; Marzoli et al., 2011) from the Newark Basin, that are both stratigraphically and geochemically similar to the Recurrent flows from Morocco.

Sample LV34 from the Amelal sill yielded a few zircon crystals (Fig. 6; Table 2). Six of them were dated by ID-TIMS, with four grains producing a weighted mean age of 201.569 ± 0.042 Ma (MSWD = 1.1; probability = 34%). This age is identical to the U–Pb age obtained by Blackburn et al. (2013) for the Amelal sill (201.564 ± 0.054 Ma). Two of the zircon grains yielded slightly younger ages. However, these were interpreted as reflecting small amounts of Pb loss since the chemical abrasion procedure was only conducted at 180 °C (further details are reported in the Supplementary Data Electronic Appendix 1; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org). Also, the calculated temperature for zircon saturation is 625 ± 10 °C (using the formula of Boehnke et al., 2013). This low temperature and the mafic nature of the sample suggests that zircon xenocrysts should not be present in this sample, therefore,
the older zircon ages should more reliably record the crystallisation of this unit. Notably, as shown below, the sample dated here (LV34) has a composition approaching those of the Lower unit lava flows, while Blackburn et al. (2013) correlated their Amelal sample to the Intermediate unit.

**Paleomagnetic results**

Four lava piles from Midelt (Ahouli), the Middle Atlas (Tounfite and Agourai) and the Western Meseta (Maaziz) were investigated flow by flow (the detailed data and the virtual geomagnetic pole plots are reported in Supplementary Data Electronic Appendix...)

Fig. 5. $^{40}$Ar/$^{39}$Ar plateau age spectra for plagioclase separates from 8 CAMP basalts from Morocco. The mini-plateau (AN504 and AN24) and plateau ages (in Ma, million years before present) are shown by the red bars with 2 sigma uncertainty. Plateau steps are shown by the filled boxes. Summary Argon age data are reported in Table 1, while the complete dataset can be found in the Supplementary Data Table S2; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org.
All 40Ar/39Ar plateau and isochron ages (± 2 sigma analytical uncertainty) and statistical data (MSWD and probability of fit, P) are shown in Table 2.

<table>
<thead>
<tr>
<th>Location</th>
<th>Sample unit</th>
<th>Lab.</th>
<th>Plateau age (Ma) ± 2σ</th>
<th>MSWD</th>
<th>P</th>
<th>% 39Ar in plateau steps</th>
<th>Isochron age (Ma) ± 2σ</th>
<th>Isochron 40Ar/39ArAr intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agouim CHA</td>
<td>AN149 Lower</td>
<td>1</td>
<td>201.35 ± 0.36</td>
<td>1.35</td>
<td>0.13</td>
<td>100</td>
<td>201.62 ± 0.45</td>
<td>281 ± 19</td>
</tr>
<tr>
<td>Ait Ouir</td>
<td>AN24 Rec</td>
<td>1</td>
<td>201.15 ± 0.70</td>
<td>1.95</td>
<td>0.06</td>
<td>55</td>
<td>200.80 ± 2.67</td>
<td>310 ± 91</td>
</tr>
<tr>
<td>Toulouet CHA</td>
<td>AN16 Lower</td>
<td>1</td>
<td>201.76 ± 0.38</td>
<td>1.74</td>
<td>0.07</td>
<td>73</td>
<td>202.41 ± 0.47</td>
<td>252 ± 25</td>
</tr>
<tr>
<td>Agoual Middle Atlas</td>
<td>AN530 Interm 1</td>
<td>202.10 ± 0.55</td>
<td>1.28</td>
<td>0.19</td>
<td>94</td>
<td>202.04 ± 0.87</td>
<td>299 ± 8</td>
<td></td>
</tr>
<tr>
<td>Tounfite Middle Atlas</td>
<td>AN525 B Lowerr?</td>
<td>200.6 ± 2.6</td>
<td>0.44</td>
<td>0.88</td>
<td>41</td>
<td>199 ± 20</td>
<td>224 ± 17</td>
<td></td>
</tr>
<tr>
<td>Maaziz W. Meseta</td>
<td>AN510 Interm 2</td>
<td>199 ± 1.0</td>
<td>1.58</td>
<td>0.14</td>
<td>97</td>
<td>205 ± 13</td>
<td>239 ± 11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AN504 Lower</td>
<td>1</td>
<td>200.07 ± 1.05</td>
<td>0.93</td>
<td>0.55</td>
<td>99</td>
<td>199 ± 1.9</td>
<td>303 ± 25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>199 ± 1.20</td>
<td>0.38</td>
<td>0.93</td>
<td>95</td>
<td>201 ± 14</td>
<td>291 ± 11</td>
</tr>
</tbody>
</table>

Analyses were performed at Curtin University (Lab. 1) and at the Berkeley Geochronology Center (Lab. 2). Retained age data are in bold, mini-plateau age is in italics. The complete Ar isotopic dataset can be found in the Supplementary Data Electronic Appendix Table S2; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org. CHA, Central High Atlas.

Table S3; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org. All four sections have flow mean directions that are consistent with previous results from CAMP basalts. Within section resolution is not as high for this study as it was for previous ones (e.g. Knight et al., 2004), but some directional groupings can be proposed based on within-section agreement of flow mean directions. At the Tounfite location, the lava flows were gently dipping due to numerous small faults. Finding a direct measurement of strike for the lava flows was very difficult due to the nature of the rocks, which were very fractured and due to the orientation of the outcrops along the roadside. In the field, we estimated the strike at ~50° and the dip at ~20° to the south. The flow mean directions from this locality have been rotated to correct for this tilting, which occurred after acquisition of the characteristic remanence magnetization.

The flow means can be placed into groups based on agreement of flow mean directions and stratigraphic patterns (Fig. 7). The groups are not very well constrained, but are distinct from one another by the Fisher mean of the flow means for samples from all sections (Fig. 7b). The small variations that differentiate directional groupings are a record of secular variation, which is a smooth and steady process. Therefore, distinct groupings suggest eruption in a pulsed manner in the Middle Atlas, which is consistent with the study on the Central High Atlas lava piles (Knight et al., 2004).

**Petrography and mineral compositions**

The CAMP lavas from Morocco have textures ranging from intergranular or intersertal to porphyritic (Supplementary Data Electronic Appendix 1; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org). The dominant phenocrysts in all four units are augitic clinopyroxene (mostly in the following range: Wollastonite 30–40%, Enstatite 40–60%, Ferrosilite 10–25%); mineral major element compositions are reported in the...
Table 2: U-Pb geochronological data for sample LV34, Argana basin, Amelal sill.

<table>
<thead>
<tr>
<th>Composition</th>
<th>Dates (Ma)</th>
<th>Isotopic Ratios</th>
<th>Fraction U(a) (pg)(b) (pg)(c) Pbc(d) (magma)(e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV34</td>
<td>2.0 (0.3)</td>
<td>2.0 (0.2)</td>
<td>2.0 (0.1)</td>
</tr>
<tr>
<td>LV34.1</td>
<td>2.0 (0.3)</td>
<td>2.0 (0.2)</td>
<td>2.0 (0.1)</td>
</tr>
<tr>
<td>LV34.2</td>
<td>2.0 (0.3)</td>
<td>2.0 (0.2)</td>
<td>2.0 (0.1)</td>
</tr>
<tr>
<td>LV34.3</td>
<td>2.0 (0.3)</td>
<td>2.0 (0.2)</td>
<td>2.0 (0.1)</td>
</tr>
<tr>
<td>LV34.4</td>
<td>2.0 (0.3)</td>
<td>2.0 (0.2)</td>
<td>2.0 (0.1)</td>
</tr>
<tr>
<td>LV34.5</td>
<td>2.0 (0.3)</td>
<td>2.0 (0.2)</td>
<td>2.0 (0.1)</td>
</tr>
<tr>
<td>LV34.6</td>
<td>2.0 (0.3)</td>
<td>2.0 (0.2)</td>
<td>2.0 (0.1)</td>
</tr>
<tr>
<td>LV34.7</td>
<td>2.0 (0.3)</td>
<td>2.0 (0.2)</td>
<td>2.0 (0.1)</td>
</tr>
<tr>
<td>LV34.8</td>
<td>2.0 (0.3)</td>
<td>2.0 (0.2)</td>
<td>2.0 (0.1)</td>
</tr>
<tr>
<td>LV34.9</td>
<td>2.0 (0.3)</td>
<td>2.0 (0.2)</td>
<td>2.0 (0.1)</td>
</tr>
</tbody>
</table>

Supplementary Data Electronic Appendix Tables S4–6; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org and plagioclase (anorthite component, An = 40–88; orthoclase < 3; Fig. 8a). Oxides (titanomagnetite, mostly and rare ilmenite) are also present in all rocks as microphenocrysts or groundmass crystals and frequently show exsolution patterns. Olivine, when present, is generally strongly altered and the few available optically fresh patches have low forsterite contents (Fo64–76), which is probably the result of late- or post-magmatic modification. Olivine is relatively frequent in Lower unit flows, while it is rare (Intermediate and Recurrent) or absent (Upper) in the other units. Low-Ca clinopyroxene (pigeonite, Wo9–10, En90–70, Fs15–30) can be abundant and present as phenocrysts, notably in the Intermediate lava flows, while it is limited to groundmass crystals in the Upper and Recurrent units. Pigeonite is sometimes found rimming augite cores.

Systematic textural and mineralogical variations are observed through the lava piles, as previously shown by Bertrand (1991). The Lower and Intermediate basalts have generally intergranular of interstitial textures with grain sizes depending on the lava flow thickness or on the distance of the sample from the lava crust. For example, the thin Lower flows at Maaziz are fine grained, whereas the Lower flows at Tiourjdal yield mm-sized crystals. A few samples (e.g. AN132, Argana and AN31, AN32, Central High Atlas) show large aggregates of mafic minerals and thus have a cumulitic whole-rock composition. Upper and Recurrent flows are always slightly porphyritic to glomeroporphyritic, i.e. they carry mm-sized phenocrysts of augite and plagioclase set in a fine-grained matrix.

Intrusive rocks display mineral compositions similar to those of the lava flows, with the exception that pigeonite is found in an intrusive Recurrent-unit sill only (AN724, Anti Atlas). The textures of sills and dykes range from porphyritic at the chilled margins of the Forn Zguid dyke and of the Amelal sill, to coarse doleritic and occasionally gabbroic and granophyric textures within the central portions of the intrusions.

Mineral major element composition

Forty plagioclase phenocrysts from 20 samples (lava flows and intrusive rocks) were investigated in detail by electron microprobe analysis (Fig. 8; Supplementary Data Electronic Appendix Table S5; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org). The analysed plagioclase for Lower and Recurrent samples have Ca/Na similar to those of their host-rocks, while some Intermediate and most Upper basalt plagioclase cores have substantially higher Ca/Na than the whole-rock compositions. Plagioclase phenocrysts from the Lower and Recurrent units are mostly labradorite (An50–75), while those from the Intermediate unit are both labradorite and bytownite (An55–85) and Upper basalt plagioclases are mostly

---

**Note:** The text contains abbreviations and specialized terms common in petrology. For a full understanding, a reader familiar with these terms would be best suited.
bytownite (An$_{70–88}$). Recurrent plagioclase is systematically depleted in K$_2$O compared to Lower and Intermediate unit samples at a similar An content.

The majority of the over 40 plagioclase phenocrysts analysed by detailed core-rim compositional traverses are normally zoned, with An decreasing towards the crystal rims (Fig. 8c). However, inverse zoning occurs in some Recurrent unit plagioclase phenocrysts (2 of 6 analysed crystals) and is frequent in Intermediate unit samples (6/9), while it is rare in the Upper unit (2/9) and absent in the Lower one. Upper basalts occasionally contain resorbed, high-An cores, surrounded by relatively low-An external zones. Notably, the zoning is much smoother in intrusive rocks, where plagioclase shows a nearly continuous decrease in An from core to rim (Fig. 8c). This suggests a prolonged evolution at relatively high temperature and at equilibrium conditions.

Augite phenocrysts are found in nearly all CAMP rocks from Morocco and 28 crystals have been analysed by detailed electron microprobe traverses (representative data are reported in the Supplementary Data Electronic Appendix Table S4; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org). Most augite cores have compositions at or close to equilibrium with their whole-rock (Fig. 8d), for example in terms of Mg# (for Kd Fe$^{2+}$/Mg of about 0.25–0.30; cf. Putirka et al., 1996; Villiger et al., 2004; Putirka, 2008). Only augites from Upper basalts show significantly lower Mg# than expected for equilibrium conditions. Augite cores from the Foum Zguid Intermediate unit samples yield slightly higher Mg# than expected, suggesting that the whole-rock is enriched in Mg due to the accumulation of mafic minerals (Fig. 8d). Most augite cores analysed in Recurrent basalts are close to equilibrium with their whole-rock, while their rim compositions are progressively depleted in Mg#.

Bertrand (1991) also highlighted systematic minor element differences in the compositions of augite and pigeonite for the four lava flow units. In general, our data confirm these differences, such as distinct Ti and
Al contents of augite cores that reflect largely whole-rock compositional differences (i.e. Lower and Recurrent augites yield highest TiO$_2$). However, in detail, we observe a large overlap in TiO$_2$ content between Intermediate (TiO$_2$ = 0.2–0.5 wt %) and Upper basalt augites (TiO$_2$ = 0.2–0.4 wt %).

A further systematic difference among the four units concerns augite zoning. Lower unit augites are generally unzoned in terms of major (e.g. Mg#) and minor elements (Ti, Al, Cr). On the contrary, Intermediate (5/11 analysed phenocrysts) and Upper unit (4/8) augites are frequently sector zoned, with abrupt variations of Ti, Al and Cr at near-constant Mg# suggesting rapid disequilibrium crystallization (Brophy et al., 1999). Augite and pigeonite from intrusive rocks are normally zoned.

**Mineral trace element data**

A few plagioclase and augite crystals from two of each of the lava flow units were analysed by laser ablation ICP-MS (data are reported in the Supplemental Data Electronic Appendix Table S7; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org). Only the elements showing concentrations well above the detection limit are considered in this study. These are LREE (La to Eu), Y, LILE (Rb, Ba, Sr) and Ti for plagioclase, and all REE, Sr, Zr, Y, in addition to Ti (measured also by electron microprobe) and transition metals (Cr, Ni, V), for augites.

Trace element contents both in plagioclase and augite show systematic differences among the four units. In general, plagioclase and augite crystals in Lower basaltic andesites are those with the highest LREE, LILE and Zr contents, while Recurrent basalt crystals yield the highest Y and HREE and the lowest Sr and Eu. Therefore, Lower and Recurrent unit augites are those with the highest and lowest La/Yb, respectively. Intermediate and Upper unit augites have quite similar trace element contents, including similar La/Yb. On the contrary, plagioclases from the Intermediate unit yield slightly higher LREE, Y, Ba and Ti relative to Upper unit plagioclase crystals. In general, La contents are similar in plagioclases and augites from the same rocks, except for the two analysed Intermediate unit basaltic andesites, where La is slightly higher in plagioclase (0.49–1.45 ppm; mean 0.71 ppm) than in augite (0.29–0.64 ppm; mean 0.48 ppm).

Chondrite-normalized REE and primitive mantle normalized (McDonough & Sun, 1995) trace element patterns for the augites (Fig. 9 a and b) show depleted light vs heavy REE and negative Zr and Ti anomalies. Eu anomalies are in general moderate in most Intermediate, Upper and Recurrent unit augites (Eu/Eu* = 0.8–1.1) while Lower unit augites always display negative Eu anomalies (Eu/Eu* = 0.6–0.8). The analysed augite and plagioclase crystals yield, in general, trace element contents and patterns similar to those obtained...
on minerals from other CAMP rocks (Dorais & Tubrett, 2008; Marzoli et al., 2014).

**Whole-rock compositions**

*Alteration*

Secondary minerals such as iddingsite, sericite, chlorite, celadonite, zeolites, quartz and calcite, replacing primary minerals or filling voids, are rare in most rocks, but may be abundant in some samples (notably in most Argana, some Middle Atlas and Anti Atlas samples). Selection of the freshest samples for geochemical investigation is thus necessary and is based both on petrographic observations and geochemical criteria. The optically and mineralogically most altered samples yield generally high LOI (loss on ignition > 2.0 wt %), Na₂O (> 2.4 wt %) and K₂O (> 1.2 wt %) and low CaO (< 9 wt %). However, in order to discriminate between secondary (alteration) and primary (magmatic differentiation) effects it is necessary to consider the systematic chemical differences among the four units (see below), i.e. the generally higher alkali content of the Lower basalts and the generally higher CaO of the Upper basalts. Accounting for such differences, 28 (Argana lava flows and sill, and Anti Atlas dyke samples, mostly) of the total set of 159 analysed samples yield anomalously high alkalis and low CaO in addition to high LOI and are thus not considered further. Nonetheless, more subtle alteration cannot be ruled out completely for several samples and is evidenced, for example, by the presence of sericite lamellae in plagioclase or by altered interstitial glass. Such alteration affects particularly the mobile elements such as the LILE, which indeed show a relatively larger scatter than immobile elements such as REE or HFSE (see below).

**Whole-rock classification and major and trace element variations**

The majority of the analysed CAMP rocks from Morocco have MgO contents varying between 10 and 6 wt % and Mg# (\(=100\text{Mg}/(\text{Mg}+\text{Fe}^2+)\), calculated for \(\text{Fe}^{2+}/\text{Fe}^{3+}=0.15\)) ranging from 66 to 56, indicating that they are moderately evolved (representative rock compositions are reported in Table 3, the complete dataset can be found in the Supplementary Data Table S7; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org). Complete LA-ICP-MS data are reported in Supplementary Data Table S7; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org.

![Figure 9](https://example.com/fig9.png)

**Figure 9.** Representative augite (dashed lines) and plagioclase (continuous lines) (a) rare earth element REE and (b) incompatible trace element compositions normalized to chondritic values (McDonough & Sun, 1995) and to Primitive mantle values (McDonough & Sun, 1995). Complete LA-ICP-MS data are reported in Supplementary Data Table S7; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org.
However, the Lower lava samples display up to 30 vol.% of olivine, suggesting accumulation of mafic minerals and cannot be considered as magmatic liquid compositions.

Lava flows
According to the TAS diagram (Le Bas et al., 1986), the Moroccan CAMP rocks can be classified as basalts and basaltic andesites (Fig. 10). In particular, most Lower and Intermediate samples are basaltic andesites, Upper lava flows straddle the basalt and basaltic andesite fields and Recurrent samples are all basalts. The TAS diagram also shows that the Lower basaltic andesites are slightly higher in alkalis than the other samples. The Moroccan CAMP samples are all low-TiO₂ basalts (TiO₂< 2.0 wt%; Fig. 11), as are the vast majority of CAMP rocks in general (Marzoli et al., 2018).
Nevertheless, TiO$_2$ decreases from the Lower basaltic andesites (average 1.45 wt %) to Intermediate (average 1.22 wt %) and then to the Upper flows (average 0.05 wt %) and is again high in the Recurrent basalts (average 1.63 wt %). Na$_2$O and P$_2$O$_5$ as well as Zr and Hf display a similar concentration decrease from the Lower to the Upper units (Figs 11 and 12), though little or no increase is observed in the Recurrent samples. The Lower flows are also characterized by the highest LIL (K$_2$O, Sr, Ba, Rb), HFSE (Nb, Ta, Th, U) and LREE (La to Eu) concentrations, but tend to have slightly lower FeO concentrations than the other units. By contrast, the Upper flows have extreme compositions in terms of high CaO and Al$_2$O$_3$, and low P$_2$O$_5$, K$_2$O and low concentrations of most incompatible trace elements, including REE, HFSE and LILE (with the exception of Sr and, to some extent, Pb). As shown in Figs 11 and 12, Intermediate flows are intermediate also in terms of major and trace element...
concentrations between Lower and Upper flows and sometimes overlap with them. Notably, most samples from these three units have similar MgO contents and Mg# as well as compatible element contents (Ni, Cr, Sc, Co). By contrast, the Recurrent basalts are slightly more evolved than the other rocks, i.e. they yield slightly lower MgO (about 5.5–6.2 wt %), Mg# (54–48) and Cr (about 100 ppm). The Recurrent basalts plot outside the general field of the other basalts and basaltic andesites and have higher TiO₂, FeOtot, V, Sc, HREE (from Gd to Lu) contents and lower SiO₂, Rb and Sr, as well as low LREE (La to Sm) and HFSE (except Zr) contents.

Regional-scale geochemical trends and unit-specific characteristics are further highlighted by comparing the geochemical compositions of the different units in multi-element diagrams (Fig. 13). Lower, Intermediate and Upper units have broadly similar incompatible element patterns, with progressively lower absolute
values of LREE and MREE from Lower to Upper basalts. Common features are negative Nb and Ta (vs Th, U and LREE) and positive Pb (vs LREE) anomalies, whereas a negative anomaly of Sr is observed in most Lower and Intermediate flows but is lacking in the Upper basalts (except one sample). The LILE (particularly K and Rb) show a large scatter of data, which may in part be related to secondary processes even for the selected and apparently slightly altered samples. The difference among these three flow units is obvious for the LREE (La to Sm), whereas it is negligible for the HREE (from Dy to Lu), resulting in broadly parallel REE patterns with a progressive decrease of LREE/HREE ratios from Lower (i.e. La/YbCN = 4.4–5.6) except for two outliers; chondrite normalized after McDonough & Sun, 1995) to intermediate (La/YbCN = 2.9–3.8) and Upper basalts (La/YbCN = 2.5–2.8). The highest La/Yb and REE concentrations as well as the

<table>
<thead>
<tr>
<th>Sample</th>
<th>AN631</th>
<th>AN633</th>
<th>AN510</th>
<th>AN627</th>
<th>AN22</th>
<th>AN57</th>
<th>AN63</th>
<th>AN140</th>
<th>AN141</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂ wt %</td>
<td>54.81</td>
<td>52.98</td>
<td>53.74</td>
<td>53.65</td>
<td>51.57</td>
<td>51.74</td>
<td>51.66</td>
<td>51.34</td>
<td>52.05</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.27</td>
<td>1.14</td>
<td>1.36</td>
<td>1.40</td>
<td>1.05</td>
<td>1.10</td>
<td>1.09</td>
<td>1.00</td>
<td>1.04</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>14.38</td>
<td>14.34</td>
<td>13.92</td>
<td>14.05</td>
<td>15.12</td>
<td>15.07</td>
<td>15.05</td>
<td>15.07</td>
<td>14.85</td>
</tr>
<tr>
<td>MnO</td>
<td>0.14</td>
<td>0.24</td>
<td>0.17</td>
<td>0.18</td>
<td>0.17</td>
<td>0.16</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>MgO</td>
<td>8.20</td>
<td>7.14</td>
<td>7.03</td>
<td>7.36</td>
<td>8.01</td>
<td>8.09</td>
<td>8.20</td>
<td>8.25</td>
<td>7.74</td>
</tr>
<tr>
<td>CaO</td>
<td>9.46</td>
<td>11.39</td>
<td>10.20</td>
<td>10.24</td>
<td>11.85</td>
<td>11.74</td>
<td>11.82</td>
<td>12.10</td>
<td>11.43</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.01</td>
<td>2.00</td>
<td>2.03</td>
<td>2.02</td>
<td>1.92</td>
<td>1.96</td>
<td>1.86</td>
<td>1.78</td>
<td>1.90</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.41</td>
<td>0.42</td>
<td>0.60</td>
<td>0.54</td>
<td>0.27</td>
<td>0.23</td>
<td>0.24</td>
<td>0.21</td>
<td>0.58</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.16</td>
<td>0.14</td>
<td>0.16</td>
<td>0.16</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Total</td>
<td>99.92</td>
<td>99.93</td>
<td>99.98</td>
<td>99.92</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>99.85</td>
<td>99.85</td>
</tr>
<tr>
<td>LOI</td>
<td>1.17</td>
<td>0.32</td>
<td>0.49</td>
<td>0.70</td>
<td>0.12</td>
<td>0.26</td>
<td>0.61</td>
<td>1.32</td>
<td>0.58</td>
</tr>
<tr>
<td>Mg# (0-15)</td>
<td>64.95</td>
<td>59.12</td>
<td>57.24</td>
<td>59.42</td>
<td>62.43</td>
<td>62.95</td>
<td>63.26</td>
<td>62.96</td>
<td>61.39</td>
</tr>
</tbody>
</table>

Note: The table continues with additional data on Ni (ppm), Cr, Rb, Sr, Y, Zr, Nb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, Pb, Th, and U. The isotopic data (Sr, Nd, Pb) for Maaziz and Ait Ourir samples are also provided, showing changes in the isotopic compositions from Lower to Upper samples.
highest contents of most other incompatible trace and major elements (e.g. TiO₂ and P₂O₅) are shown by the Lower basalts from the Midelt section (AN206 and AN215; Figs 11 and 12). The outlier of the Lower flows which yields low La/Yb (3.5) similar to those of Intermediate flows is sample AN137C from Tioirjadal (southern Central High Atlas), which is instead characterized by relatively high TiO₂ (1.43 wt %).

By contrast, Recurrent basalts, which are all remarkably similar, yield markedly different incompatible element and particularly REE contents and patterns compared to the other flows. The most significant difference concerns the almost flat REE patterns (La/YbCN = 1.4–1.3, Sm/YbCN = 1.04–0.95), which resemble those of E-MORB, even if E-MORB have much lower REE contents (Sun & McDonough, 1989). Unlike most
### Table 3: Continued

<table>
<thead>
<tr>
<th>Sample</th>
<th>AN 709</th>
<th>AN 711</th>
<th>AN 725</th>
<th>AN 726</th>
<th>AN 728</th>
<th>AN 724</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit area</td>
<td>Upper</td>
<td>Upper</td>
<td>Upper</td>
<td>Upper</td>
<td>Upper</td>
<td>Rec</td>
</tr>
<tr>
<td>SiO₂ wt %</td>
<td>50.63</td>
<td>50.76</td>
<td>50.63</td>
<td>51.48</td>
<td>50.88</td>
<td>50.21</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.98</td>
<td>1.00</td>
<td>0.82</td>
<td>0.93</td>
<td>0.92</td>
<td>1.42</td>
</tr>
<tr>
<td>MnO</td>
<td>0.17</td>
<td>0.17</td>
<td>0.18</td>
<td>0.17</td>
<td>0.17</td>
<td>0.25</td>
</tr>
<tr>
<td>MgO</td>
<td>7.95</td>
<td>7.96</td>
<td>11.91</td>
<td>8.01</td>
<td>8.91</td>
<td>5.70</td>
</tr>
<tr>
<td>CaO</td>
<td>11.68</td>
<td>11.50</td>
<td>12.30</td>
<td>12.05</td>
<td>12.14</td>
<td>9.96</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.87</td>
<td>1.89</td>
<td>1.48</td>
<td>1.97</td>
<td>1.85</td>
<td>2.24</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.45</td>
<td>0.71</td>
<td>0.31</td>
<td>0.39</td>
<td>0.40</td>
<td>0.50</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.10</td>
<td>0.10</td>
<td>0.08</td>
<td>0.09</td>
<td>0.09</td>
<td>0.13</td>
</tr>
<tr>
<td>Total</td>
<td>98.26</td>
<td>98.59</td>
<td>99.13</td>
<td>99.59</td>
<td>99.43</td>
<td>98.45</td>
</tr>
<tr>
<td>LOI</td>
<td>0.14</td>
<td>0.22</td>
<td>0.06</td>
<td>-0.16</td>
<td>0.38</td>
<td>0.01</td>
</tr>
<tr>
<td>Mg# (0.15)</td>
<td>64.87</td>
<td>64.53</td>
<td>73.27</td>
<td>65.59</td>
<td>68.16</td>
<td>46.55</td>
</tr>
<tr>
<td>Ni (ppm)</td>
<td>97</td>
<td>91</td>
<td>181</td>
<td>87</td>
<td>114</td>
<td>53</td>
</tr>
<tr>
<td>Cr</td>
<td>195</td>
<td>216</td>
<td>753</td>
<td>236</td>
<td>320</td>
<td>51</td>
</tr>
<tr>
<td>Rb</td>
<td>12.50</td>
<td>18.67</td>
<td>8.76</td>
<td>10.85</td>
<td>10.85</td>
<td>17.03</td>
</tr>
<tr>
<td>Sr</td>
<td>180.67</td>
<td>209.12</td>
<td>137.47</td>
<td>174.78</td>
<td>194.27</td>
<td>125.27</td>
</tr>
<tr>
<td>Y</td>
<td>21.32</td>
<td>21.80</td>
<td>18.48</td>
<td>20.12</td>
<td>19.70</td>
<td>42.28</td>
</tr>
<tr>
<td>Zr</td>
<td>49.85</td>
<td>78.38</td>
<td>63.44</td>
<td>72.13</td>
<td>69.76</td>
<td>107.64</td>
</tr>
<tr>
<td>Nb</td>
<td>5.04</td>
<td>5.00</td>
<td>4.05</td>
<td>4.62</td>
<td>4.54</td>
<td>4.88</td>
</tr>
<tr>
<td>Cs</td>
<td>0.86</td>
<td>1.42</td>
<td>0.56</td>
<td>0.50</td>
<td>0.50</td>
<td>1.77</td>
</tr>
<tr>
<td>Ba</td>
<td>124.87</td>
<td>132.53</td>
<td>105.59</td>
<td>107.26</td>
<td>111.28</td>
<td>117.55</td>
</tr>
<tr>
<td>La</td>
<td>7.23</td>
<td>7.21</td>
<td>6.04</td>
<td>6.71</td>
<td>6.57</td>
<td>8.05</td>
</tr>
<tr>
<td>Ce</td>
<td>16.70</td>
<td>16.56</td>
<td>13.84</td>
<td>15.50</td>
<td>15.11</td>
<td>18.55</td>
</tr>
<tr>
<td>Pr</td>
<td>2.28</td>
<td>2.27</td>
<td>1.91</td>
<td>2.12</td>
<td>2.08</td>
<td>2.54</td>
</tr>
<tr>
<td>Nd</td>
<td>10.40</td>
<td>10.39</td>
<td>8.76</td>
<td>9.66</td>
<td>9.44</td>
<td>11.92</td>
</tr>
<tr>
<td>Sm</td>
<td>2.79</td>
<td>2.81</td>
<td>2.41</td>
<td>2.65</td>
<td>2.57</td>
<td>3.68</td>
</tr>
<tr>
<td>Eu</td>
<td>0.97</td>
<td>0.97</td>
<td>0.81</td>
<td>0.92</td>
<td>0.89</td>
<td>1.26</td>
</tr>
<tr>
<td>Gd</td>
<td>3.37</td>
<td>3.36</td>
<td>2.90</td>
<td>3.12</td>
<td>3.06</td>
<td>5.11</td>
</tr>
<tr>
<td>Tb</td>
<td>0.57</td>
<td>0.58</td>
<td>0.49</td>
<td>0.53</td>
<td>0.52</td>
<td>0.95</td>
</tr>
<tr>
<td>Dy</td>
<td>3.61</td>
<td>3.67</td>
<td>3.15</td>
<td>3.38</td>
<td>3.30</td>
<td>6.50</td>
</tr>
<tr>
<td>Ho</td>
<td>0.76</td>
<td>0.77</td>
<td>0.67</td>
<td>0.72</td>
<td>0.69</td>
<td>1.44</td>
</tr>
<tr>
<td>Er</td>
<td>2.14</td>
<td>2.18</td>
<td>1.90</td>
<td>2.03</td>
<td>1.98</td>
<td>4.25</td>
</tr>
<tr>
<td>Tm</td>
<td>2.27</td>
<td>2.26</td>
<td>2.07</td>
<td>2.39</td>
<td>2.33</td>
<td>2.80</td>
</tr>
<tr>
<td>Yb</td>
<td>1.93</td>
<td>2.00</td>
<td>1.74</td>
<td>1.86</td>
<td>1.81</td>
<td>4.10</td>
</tr>
<tr>
<td>Lu</td>
<td>0.28</td>
<td>0.29</td>
<td>0.25</td>
<td>0.27</td>
<td>0.26</td>
<td>0.60</td>
</tr>
<tr>
<td>Hf</td>
<td>1.43</td>
<td>2.00</td>
<td>1.67</td>
<td>1.86</td>
<td>1.78</td>
<td>2.78</td>
</tr>
<tr>
<td>Ta</td>
<td>0.32</td>
<td>0.32</td>
<td>0.26</td>
<td>0.29</td>
<td>0.29</td>
<td>0.31</td>
</tr>
<tr>
<td>Pb</td>
<td>2.15</td>
<td>4.61</td>
<td>2.04</td>
<td>2.33</td>
<td>2.00</td>
<td>6.36</td>
</tr>
<tr>
<td>Th</td>
<td>1.14</td>
<td>1.19</td>
<td>1.02</td>
<td>1.14</td>
<td>1.06</td>
<td>1.95</td>
</tr>
<tr>
<td>U</td>
<td>0.25</td>
<td>0.29</td>
<td>0.25</td>
<td>0.28</td>
<td>0.26</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Major elements, Cr and Ni analysed by X-ray fluorescence, other trace elements by ICP-MS. Mg# = 100 × [Mg/(Mg+Fe²⁺)], for Fe³⁺/Fe²⁺ = 0.15. Sampling coordinates are given in Supplementary Data Table S1; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org. The complete whole-rock data set is reported in the Supplementary Data Electronic Appendix Table S8; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org. CHA, Centra High Atlas; B. D., Bas Draa; F. Z., Foum Zguid.

other samples, all Recurrent basalts display a marked negative Eu (Eu/Eu* = 0.8) and negative Sr and Ti anomalies (relative to LREE and HREE, respectively), which are moderate to absent in most Lower, Intermediate and Upper flows. Recurrent basalts are also relatively enriched in Th and U relative to Nb and Ta (Th/Nb = 0.39–0.41, U/Ta = 1.6–1.9 vs 0.19–0.40 and 1.3–0.7 for the other rocks).

Intra-unit variations are rather scattered and do not display clear trends, which might be due to the somewhat restricted MgO (i.e. differentiation) range of each unit. Nonetheless, for the Lower unit there is a tendency
for the most differentiated samples (MgO < 6 wt%) to yield slightly higher SiO2, Na2O and incompatible element contents (including TiO2) and La/Yb. Intermediate lava flows show a restricted range of composition and of differentiation (e.g. MgO generally in the range 9–7 wt%), while Intermediate intrusive rocks from the Anti Atlas and parts of the Amelal sill tend to be more evolved (MgO as low as 4 wt%). Most Upper unit rocks plot in a fairly restricted range in terms of major and trace element concentrations, except for one lava flow from the Middle Atlas (AN540) and two sill samples from the Anti Atlas (MOR1015, AN725), which are MgO-rich (10–11.9 wt%). The regional variations within each lava flow unit, for example between the High Atlas and the Middle Atlas and Meseta, are negligible and not systematic. Instead, subtle geochemical differences are revealed within some of the sections analysed in most detail (Fig. 14). As an example, the Tiourjdal section of the southern Central High Atlas shows in general significant compositional jumps between the four lava units. However, in some cases, such abrupt discontinuities between the different units do not coincide for all chemical elements. For instance, the basaltic andesite AN137C sampled about halfway up the Tiourjdal section may be regarded either as the last of the Lower flows because of its high TiO2 (14.3 wt%) similar to those of the Lower flows, or as the first of the Intermediate flows because of its low Zr (105 ppm), Nb (7.8 ppm), La/Yb (5.1) and highly incompatible trace element contents (Zr and Nd isotopic variations are shown in Fig. 14 a and e). Similar features apply for the Telouet, southern Central High Atlas and Agourai (Middle Atlas) sections (not shown in Fig. 14), where samples AN159 and AN525b yield Lower unit-like major elements and Intermediate unit-like incompatible trace elements. The Midelt samples (Fig. 14c and g) show among the highest incompatible trace element contents, in particular for the Lower unit, yet the general up-section variations are similar to those from the Central High Atlas. The most marked difference and compositional jump from the Lower to the Intermediate unit is instead shown for the Maaziz section (Western Meseta). However, here the topmost Intermediate samples show an increase of TiO2, but not of incompatible trace elements. We note a similar increase in TiO2 towards the top of the Intermediate unit at Tounfite (Middle Atlas). Finally, the Agourai section (not shown in Fig. 14) of the Middle Atlas consists of flows with Intermediate unit-like geochemical affinities, except for the previously cited sample AN525b and for sample AN633, collected towards the top of the section, with major and trace element compositions approaching those of Upper unit samples (e.g. TiO2 = 1.14 wt%; La/YbCN = 2.3).

Geochemical data obtained for samples previously collected for magnetostratigraphic analyses (Knight et al., 2004) at Tiourjdal, Telouet and Oued Lahr in the Central High Atlas offer further insights into both the temporal and spatial variability of the units. Even if slightly altered, poorly mobile elements such as Ti and other HFSE can be readily used to describe the up-section variation of these densely-sampled lava piles (Fig. 15). Based on these data, correlations can be established among these three sections. These show that the Lower unit seems to be complete only at Tiourjdal, while at Telouet and Oued Lahr about the lower half of the Lower unit is missing (or not cropping out). By contrast, the transition from the Lower to the Intermediate units is well expressed in all sections, with a general clear compositional shift (with the exceptions described above).

**Intrusive rocks**

Direct comparison of effusive and intrusive rocks can be hampered by the (partially) cumulative nature of the...
Fig. 11. Whole-rock major element compositions of CAMP lava flows and intrusives from Morocco. Same symbols and abbreviations as in Fig. 10. Grey field is the compositional range of CAMP basalts from other parts of the province. MELTS (Ghiorso & Sack, 1995) liquid lines of descent have been calculated starting from AN133 (Lower unit) as the parental magma composition at 0.9 GPa (dashed line) and 0.1 GPa (full line), 0.5 wt % H2O in the starting magma, fO2 at the QFM buffer. The most evolved composition on the MELTS lines corresponds to about 25 and 35 wt % fractionation at 0.9 and 0.1 GPa, respectively. The pMELTS (Ghiorso et al., 2002) liquid line of descent (black lines with tick marks) is calculated at 1 GPa, the parental magma (MgO = 15.5 wt %, off-scale on diagrams) is a 6.8% melt of KLB-1 peridotite (Hirose & Kushiro, 1993) calculated for 1.5 GPa, 1400°C. Tick marks on the pMELTS lines represent 5% increments of fractional crystallization at T decreasing from 1350 to 1200°C, i.e. the most evolved composition corresponds to about 35 wt % fractionation. Note: pMELTS lines are not shown for K2O and P2O5, as these are trace elements that are not properly modelled with this program.
Fig. 12. (a–h) Selected trace element variation vs MgO (wt.%) and La (ppm). Same symbols as in Fig. 10. Zr measured by X-ray fluorescence, La, Nb, Th by ICP-MS. EC-AFC paths (Spera & Bohrson, 2001) in (g) and (h) are calculated starting from an Upper and from a Lower initial composition, considering the following rocks as crustal contaminants: an Eburnean granite (more enriched), a Pan-African granite (slightly less enriched) and a lower crustal granulite (in (e) only; in (d) the granulite EC-AFC curve overlaps with the Eburnean granite curve). Parameters used in EC-AFC are reported in Table 5. Grey field is CAMP basalts from other parts of the province (data from Marzoli et al., 2018 and references therein). In (g) and (h), the closed system FC (fractional crystallization) line represents 50% fractionation from a hypothetical parental Upper magma (black arrow) and has been calculated assuming 40% augite and 10% plagioclase fractionation (partition coefficients from Aigner-Torres et al. (2007) and Bédard (2014)). (i, j) Zr/Y vs Nb/Y (logarithmic scale) and La/Nb vs delta-Nb (\(= \frac{1.74+\log(\text{Nb/}Y)}{0.92} \times \log(\text{Zr/Y})\); see text for explanation; Fitton et al., 1997) for Moroccan CAMP basalts. The grey field represents the Icelandic mantle array as defined in Fitton et al. (1997); Mesozoic Atlantic MORB data are from Janney & Castillo (2001); southern Karoo picrites are from Heinonen et al. (2010) and Luttinen (2018); Pan-African and Eburnean granite compositions are from Toummite et al. (2013) and from Ennih & Liégeois (2008).
latter samples, as they may not reflect magmatic liquid compositions. In the case of the Amelal sill, these difficulties are enhanced by the pervasive alteration of the sill. Nevertheless, relying mainly on immobile incompatible minor and trace element compositions, Moroccan CAMP intrusive rocks can be assigned to the four main magmatic units.

Most of the sampled rocks from the Amelal sill have major and trace element compositions similar to Intermediate unit lava flows (Figs 11 and 12). However, a few samples are relatively depleted in Ti and other incompatible elements, as observed for Upper unit basalts (e.g. sample LV37). One sample from the Amelal sill, LV34, is compositionally rather distinct from the remainder of the sill. LV34 is in general enriched in incompatible minor and trace elements, approaching the composition of Lower basaltic andesitic lava flows. The similarity between LV34 and Lower lava flows is also evidenced by incompatible element ratios, such as TiO$_2$/Y or Zr/Y (Fig. 12e and f). The Jbilet intrusives include a dyke sample with Lower unit composition (AN320), as well as one dyke and one sill with Intermediate composition.

Intrusive rocks from the Anti Atlas (Foum Zguid dyke and Bas Draa sills) can be readily assigned to three (out of the four) magmatic units as they share strong similarities with the lava flows at least in terms of incompatible major and trace elements and trace element ratios. Most Foum Zguid dyke samples overlap the compositional field defined by Intermediate lava flows, for example in TiO$_2$, P$_2$O$_5$, La/Yb etc. By contrast, four Foum Zguid dyke samples also have Upper-unit like compositions and one small dyke parallel to the main Foum Zguid dyke has a Recurrent-like composition. The Foum Zguid dyke appears to be a composite dyke, intruded by Intermediate and Upper magmas. In fact, at two
basalts of the CAMP (Fig. 16), with \( {\frac{87}{86}}{\text{Sr}} \) in the range of typical low-Ti Sr–Nd–Pb isotopic compositions of CAMP basalts from Morocco (Table 3) fall in the field of rocks and represent the various CAMP localities of samples belong to the four lava flow units and intrusive Intermediate flow (AN128) and one Intermediate Anti-1984). One Argana Lower flow (AN115b), one Argana Northern Hemisphere Reference Line, NHRL; Hart, hues (18).

\( \frac{87}{86} \text{Sr} \) ratios reflects a secondary alteration finger-print rather than a primary compositional feature, as also suggested by the higher Sr contents of these same samples (enrichment excess by c.50–70 ppm) compared to samples of the same unit.

Systematic differences in Sr and Nd initial isotopic ratios characterize the four Moroccan CAMP lava flow units and their intrusive equivalents (Fig. 16). With the exception of the sample thought to be altered (AN115b), Lower flows yield relatively high \( {\frac{87}{86}}{\text{Sr}} \) (0.7058–0.706) and moderate \( {\frac{143}{144}}{\text{Nd}} \) (0.51231–0.51239). Intermediate flows trend to lower \( {\frac{143}{144}}{\text{Nd}} \) (0.51225–0.5125) with similar \( {\frac{87}{86}}{\text{Sr}} \) (0.7057–0.7065), again excluding altered samples. Pb isotopic compositions for Lower and Intermediate flows overlap, even if these latter show a slightly larger spread (206\(^{\text{Pb}}\)/204\(^{\text{Pb}}\) (18–18.4) and plot at slightly higher 207\(^{\text{Pb}}\)/204\(^{\text{Pb}}\) and 208\(^{\text{Pb}}\)/204\(^{\text{Pb}}\) for a given 206\(^{\text{Pb}}\)/204\(^{\text{Pb}}\). Upper basalt lava flows and half of the Upper unit intrusive rocks yield a restricted Sr-Nd isotopic range (0.7055–0.7056, 0.51235–0.51233, respectively) having lower \( {\frac{87}{86}}{\text{Sr}} \) compared to Lower and Intermediate flows. Upper unit basalt samples plot towards the less radiogenic end in Pb isotopic space for low-Ti CAMP basalts.

Sr–Nd–Pb–Os isotopic compositions. For this study, we obtained 52 \( {\frac{87}{86}}{\text{Sr}} \) and 143\(^{\text{Nd}}\)/144\(^{\text{Nd}}\), 33 Pb and 13 Os isotopic analyses on whole-rock samples. The selected samples belong to the four lava flow units and intrusive rocks and represent the various CAMP localities of Morocco. Initial isotopic compositions were back-calculated to 201Ma to correct the measured isotopic ratios for in situ decay of the radioactive element. Initial Sr–Nd–Pb isotopic compositions of CAMP basalts from Morocco (Table 3) fall in the field of typical low-Ti basalts of the CAMP (Fig. 16), with \( {\frac{87}{86}}{\text{Sr}} \) in the range 0.705–0.707, 143\(^{\text{Nd}}\)/144\(^{\text{Nd}}\) 0.5125–0.5122 (\( {\text{Nd}} \), from 4–2 to 3) and high 207\(^{\text{Pb}}\)/204\(^{\text{Pb}}\) (15.59–15.67) and 208\(^{\text{Pb}}\)/204\(^{\text{Pb}}\), (37–38) at moderate 206\(^{\text{Pb}}\)/204\(^{\text{Pb}}\) (18–18.9), resulting in high \( \Delta\text{7/4} \) (10–18) and \( \Delta\text{8/4} \) (32–61) values (\( \Delta \) values indicating difference with respect to the Northern Hemisphere Reference Line, NHRL; Hart, 1984). One Argana Lower flow (AN115b), one Argana Intermediate flow (AN128) and one Intermediate Antith (Foum Zguid) dyke sample (AN734) yield higher 87\(^{\text{Sr}}\)/86\(^{\text{Sr}}\) (0.7072–0.7089), plotting off the field of other Lower and Intermediate basaltic andesites at similar 143\(^{\text{Nd}}\)/144\(^{\text{Nd}}\) (0.51238 and 0.51235). This shift to higher 87\(^{\text{Sr}}\)/86\(^{\text{Sr}}\) ratios reflects a secondary alteration fingerprint rather than a primary compositional feature, as also suggested by the higher Sr contents of these same samples (enrichment excess by c.50–70 ppm) compared to samples of the same unit.

Systematic differences in Sr and Nd initial isotopic ratios characterize the four Moroccan CAMP lava flow units and their intrusive equivalents (Fig. 16). With the exception of the sample thought to be altered (AN115b), Lower flows yield relatively high 87\(^{\text{Sr}}\)/86\(^{\text{Sr}}\) (0.7058–0.706) and moderate 143\(^{\text{Nd}}\)/144\(^{\text{Nd}}\) (0.51231–0.51239). Intermediate flows trend to lower 143\(^{\text{Nd}}\)/144\(^{\text{Nd}}\) (0.51225–0.5125) with similar 87\(^{\text{Sr}}\)/86\(^{\text{Sr}}\) (0.7057–0.7065), again excluding altered samples. Pb isotopic compositions for Lower and Intermediate flows overlap, even if these latter show a slightly larger spread (206\(^{\text{Pb}}\)/204\(^{\text{Pb}}\) (18–18.4) and plot at slightly higher 207\(^{\text{Pb}}\)/204\(^{\text{Pb}}\) and 208\(^{\text{Pb}}\)/204\(^{\text{Pb}}\) for a given 206\(^{\text{Pb}}\)/204\(^{\text{Pb}}\). Upper basalt lava flows and half of the Upper unit intrusive rocks yield a restricted Sr-Nd isotopic range (0.7055–0.7056, 0.51235–0.51233, respectively) having lower 87\(^{\text{Sr}}\)/86\(^{\text{Sr}}\) compared to Lower and Intermediate flows. Upper unit basalt samples plot towards the less radiogenic end in Pb isotopic space for low-Ti CAMP basalts.

Recurrent basalts can be clearly distinguished from the other CAMP units. They show limited variations of Nd and Sr initial isotopic compositions and have lower 87\(^{\text{Sr}}\)/86\(^{\text{Sr}}\) (0.7049–0.7053) and higher 143\(^{\text{Nd}}\)/144\(^{\text{Nd}}\) (0.51244–0.51248) compared to the other units. In addition, they yield the highest 206\(^{\text{Pb}}\)/204\(^{\text{Pb}}\) (18.45–18.65) and 208\(^{\text{Pb}}\)/204\(^{\text{Pb}}\) (38.42–38.54) of all magmatic units. Recurrent basalts are also characterized by correlated Sr and Pb isotopic compositions, a feature that is not observed in other units. They also yield slightly decreasing 207\(^{\text{Pb}}\)/204\(^{\text{Pb}}\) (15.66–15.64) at increasing 206\(^{\text{Pb}}\)/204\(^{\text{Pb}}\) and slightly lower \( \Delta\text{8/4} \) (32–48) compared to the other samples (43–60).

Thirteen of the freshest samples from the four Moroccan CAMP lava flow units were analysed also for
Re–Os isotopic compositions (Fig. 17; Table 4). Re contents range from 130 to 678 ppt, with the exception of samples AN44 and AN24 from the Recurrent basalts, which contain 1953 and 5502 ppt, respectively. Re has the lowest content in the Lower basaltic andesites and by far the highest one in the Recurrent basalts. Os contents range from 22 to 482 ppt. The lowest Os concentrations are found in Upper and Recurrent basalts and are in general correlated with MgO, Cr and Ni. Measured $^{187}\text{Os}/^{188}\text{Os}$ is roughly correlated with $^{187}\text{Re}/^{188}\text{Os}$ (MSWD = 62) in all analysed samples except one (Recurrent basalt AN24) and yields an apparent Re–Os age (202 ± 6 Ma, 2σ uncertainty) indistinguishable from the 40Ar/39Ar ages of the Moroccan CAMP, with a $^{187}\text{Os}/^{188}\text{Os}$ intercept of 0.127 ± 0.03, 1σ compared to the heterogeneous Intermediate and Upper flows. These latter units yield the lowest (c.0.11) and highest $^{187}\text{Os}/^{188}\text{Os}$ (c.0.14) values among the studied units. This may reflect the fact that the Lower basalts have the highest Os contents and thus the lowest $^{187}\text{Re}/^{188}\text{Os}$ ratios and so are subject to the smallest corrections for radiogenic ingrowth, leading to the most robust estimates of initial ratio. In general, Os isotopic compositions are poorly correlated with Sr–Nd–Pb isotopic compositions, with the exception of Lower unit samples which show a relatively good correlation for Os vs Nd and Pb isotopic ratios (Fig. 17).

The differences in isotopic composition among the four units are also highlighted for some sections analysed in detail (Figs 14 and 15). In particular, at Tiourjdal, Sr–Nd–Pb–Os isotopic data are available for all the four units and show a similar $^{87}\text{Sr}/^{86}\text{Sr}$ for Lower and Intermediate flows and then a decrease for Upper and Recurrent samples; $^{143}\text{Nd}/^{144}\text{Nd}$ is slightly higher for Lower and Upper flows compared to Intermediate ones, whereas the Recurrent basalt yields the highest value. Although not shown in the figures, Pb and Os isotopes show comparable variations, with almost indistinguishable isotopic ratios in Lower and Intermediate flows, showing the lowest values for the Upper basalt and the highest values for the Recurrent basalt. Similar variations can also be seen for the Ait Ourir (northern central High Atlas), Ahouli (Midelt) and Maaziz (western
Meseta), although the isotopic data are sparser for these sections.

Isotopic compositions are in general poorly correlated with major and trace element concentrations and ratios. The best, although still scattered, correlations are shown between $^{87}\text{Sr}/^{86}\text{Sr}$ and SiO$_2$ and La/Yb (Supplementary Data Electronic Appendix 1; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org), which is consistent with the cited differences among the four lava flows units. No correlations are observed with MgO, Mg# or any incompatible element variations, neither at global or intra-unit variation scales.

**Comparison with other CAMP basalts**

Compared to other CAMP basalts, those from Morocco plot within the field of low-Ti samples from Africa, Europe, North and South America in terms of major and trace element contents and of Sr, Nd and Pb isotopic compositions (Figs 16 and 18). Marzoli et al. (2018) identified six main geochemical groups of magmatic compositions from the entire CAMP (Fig. 18). In detail, Moroccan Lower basalts belong to the Tiourjdal group along with some dykes and sills from Mali (Taoudenni Basin; Verati et al., 2005) and with Lower lava flows from Algeria (Meddah et al., 2017). Samples of this group are significantly more enriched in terms of incompatible trace element contents and have higher ratios of strongly vs moderately incompatible elements (e.g. La/Yb) than any other group of low-Ti CAMP rocks from the circum-Atlantic basins (Portugal, Canada, U.S.A.; Tollo & Gottfried, 1992; Callegaro et al., 2013, 2014a; Merle et al., 2014) or from Brazil and Bolivia (De Min et al., 2003; Merle et al., 2011; Bertrand et al., 2014; Marzoli et al., 2018). However, the Sr–Nd–Pb isotopic compositions of Moroccan Lower flows and of the
Fig. 17. Re–Os isotopic compositions of CAMP lava flows from Morocco. (a) $^{187}$Os/$^{188}$Os vs $^{187}$Re/$^{188}$Os diagram showing alignment of all analysed points (except Recurrent basalt AN24) in a pseudo-isochron which yields an apparent age of 202.3 ± 5.8 Ma. Isochron calculated using Isoplot (Ludwig, 2003); uncertainties on $^{187}$Re/$^{188}$Os and $^{187}$Os/$^{188}$Os are listed in Table 5. The apparent age does not have statistical validity (MSWD 62, probability close to zero), but indicates that the Re–Os systematics of the analysed rocks (except AN24, not included in the diagram) were not greatly modified by post-crystallization processes. (b) Initial Os content (in ppb) vs $^{187}$Os/$^{188}$Os. (c–d) Nd and Pb vs Os isotopic compositions. EC-AFC assimilation paths starting from two different initial compositions are shown; parameters reported in Table 5. The green vertical lines in (b) and (c) and the horizontal line in (d) represent the $^{187}$Os/$^{188}$Os of the primitive upper mantle (PUM) calculated for 201 Ma (0.1281 ± 0.0008, derived from the present-day value of PUM of 0.1296; Meisel et al., 2001). Black bars on symbols represent uncertainties on calculated initial $^{187}$Os/$^{188}$Os.

Table 4: Re–Os isotopic data. Os isotopic ratios were normalized to $^{192}$Os/$^{188}$Os = 3.08271

<table>
<thead>
<tr>
<th>Unit</th>
<th>[Re] (ppt)</th>
<th>[Os] (ppt)</th>
<th>$^{188}$Os M g$^{-1}$</th>
<th>$^{187}$Os/$^{188}$Os</th>
<th>2$\sigma$</th>
<th>$^{187}$Re/$^{188}$Os</th>
<th>2$\sigma$</th>
<th>$^{187}$Os/$^{188}$Os_{201Ma}</th>
<th>2$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AN 49</td>
<td>lower</td>
<td>269</td>
<td>75.6</td>
<td>5.24E-14</td>
<td>0.18427</td>
<td>0.0055</td>
<td>0.25013</td>
<td>0.1263</td>
<td>0.00001</td>
</tr>
<tr>
<td>AN 32</td>
<td>lower</td>
<td>176</td>
<td>321.8</td>
<td>2.24E-13</td>
<td>0.13615</td>
<td>0.0034</td>
<td>0.16217</td>
<td>0.1273</td>
<td>0.00004</td>
</tr>
<tr>
<td>AN 134</td>
<td>lower</td>
<td>340</td>
<td>108.5</td>
<td>7.53E-14</td>
<td>0.17481</td>
<td>0.0058</td>
<td>0.15215</td>
<td>0.1239</td>
<td>0.00012</td>
</tr>
<tr>
<td>AN 132</td>
<td>lower</td>
<td>130</td>
<td>482.1</td>
<td>3.38E-13</td>
<td>0.13507</td>
<td>0.0063</td>
<td>0.16087</td>
<td>0.1307</td>
<td>0.00007</td>
</tr>
<tr>
<td>AN 18</td>
<td>intermediate</td>
<td>678</td>
<td>39.3</td>
<td>2.66E-14</td>
<td>0.37918</td>
<td>0.0012</td>
<td>0.8584</td>
<td>0.1256</td>
<td>0.00044</td>
</tr>
<tr>
<td>AN 138</td>
<td>intermediate</td>
<td>365</td>
<td>152.6</td>
<td>1.06E-13</td>
<td>0.16408</td>
<td>0.0050</td>
<td>0.1160</td>
<td>0.1243</td>
<td>0.00010</td>
</tr>
<tr>
<td>AN 39</td>
<td>intermediate</td>
<td>639</td>
<td>44.7</td>
<td>3.04E-14</td>
<td>0.35646</td>
<td>0.0010</td>
<td>0.7082</td>
<td>0.1191</td>
<td>0.00037</td>
</tr>
<tr>
<td>AN 510</td>
<td>intermediate</td>
<td>465</td>
<td>50.7</td>
<td>3.46E-14</td>
<td>0.29484</td>
<td>0.0014</td>
<td>0.4522</td>
<td>0.1431</td>
<td>0.00025</td>
</tr>
<tr>
<td>AN 141</td>
<td>upper</td>
<td>446</td>
<td>35.1</td>
<td>2.40E-14</td>
<td>0.32465</td>
<td>0.0013</td>
<td>0.6266</td>
<td>0.1146</td>
<td>0.00037</td>
</tr>
<tr>
<td>AN 22</td>
<td>upper</td>
<td>526</td>
<td>22.3</td>
<td>1.47E-14</td>
<td>0.53935</td>
<td>0.0030</td>
<td>1.2026</td>
<td>0.1336</td>
<td>0.00060</td>
</tr>
<tr>
<td>AN 540</td>
<td>upper</td>
<td>559</td>
<td>57.4</td>
<td>3.93E-14</td>
<td>0.27114</td>
<td>0.0009</td>
<td>0.4790</td>
<td>0.1105</td>
<td>0.00021</td>
</tr>
<tr>
<td>AN 44</td>
<td>recurrent</td>
<td>1953</td>
<td>37.7</td>
<td>2.07E-14</td>
<td>1.1994</td>
<td>0.0060</td>
<td>0.3171</td>
<td>0.1360</td>
<td>0.00017</td>
</tr>
<tr>
<td>AN 24</td>
<td>recurrent</td>
<td>5502</td>
<td>34.2</td>
<td>1.51E-14</td>
<td>4.564</td>
<td>0.0037</td>
<td>1.2254</td>
<td>0.4535</td>
<td>0.00077</td>
</tr>
</tbody>
</table>

All uncertainties are 2$\sigma$. Uncertainties listed for the measured $^{187}$Os/$^{188}$Os ratios include those related to in-run statistics, standard reproducibility and blank variability. Initial ratios were calculated using a decay constant $t = 1.666$ x10-11 (Smoliar et al., 1996). Uncertainties on initial ratios include those related to in-run errors, blank corrections and weighing errors. Uncertainties on age and $^{187}$Re decay constant are not included as these produce systematic rather than random errors on initial ratios.
Tiourjdal group samples in general fall in the field of most other low-Ti CAMP rocks.

Intermediate and Upper basalts belong to the Prevalent group (Marzoli et al., 2018) and share incompatible element contents and ratios with the oldest basalts from the Newark basins (e.g. Orange Mt. basalt), all CAMP basalts from SW Europe and some Taoudenni dykes from Mali (Cebrià et al., 2003; Verati et al., 2005; Martins et al., 2008; Callegaro et al., 2014; Merle et al., 2014). Intermediate Moroccan basaltic andesites display some of the highest \(^{207}\text{Pb}/^{204}\text{Pb}\) and thus \(^{207}\text{Pb}/^{204}\text{Pb}\) of all CAMP rocks and the Moroccan Upper basalts yield among the least radiogenic Pb isotopic compositions of CAMP low-Ti samples (except for SE-USA dykes; Callegaro et al., 2013).

Finally, Recurrent basalts from Morocco along with the Hook Mt. and Hampden basalts from the U.S.A. (Merle et al., 2014) belong to the Recurrent group (Marzoli et al., 2018) and yield among the lowest Sr and highest Nd and Pb isotopic ratios of all CAMP low-Ti basalts. This rock group is also characterized by similar systematics in trace element contents and ratios, for example little fractionated MREE/HREE patterns.

Several of the Moroccan samples show lower \(^{187}\text{Os}/^{188}\text{Os}\) than the great majority of CAMP rocks so far. In particular, four samples (two Intermediate and two Upper basalts) display \(^{187}\text{Os}/^{188}\text{Os}\) lower than 0.120, implying derivation from a mantle source that experienced melt extraction more than 1.3 billion years ago (assuming that the \(^{187}\text{Re}/^{188}\text{Os}\) ratios of these samples have been unperturbed). This has rarely been observed elsewhere in the CAMP province. On the other hand, the Lower basalt samples, which have the highest Os concentrations, have \(^{187}\text{Os}/^{188}\text{Os}\) values fairly close to those analysed so far within the CAMP and close to the Primitive Upper Mantle (PUM) value at 201 Ma (0.1281 ± 0.0008, derived from the present-day value of PUM of 0.1296; Meisel et al., 2001).

DISCUSSION

The CAMP in Morocco: age, duration, volcanostratigraphic correlations

Geochemical data show that the lava flow sequences share similar time-related variations throughout Morocco (Figs 14 and 15). In particular, throughout Morocco, lava flows of the Lower and Intermediate units are nearly ubiquitous. The thickness of Lower basalts diminishes from south (Central High Atlas, Argana) to north (Middle Atlas and Meseta), while that of Intermediate basalts increases. Upper flows are relatively less abundant but can be found in the Central High Atlas and Middle Atlas, while they are (to our knowledge) absent in the Eastern and Western Meseta and at Argana. Recurrent lava flows are limited to the Central High Atlas.

Combined with previously published geochronologic, magnetostratigraphic and palynological data (Sebai et al., 1991; Knight et al., 2004; Marzoli et al., 2004; Nomade et al., 2007; Verati et al., 2007; Blackburn et al., 2013; Davies et al., 2017; Panfili et al., 2019) the ages presented in this study, paleomagnetic and geochemical data constrain the emplacement history of the CAMP in Morocco. The new \(^{40}\text{Ar}/^{39}\text{Ar}\) ages for the
Middle High Atlas and Meseta lava flows are similar to those for the Central High Atlas (previous and new data) and suggest a synchronous eruption all over Morocco with peak activity at c.201.4 Ma (Figs 2 and 6). The now quite large set of $^{40}$Ar/$^{39}$Ar ages for the Lower and Intermediate unit lava flows (15 and 8 ages, respectively) suggests also that Lower and Intermediate lavas were erupted over a short time span. These findings are consistent with new palynological data (Marzoli et al., 2004; Deenen et al., 2010; Panfill et al., 2019), which show that Lower to Upper basalts from throughout Morocco were emplaced on sedimentary strata with an identical palynological association, i.e. with identical biostratigraphic age. Combined with carbon isotope data on the associated sedimentary strata (Deenen et al., 2010; Dal Corso et al., 2014), the palynological data suggest that the Lower to Upper basalts were erupted at the very beginning of the end-Triassic extinction interval (c.201.51 ± 0.15 Ma) and ceased their activity before the Triassic-Jurassic boundary (c.201.36 ± 0.15 Ma; U/Pb ages from Schoene et al., 2010, recalculated by Wotzlaw et al., 2014). The new magnetostratigraphic data for the Middle Atlas and Meseta sections, even if slightly more scattered than similar data for the Central High Atlas (Knight et al., 2004), confirm that lava flows from northern Morocco were also erupted in short successive pulses. Following Knight et al. (2004) and Font et al. (2011), five volcanic pulses may have occurred in Morocco. Finally, the new U/Pb age for the Amelal sill sample LV34 (201.569 ± 0.042 Ma), which we correlate to the Lower unit, constrains the onset of the CAMP volcanism in Morocco. This age is identical to the U–Pb age (201.564 ± 0.054 Ma) obtained by Blackburn et al. (2013) for an Amelal sill sample, which those authors attributed to the Intermediate unit. These ages suggest that emplacement of Lower and Intermediate basalts was essentially synchronous, given that their age difference is less than c.0.1 Ma considering the uncertainty on the ages. Based on field evidence and on previous geochronologic data, only Recurrent basalts seem to be significantly younger than the main peak of CAMP activity in Morocco, consistent with the separation by about 50 m of sediments. However, our new mini-platoe age for the Recurrent basalt AN24 (201.15 ± 0.70 Ma) suggests that the time interval between emplacement of the peak volcanic activity (Lower to Upper flows) and emplacement of the Recurrent basalt may have been relatively short (<1 Ma).

The global picture that emerges, based on palaeomagnetic, palynological, geochronologic data, is that of a very rapid emplacement (possibly in less than 0.1 Ma) of over 95 vol. % (i.e. Lower to Upper units) of the basaltic lava flows. All over Morocco, lavas of each unit have near-identical composition and lava piles display near-identical stratigraphic evolution. CAMP lava flows were probably present in the entire High Atlas basin, even if in Eastern Morocco they are probably buried under the Jurassic and Cretaceous sedimentary cover. On the other hand, there are no observations demonstrating that CAMP lavas ever flowed out of the basins, i.e. that they flooded over the Hercynian basement. It also remains unclear if CAMP magmas were erupted in the Anti Atlas (see next section). Taking into account the area shown by the dashed line in Fig. 1b, the CAMP in Morocco may have reached a total surface area of about 0.13 million km$^2$. Considering an average thickness of the lava piles of 100 m, the total erupted volume would be around 10$^4$ km$^3$ and the average eruption rate about 0.1 km$^3$/year, assuming a duration of 0.1 Ma. Such an eruption rate is comparable to that at Hawaii (Lipman et al., 2006; Jourdan et al., 2012). However, if we consider that Lower to Upper CAMP flows in Morocco were erupted in four pulses each lasting about 400 years (Knight et al., 2004; Font et al., 2011), the eruption rate during the pulses would be about 8 km$^3$/year. Such an eruption rate is over one order of magnitude higher than at Hawaii and similar to e.g. the Laki eruption in Iceland (15 km$^3$ in 9 months during the years 1783–1784), which had a considerable effect on the climate in the northern hemisphere (Thordarson & Self, 1993).

Magmatic plumbing system: dykes and sills from the Anti Atlas, Argana and the Jbelits Mt

Correlations of intrusive rocks from the Anti Atlas, the Argana Valley (Amelal sill) and the Jbelits Mountains with effusive rocks are based on geochemical analyses. In particular, the best constraint is provided by comparison of minor (Ti and P) and trace element (e.g. HFSE and REE) contents and ratios. The overlap of major element compositions of intrusive and effusive rocks is not perfect. This is probably due to the fact that, unlike most of the lava flows, dykes and sills are significantly different from near-liquidus melt compositions. Isotopic data are also useful to correlate intrusive and effusive rocks, even if the $^{87}$Sr/$^{86}$Sr of the intrusive rocks seems to be slightly modified by alteration effects.

Our geochemical data and field observations indicate that the large dykes and sills were formed mainly by magmas of the Intermediate and Upper units. In the Anti Atlas, multiple intrusions of magmas with Intermediate and Upper composition occurred at some localities along the ~200 km long Fous Zguid dyke (e.g. near Bou Azzer or near Tazirt, Fig. 1b). This indicates that the Fous Zguid dyke was intruded by compositionally distinct magmas probably during successive magma injection events. Near Tissint, a small dyke paralleling the main Fous Zguid dyke can be assigned to the Recurrent unit, while the main body of the Fous Zguid dyke corresponds to the Intermediate unit. However, it remains unclear if the Anti Atlas dyke system ever fed any lava flows. It is notable that the c. N30 orientation of the Fous Zguid dyke does not intersect the areas where CAMP lava flows crop out in the High Atlas. Notably, the Fous Zguid dyke runs along the main axis of the Anti Atlas Paleozoic basins and and
intrudes Proterozoic basement and Paleozoic sediments. It follows the direction intruded by a late Proterozoic dyke.

The few samples from the Jbilet dyke (except sample AN320 akin to the Lower basalts) and NNE–SSW orientation of the dyke, pointing towards the Argana Valley, suggest that this rather large (even if poorly outcropping) dyke fed the Intermediate lava flows of the Argana basin. The Amelal sill in the Argana basin was mainly formed by Intermediate-type magmas (Fig. 12). Only one sample (LV37) approaches the Upper magma composition, even if it should be considered that pervasive alteration of this rock hinders a clear correlation with lava flow compositions. One sample from the central part of the Amelal sill (LV34) has a composition quite different from the rest of the Amelal rocks; LV34 is similar to Lower lava flows, even if its geochemical overlap with the Lower basaltic lava flows is not perfect. Sample LV34 is of major importance, since it contains zircon and yielded a U/Pb age. LV34 has an evolved composition (MgO = 4.66 wt %, SiO2 = 54.86 wt %) and relatively high contents of incompatible major (TiO2 1.87 wt %, P2O5 0.21 wt %) and incompatible trace elements (e.g. Th = 3.9 ppm; Nb = 12.2 ppm; La = 18.3 ppm; Zr = 175 ppm), as well as high values for most ratios of strongly to moderately incompatible elements (e.g. TiO2/Y, Zr/Y; Fig. 12). These values are similar to those of the Lower lava flows and clearly higher than those shown by even the most evolved Intermediate lava samples. They are also different from the values of all other Amelal sill samples, which instead are of Intermediate or Upper affinity. However, LV34 differs from Lower basalts in terms of its relatively low La/Yb (5.19, while most Lower basalts have La/Yb >6.2). In general, it may be concluded that the Amelal sill is composite in composition, i.e. it was formed by multiple intrusions of distinct magma batches. However, the Amelal sill is not only quite altered but also coarse-grained, making the comparison with lava flow samples difficult.

In general, one pattern that emerges is that intrusive rocks with compositions pertaining to the Lower unit are virtually absent in Morocco with the possible exception of the U/Pb dated Amelal sill sample LV34 and of a Jbilet dyke sample (AN320). The reason for the lack of outcropping Lower-type dykes and sills is unclear and we can only propose tentative interpretations. For example, it may be suggested that during the initial stages the magmatism was focused mainly in the Triassic rift basins, where the extension was strongest. Therefore, Lower basalts are present only in those basins and are thickest in the High Atlas in particular. Later, during more mature extension, Intermediate to Upper basalts were also emplaced outside the Triassic basins.

**Pressure, temperature, H2O content and oxygen fugacity of CAMP magmas**

Clinopyroxene phenocryst compositions can be used to constrain the pressure–temperature conditions of the magmas before eruption or intrusion. However, it should be noted that none of the investigated magmatic rocks corresponds to a primary (or near-primary) magmatic composition, i.e. all the samples are evolved and their calculated temperatures and pressures are most probably lower than those of their parental magmas. Equilibrium temperature and pressure were calculated after Putirka et al. (1996; see also Putirka, 2008; Neave & Putirka, 2017) for augite compositions that are considered in equilibrium with their host rock (Fig. 19). Following criteria outlined, for example, in Putirka et al. (2009), equilibrium augites should have Fe2+/Mg, which ranges between 0.27 and 0.33 that of the whole-rock (assuming that Fe2+ equals to FeTot in augites and is 87% of FeTot in the whole rocks). Moreover, the difference between calculated and observed clinopyroxene components should not exceed 5% relative error. According to these criteria, few augites from the Lower basaltic andesites are in equilibrium with their host rock, while a large number of augites from the other three units could be selected for pressure-temperature calculation. It should also be noted that the calculated pressure and temperature is strongly controlled by the Na concentration measured in the augites (Na2O ranges generally between 0.15 and 0.25 wt % for all analysed augites). Since the analytical uncertainty for electron microprobe analysis of this relatively volatile element is conservatively estimated at ca. 10%, this propagates uncertainties of ±0.1 GPa and ±1.5°C to the calculated pressures and temperatures, respectively.

Calculated pressures (±0.2–0.6 GPa) and temperatures (±1180–1220°C) obtained from augite...
compositions are broadly similar for effusive rocks from the Lower, Intermediate and Upper units. In detail, a subset of the Intermediate flows are characterized by slightly lower calculated pressures for a given temperature, relative to both Lower, Upper and other Intermediate lavas (Fig. 19). The Lower unit has the smallest \( P-T \) range of all units, slightly displaced on average toward both higher equilibrium depths and lower temperatures relative to those of Intermediate and Upper units (Fig. 19). Although Recurrent lavas are equilibrated in a pressure range encompassed by those \((0.2-0.4 \text{ GPa})\) of Lower, Intermediate and Upper samples, they have significantly lower equilibrium temperature \((c.25 \text{ C} \text{ less for a given pressure})\). With regard to intrusive rocks, the \( T \)-ranges calculated for an Intermediate unit sample from the Foum Zguid dyke and for a small Recurrent-unit dyke from the Anti Atlas are shifted toward lower values than those of their eruptive counterparts at similar pressure ranges, which is mostly probably due to the slow cooling of the intrusions. Calculated pressure ranges obtained for augites from intrusive rocks are roughly consistent with estimated thickness of the sedimentary strata \((\text{about 5 km})\) under which these magmas intruded in the Anti Atlas, as well as with the depth range of CAMP sill intrusions in eastern North America \((c.5 \text{ km}, \text{ e.g. Weems et al., 2016})\).

The geobarometric data suggest that crystallization of most augites mainly happened at mid-crustal depths \((7 \to 20 \text{ km})\). This indicates that Moroccan CAMP basalts were mainly erupted from a mid-crustal plumbing system, assuming that the crust was not significantly thinned due to extensional tectonics. At the regional scale, it is important to notice that mid-crustal plumbing depths \((10-20 \text{ km})\) have also been estimated for the Freetown layered complex \((Chalokwu, 2001; Callegaro et al., 2017)\). In addition, since none of the analysed rocks can be considered as primary and since most analysed augites would be in equilibrium with a relatively evolved magma \((\text{Mg}^\#<60)\), it is likely that significant early fractionation may have occurred at depths higher than those yielded by the analysed augites. Such high pressure fractionation may have been located at or close to the Moho, or even within the uppermost mantle, where it is generally considered that primary LIP magmas may differentiate to more evolved compositions by fractionation of mafic minerals \((\text{cf. Cox, 1980; Hole, 2018})\).

Pigeonite crystallization temperatures have also been calculated following Ishii (1975). The calculated values range between \(c.1050 \to 1180 ^\circ \text{C} \text{ for most analysed pigeonite crystals} \). A slightly lower crystallization temperature for pigeonite compared to augite seems consistent with petrographic observations, which indicate that pigeonite is a relatively late crystallizing mineral. Among all pigeonites, those from the Recurrent basalts yield the lowest temperatures \((<1080 ^\circ \text{C})\).

Plagioclase crystallization temperatures calculated after Thy et al. (2013) range between 1100 and 1220 \(^\circ\)C for most analysed crystals. Again, Recurrent basalts yield the lowest values \((<1170 ^\circ \text{C})\), while most Upper basalts yield temperature higher than 1170 \(^\circ\)C. Similar temperatures have been obtained with the plagioclase-melt geothermometer of Putirka (2005).

MELTS modelling (Ghiorso & Sack, 1995) further constrains the liquidus temperature for the Moroccan samples. Representative samples from the four units yield liquidus temperatures of about 1180 to 1220 \(^\circ\)C at 0.1 \text{ GPa}, rising to 1250–1280 \(^\circ\)C at 0.5 \text{ GPa} and 1320–1350 \(^\circ\)C at 0.9 \text{ GPa} for dry conditions (Fig. 19). Slightly hydrous conditions \((1 \text{ wt} \% \text{ H}_2\text{O})\) would decrease the liquidus temperature by about 60 \(^\circ\)C. The liquidus temperatures provided by MELTS at pressures of 0.1 and 0.7 \text{ GPa} are compared to the \( P-T \) estimates for the augites, based on Putirka’s (1996) geothermometer. Assuming that the augites crystallized at temperature slightly lower than the liquidus temperature, dry to weakly hydrous conditions \((\text{e.g. 0–0.5 wt} \% \text{ H}_2\text{O})\) may be suggested for the Lower and Intermediate magmas. On the contrary, a slightly higher depth of crystallization and slightly more hydrous conditions \((\text{approximately} 1 \text{ wt} \% \text{ H}_2\text{O})\) may be suggested for some Upper basalts in order to fit both their liquidus temperature calculated with MELTS and their calculated clinopyroxene crystallization temperatures. The high anorthite component in plagioclase from the Upper basalts may support relatively high water contents in these magmas. The hygrometer of Putirka (2005) indicates the presence of higher \text{H}_2\text{O} \text{ contents in Upper and Recurrent basalts compared to Intermediate basalts and Lower basaltic andesites. However, the water contents estimated using the} Putirka (2005) \text{ hygrometer \((c.2.0 \text{ wt} \% \text{ for Upper and Recurrent basalts; c.1.0–1.5 wt} \% \text{ for Intermediate and Lower samples})\) seem to be too high for the tholeiitic basalt compositions of the studied rocks. Moreover, these calculated water contents appear higher than those obtained with MELTS modelling. Pairs of unexsolved Ti-magnetite and ilmenite microphenocrysts analysed in some Lower, Intermediate and Recurrent flows and one sill from Argana \((\text{geochemically similar to the Intermediate flows})\) yielded equilibrium temperatures ranging from about 1350 to 790 \(^\circ\)C. The calculated oxygen fugacity values range from \(10^{-9}\) to \(10^{-16} \text{bar} \), corresponding to slightly more reduced values than the QFM buffer \((\text{the highest} \text{ T and f} \text{O}_2 \text{ values refer to the Amelal sill from the Argana valley})\). Such relatively low \text{f} \text{O}_2 \text{ values are typical of low-Ti CAMP basalt in general (Marzoli et al., 2018) as well as of other low-Ti LIP basalts \text{e.g. Melluso et al., 1995})}.

**Mineral trace element contents and calculated magmas**

Mineral minor and trace element contents contribute to our interpretation of the genesis of the CAMP magmas in Morocco. The first observation is that augite and plagioclase have minor and trace element contents and trace element ratios that are generally consistent with the distinct whole-rock compositions of the four respective units. For example, Lower unit augites have...
Fig. 20. Large symbols show melt compositions calculated from plagioclase (a, b) and augite (c–f) core compositions, LA-ICP-MS analyses. Blue circles, Lower sample data; red squares, Intermediate; yellow circles, Upper; green squares, Recurrent. Considered partition coefficients are reported in the Supplementary Data Table S9; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org. Moroccan CAMP whole-rock compositions for each of the 4 lava units are shown by fields color-coded as in previous figures. (e, f) Chondrite normalized REE contents of melts calculated from augite compositions of Lower, Intermediate, Upper (e) and Recurrent augites (f). Chondrite values after McDonough & Sun (1995). Thick dashed lines in (e) and (f) represent average compositions for Lower (blue), Intermediate (red), Upper (black) and Recurrent (green) whole-rocks.
the highest La/Yb ratio, while this ratio is lowest in Recurrent basalts augites. Further systematic differences, consistent with whole-rock variations, are shown for example by Ba and Sr contents in plagioclase and by Ti and Zr in augite (see also Bertrand, 1991).

Compositions of equilibrium melts were calculated using the partition coefficients of Bédard (2014) and of Aigner-Torres et al. (2007) for augite and plagioclase, respectively (Fig. 20; Supplementary Data Table S9; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org). Despite uncertainties related to the chosen partition coefficients, a quite good overlap of calculated melt and host whole-rock fields is obtained for REE data (LREE for plagioclase) or Ce/Y ratio, for example. The slightly more depleted calculated magma vs observed whole-rock compositions may be either due to the chosen partition coefficients or to the fact that the crystal cores analysed by LA-ICP-MS may have crystallized from slightly less evolved magmas compared to those represented by the whole-rocks. However, the trace element patterns and incompatible trace element ratios of the calculated melts generally overlap with the whole-rock compositions and display features typical of CAMP basalts. This is true, for example, for low TiO₂ contents and slightly enriched REE patterns (Fig. 20e).

In detail, however, some significant differences between the calculated melts and observed whole-rock compositions must be noted. First, REE patterns of melts calculated from augites of the Lower basaltic andesites and to a lesser extent those from Recurrent basalts and from a few Intermediate samples, exhibit Eu troughs (Fig. 20e and f). This suggests that plagioclase crystallized early in these magmas. Except for the Eu anomalies, REE patterns calculated from Recurrent unit augites are nearly flat (Fig. 20l), with chondrite normalized LREE/HREE ratios close to or below 1-0 (Ce/YbN = 0.7-1.2, mean 0.9), while the associated whole-rocks have slightly enriched LREE (Ce/YbN = 1.2-1.3).

A further notable difference between whole-rocks and melts calculated from augite compositions pertains to the Intermediate unit. Melts calculated from augite compositions from the Intermediate unit overlap with the compositions of Upper basalt whole-rocks, for example for REE contents and ratios (e.g. Ce/Yb and Ce contents) and for TiO₂ (Fig. 20). Sr and Zr contents (these latter elements are not shown in Fig. 20). In contrast, melts calculated from plagioclase from the same Intermediate rocks have enriched LREE and Sr compared to melts calculated from augites and overlap with Intermediate whole-rock compositions. This may suggest that the analysed augites of the Intermediate unit are in fact antecrysts or xenocrysts crystallized from magmas similar to the Upper basalt, pointing to an open-system evolution. On the contrary, the plagioclase crystallized as phenocrysts from the Intermediate unit-type melt.

**Fractional crystallization at crustal depths**

Whole-rock major and trace element variations within each group of lava flows, i.e. Lower, Intermediate, Upper and Recurrent basalts are relatively limited, hindering recognition of clear magma evolution trends. Recurrent basalts are slightly more evolved than Lower to Upper basalts, i.e. they have relatively low MgO contents. This is also confirmed by the negative anomalies of Sr and Ti, which argue for a significant plagioclase and oxide fractionation in the Recurrent basalts. Consistently, Recurrent basalts also yield lower crystallization temperatures based on augite, pigeonite and plagioclase geothermometers. Intrusive rocks display a slightly larger major element compositional range than the lava flows, but this may be related to mineral accumulation rather than to fractional crystallization.

Figure 11 shows liquid lines of descent calculated using MELTS (Ghiorso & Sack, 1995) from the same parental melt (Lower magma AN133) at distinct pressure conditions (0.1 and 0.9 GPa). Moreover, we also plotted the liquid line of descent at 1 GPa of a calculated primary liquid with a MgO content of about 15 wt %. The composition of this primary melt is calculated with the pMELTS software (Ghiorso et al., 2002) for 8% partial melting of KLB1 peridotite (e.g. Hirose & Kushiro, 1993; Baker & Stolper, 1994) at 1.5 GPa. Redox conditions for the fractional crystallization models are set at the QFM buffer and initial water contents are 0.5 wt %. For AN133 and 0.4 wt % for the calculated primary melt. Notably, water contents influence the temperature of saturation for plagioclase, while F₂O influences the crystallization temperature of Fe-Ti-oxides. However, by varying these parameters in a reasonable manner, i.e. consistent with the mineral compositions, MELTS liquid lines of descent still do not reproduce the entire range of the Moroccan CAMP basalts and basaltic andesites, starting from a single parental magma (Fig. 11). In particular, the differences in SiO₂, TiO₂, CaO, Al₂O₃, P₂O₅ among the four units cannot be attributed to closed-system fractional crystallization processes, but require distinct parental magmas or open-system conditions, e.g. distinct crustal assimilation processes. Likewise, the systematic differences in incompatible element contents and ratios (e.g. La/Yb, Zr/Y; Fig. 12) among the four lava flow units cannot only be attributed to low-pressure, closed system differentiation including crystallization of the observed mineral phases (clinopyroxene, plagioclase, olivine, Fe-Ti oxides). Notably, the distinct Sr, Nd and Pb isotope compositions of the four units formally exclude the possibility that they differentiated from the same parental magma under closed-system conditions.

Mass balance calculations have been performed to further constrain the fractionating mineral assemblage. The transition from a relatively little evolved (AN37) to a more evolved Lower basaltic andesite (AN86) would be consistent (sum of square residuals, ∑R² = 0.19) with
21 wt % fractionation of clinopyroxene (10 wt %), plagioclase (5 wt %), olivine (4 wt %) and magnetite (2 wt %). Likewise, an evolved Upper basalt (AN213) could be derived from a little evolved Upper basalt (AN725) by 45 wt % fractionation of clinopyroxene (31 wt %), plagioclase (10 wt %), olivine (2 wt %) and magnetite (2 wt %; $\sum R^2 = 0.19$).

**Open system differentiation**

Interaction with the continental crust in the magmatic plumbing system is nearly inevitable in high magma flux systems and may significantly modify the compositions of evolving magmas, notably their isotopic ratios (e.g. Kerr et al., 1995; Tegner et al., 2005). Mineral and whole-rock data suggest differentiation of Moroccan CAMP magmas in mid to upper crustal magma chambers, as well as probably in deeper magma chambers where the primary mantle-derived magmas initially evolved. To develop a full understanding of the possible effects of assimilation of the local crust, we would need a complete geochemical data set representative of upper and lower crustal rocks. However, Pb and Os isotopic data are missing and Sr–Nd isotopic analyses are quite rare for the local lower crustal rocks. The local basement was principally formed during three orogenic cycles, the Eburnean (c. 2–1 Ga), Pan-African (c. 0.6 Ga) and Hercynian events (c. 0.3 Ga). Pan-African granitic rocks from the Anti Atlas in southern Morocco (e.g. Toummite et al., 2013) yield Sr and Nd isotopic ratios (calculated for 201 Ma) in the range 0.706–0.712 and 0.5122–0.5124, respectively, probably in the same range as most Hercynian rocks from the Meseta in central-northern Morocco (e.g. Chalot Prat, 1995). Eburnean felsic rocks cropping out in the Anti Atlas are both more evolved and older, yielding more extreme isotopic compositions ($^{87}\text{Sr}/^{86}\text{Sr}_{201}\text{Ma} > 0.740$; $^{143}\text{Nd}/^{144}\text{Nd}_{201}\text{Ma}$ generally in the range 0.511–0.512; Ennih & Liégeois, 2008). Pb isotopic data for the local upper crust are not available, however Saharan dust has been analysed for Pb isotopes (Grousset & Biscaye (2005) and references therein) and such data will be used here as proxies for the upper crust (Table 5). Sr–Nd isotopic ratios of Middle Atlas granulitic xenoliths, entrained in Cenozoic–Quaternary alkali basalts, range from 0.705 to 0.718 and from 0.5121 to 0.5117, respectively (Moukadiri, 1999). These are the only available proxies for the composition of the lower crust. Since no Pb isotope data are available for these granulites and since world-wide granulites cover a very wide spectrum in Pb isotopic space (Meyzen et al., 2005), we considered for the Moroccan granulites end-member compositions with either very low or very high Pb isotopic ratios ($^{206}\text{Pb}/^{204}\text{Pb} = 17$ or 19, respectively). Finally, Os isotopic values have been calculated considering estimated average upper and lower crustal values (Saal et al., 1998; Peucker-Ehrenbrink & Jahn, 2001) and the distinct ages of the considered crustal contaminants. The considered crustal compositions are reported in Table 5.

EC-AFC modelling (Spera & Bohrson, 2001) starting from a composition similar to an Upper basalt, shows that crustal assimilation explains part but not all of the geochemical variations observed in the Moroccan CAMP basalts (Figs 12 and 16). In particular, variations within each unit, for example the Nd isotopic compositions of Lower and Intermediate basaltic andesites can be reproduced by quite small amounts of assimilation of upper crustal rocks (for example c.5–8% assimilation of the Eburnean granite). For such low degrees of assimilation of Eburnean granitic rocks, the shift of Sr, Nd and Pb isotopic ratios is moderate ($^{87}\text{Sr}/^{86}\text{Sr}$ from 0.7055 to 0.7065; $^{206}\text{Pb}/^{204}\text{Pb}$ from 18.20 to 18.51, $^{143}\text{Nd}/^{144}\text{Nd}$ from 0.5124 to 0.5122, respectively), consistent with the observed data. On the contrary, the Os isotopic ratio changes substantially (e.g. $^{187}\text{Os}/^{188}\text{Os}$ would change by about 0.03), though this range is speculative given that the Os composition of both the contaminant and the starting magma, as well as the Os partition coefficients, are poorly constrained. If the parental magma is assumed to have a $^{187}\text{Os}/^{188}\text{Os}$ ratio of 0.125, a highly plausible composition for a mantle-derived magma at 200 Ma, coupled with a $^{142}\text{Nd}/^{144}\text{Nd}$ ratio of 0.5124, calculated Os vs Nd isotopic variations due to assimilation of Eburnean granite are comparable to the observed variations displayed by the analysed Lower unit samples. Similar curves could be compatible with variations of most Upper and Intermediate samples, but only if a magma with very low $^{187}\text{Os}/^{188}\text{Os}$ (~0.110) is used as the starting composition (Fig. 17c), which seems extremely unlikely.

Assimilation of Pan-African granulites would also be compatible with the observed Sr–Nd–Pb isotopic variations, but would require higher assimilation degrees (>15%). Assimilation of granulitic rocks with low $^{206}\text{Pb}/^{204}\text{Pb}$ (e.g. 17.5) does not reproduce the observed Pb isotopic variations, while assimilation of about 10% high $^{206}\text{Pb}/^{204}\text{Pb}$ (19.0) granulite could be consistent with the observed Sr–Nd–Pb isotopic data. In Nd–Os isotopic space, the calculated EC-AFC trends for granulite assimilation are not consistent with the observed data for variations within the Lower basaltic andesite group, but could explain the relatively high $^{187}\text{Os}/^{188}\text{Os}$ of one Intermediate and one Upper sample (Fig. 17c). It could perhaps also explain the relatively higher $^{187}\text{Os}/^{188}\text{Os}$ of Lower vs two of the three Upper basalts. Nevertheless, caution should be used when interpreting the initial $^{187}\text{Os}/^{188}\text{Os}$ values of samples with highly radiogenic measured Os compositions as these require large age corrections. Such large corrections could be influenced by small perturbations in the measured $^{187}\text{Re}/^{188}\text{Os}$ ratios caused by minor geological alteration or non-recognized analytical factors. It is perhaps significant that the initial $^{187}\text{Os}/^{188}\text{Os}$ ratios of all samples with $^{187}\text{Re}/^{188}\text{Os} < 20$ are restricted to a fairly narrow range (0.1239 to 0.1307).
Table 5: Geochemical parameters used in EC-AFC modelling. La, Sm, Yb, Nb, Sr, Pb contents are given in ppm, Os in ppt.

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>La</th>
<th>Sm</th>
<th>Yb</th>
<th>Nb</th>
<th>Sr</th>
<th>Os</th>
</tr>
</thead>
<tbody>
<tr>
<td>P. African granite</td>
<td>35</td>
<td>8</td>
<td>195</td>
<td>171</td>
<td>5115</td>
<td>5</td>
</tr>
<tr>
<td>Eburnean granite</td>
<td>25</td>
<td>740</td>
<td>5</td>
<td>19</td>
<td>5117</td>
<td>5</td>
</tr>
<tr>
<td>Granulite</td>
<td>250</td>
<td>717</td>
<td>10</td>
<td>0</td>
<td>5116</td>
<td>5</td>
</tr>
<tr>
<td>Initial Magma</td>
<td>6</td>
<td>183</td>
<td>510</td>
<td>200</td>
<td>5120</td>
<td>5</td>
</tr>
</tbody>
</table>


Nd–Os isotopic modelling (Fig. 17), where the initial magma is similar to the Lower basalts (shown in italics in the Table). Magma partition coefficients in brackets (last line) have been calculated after Aigner-Torres (2007) and Bedard (2014). For Os the same partition coefficients as those in previous studies on the CAMP (Callegaro et al., 2013; Merle et al., 2014).

Variations of trace element contents and ratios are also partly reproduced by crustal assimilation models. This applies for example to La/Nb and La/Yb variations as shown in Fig. 12g and h where it appears that part of the variability within the Lower unit and the variation from Upper to Intermediate samples can be attained by c.5–15% assimilation of Eburnean or Pan-African granite or c.10% assimilation of granulite. Consistently, contamination of Upper basalts could lead to the slightly more evolved compositions (e.g. higher $^{87}$Sr/$^{86}$Sr and $^{206}$Pb/$^{204}$Pb and lower $^{143}$Nd/$^{144}$Nd) of the Intermediate basaltic andesites.

A common origin for the Upper and Intermediate magmas is also suggested by the similar trace element contents of equilibrium melt compositions calculated from clinopyroxenes from the two units, as opposed to the distinct compositions calculated from plagioclase crystals (Fig. 20). These mineral trace element data may constrain the timing of the crustal assimilation process, which possibly happened after crystallization of clinopyroxene cores analysed by LA-ICP-MS and before crystallization of plagioclase crystals in the Intermediate magmas.

In further detail and considering the La/Nb variations (Fig. 12g), we suggest that distinct crustal contaminants may explain the slight difference between Central High Atlas (red circles, CHA samples) and Middle Atlas (red triangles, MM samples) Intermediate lavas. The latter yield in general higher La/Nb than the Central High Atlas samples and such a difference may suggest that the Middle Atlas Intermediate magmas were contaminated by a crustal rock with fairly high La/Nb, e.g. a rock similar to Eburnean granite (Ennih & Liégeois, 2008). On the contrary, the relatively low La/Nb of Central High Atlas Intermediate samples is indicative of contamination by a crustal rock with low La/Nb, like average lower crustal rocks (Rudnick & Gao, 2003) or Pan-African granite (Toummite et al., 2013).

The $\Delta$Nb parameter (expressed as $1.74 + \log(\text{Nb} / \text{Y}) - 1.92 + \log(\text{Zr} / \text{Y})$; Fitton et al., 1997) was originally proposed to distinguish between plume-related Icelandic and mid-ocean ridge basalts. In the case of continental LIPs, positive $\Delta$Nb values are typical of Nb undepleted mantle-derived basalts and have been related to mantle-plume activity, while negative $\Delta$Nb indicates either a Nb-depleted mantle source (e.g. DMM) or extensive crustal contamination. In Morocco, most Intermediate basaltic andesites yield negative $\Delta$Nb values, combined with relatively high La/Nb (Fig. 12i and j), the latter being a tracer for lithospheric input. On the contrary, most Lower and Upper basalts yield $\Delta$Nb values close to zero (Fig. 12i) combined with relatively low La/Nb, like those of basalts and picrites from the southern Karoo, which are considered as uncontaminated by the continental crust (e.g. Heinonen et al., 2010, 2016; Ware et al., 2018; Buttinen, 2018).

Recurrent basalts plot off any possible assimilation trend starting from a parental magma with Lower to Upper trace element and isotopic composition. Internal
variability within the Recurrent unit is negligible, in general, hampering any assimilation modelling. Nonetheless, some level of crustal contamination is still plausible for Recurrent basalt, as suggested in particular by the high $^{187}\text{Os}/^{188}\text{Os}$ of sample AN24, well above that of typical mantle-derived basalts. This sample yields a low Os (34 ppt) and strikingly high Re concentration (5502 ppt) and thus a quite large uncertainty on the Re/Os ratio, resulting in a very large uncertainty after error propagation on the calculated initial Os isotopic composition ($0.453 \pm 0.077$). Nevertheless, even taking the uncertainties into account, the initial Os isotopic composition of this sample is much more radiogenic than expected for any mantle-derived melt. Such a high Os isotopic ratio would suggest the assimilation of at least 22% of a granitic rock with $^{187}\text{Os}/^{188}\text{Os} = 1.2$ and about 300 ppt Os content (an improbably high Os concentration for a granite), starting from a parental magma with $^{187}\text{Os}/^{188}\text{Os}$ of 0.130 and 300 ppt [Os]. Alternatively, and probably more realistically, the extremely high Re content of this sample may indicate assimilation of a sulfide phase, such as molybdenite, which would also be consistent with the high initial ratio. The other analysed Recurrent basalt, AN44, has a much lower $^{187}\text{Os}/^{188}\text{Os}$ ($0.136 \pm 0.017$), but due to its large uncertainty it is not possible to confirm or exclude a crustal contribution. The maximum $^{187}\text{Os}/^{188}\text{Os}$ of c.0.153 of this sample would require fairly low amounts of assimilation, i.e., about 8% assimilation of a highly-evolved granite ($^{187}\text{Os}/^{188}\text{Os} = 1.2$) or 6% of a granulite (with $^{187}\text{Os}/^{188}\text{Os} = 0.3$), starting from an initial magma with $^{187}\text{Os}/^{188}\text{Os} = 0.124$. The apparent discrepancy in assimilation rate between the two Recurrent basalt samples are not compatible with otherwise nearly indistinguishable major and trace element and Sr–Nd–Pb isotopic compositions. The most likely explanation is that radiogenic, Re-rich sulfide was added to AN24, either through assimilation or during a post-magmatic alteration event. Therefore, the sample with lower $^{187}\text{Os}/^{188}\text{Os}$, thus probably better constrains the upper limit of silicate rock assimilation of the Recurrent magmas.

Finally, we also attempted modelling the EC-AFC paths starting from a hypothetical primitive magma with fairly depleted, MORB-like characteristics (Fig. 16). The modelled magmas would reproduce the observed Sr–Nd–Pb isotopic compositions of the Moroccan CAMP basalts and basaltic andesites only through massive assimilation (>20%) of crustal rocks similar to the Pan-African granites (assimilation of Eburnean granites does not fit the data). However, such large amounts of assimilated granite combined with high amounts of fractional crystallization (the fractionated/assimilated mass would be in the range 0.6–0.9) would substantially modify the major and trace element compositions of the magmas, probably leading to the formation of quite high SiO$_2$ and MgO-poor magmas, unlike those observed. Moreover, the Os isotope compositions of heavily contaminated magmas are quite unlikely to be as low as those observed for our samples, even considering the large uncertainties related to the Re–Os systematics of the samples and of the crustal assimilates. Considering the same Os isotopic composition for the granitic assimilate as reported in Table 5, the $^{187}\text{Os}/^{188}\text{Os}$ of 15–20% contaminated magmas would shift from 0.13 to over 0.20, i.e. to compositions significantly higher than the measured (not age-corrected) $^{187}\text{Os}/^{188}\text{Os}$ of most Moroccan CAMP basalts.

To sum up, we suggest that low amounts of crustal assimilation (less than 10%) can explain the isotopic and trace element variations within single units. Even considering the uncertainties on the initial Os isotopic composition related to the high Re/Os of the analysed basalts and considering the lack of Re–Os data for the local crust, Os systematics rule out crustal assimilation significantly higher than 10% for most of the samples. This is consistent with detailed modelling of crustal assimilation for LIP basalts from other provinces (e.g. Karoo, Paraná; Heinonen et al., 2010, 2016; De Min et al., 2018). Such relatively low degrees of assimilation cannot account for most inter-unit chemical variations and exclude derivation of the Moroccan CAMP basalts from a single mantle source similar to those of Central Atlantic MORB. Nevertheless, EC-AFC modelling suggests that Intermediate magmas may be formed from contaminated parental Upper-like basalts.

**Mantle source, major and trace element constraints**

The data discussed so far indicate that subtle, but systematic differences exist among the four lava flow units and associated intrusive CAMP rocks from Morocco. As discussed before, these differences are in part explained by distinct amounts of fractional crystallization and crustal assimilation. In particular, crustal assimilation may partly explain the difference between the Upper and Intermediate rocks, the latter being more enriched and more contaminated, but nevertheless probably derived from a parental magma similar to that of the Upper basalts. On the contrary, the Lower and Recurrent basalts both have geochemical characteristics that are not compatible with their derivation from a parental magma equivalent to that of any other unit. Therefore, at least three distinct parental magma types (Lower, Upper, Recurrent) derived from somewhat distinct magma sources are required to explain the overall range of geochemical compositions.

None of the Moroccan CAMP samples can be considered as a primary mantle melt. Direct comparison with experimentally formed melts of possible mantle ultramafic or mafic source rocks is, therefore, not straightforward. In Fig. 11, we reported a liquid line of descent from a primary magma obtained from the peridotite KLB1 (Hirose & Kushiro, 1993; Baker & Stolper, 1994) at c.8% partial melting (primary melt composition calculated with pMELTS; Ghiorsso et al., 2002). This liquid line of descent reproduces the composition of the Upper
Basalts quite well. The relatively high Ca contents of the Upper basalts may reflect large melting degrees as suggested by experimental data for batch melting of spinel lherzolite (e.g. Hirose & Kushiro, 1993), which show that the highest Ca contents in peridotite melts are attained just before clinopyroxene exhaustion. By analogy, the high Al of the Upper basalts suggests that their melting occurred at temperatures lower than the complete melting (liquidus temperature) of the aluminiferous phase.

Lower basaltic andesites are relatively enriched in Si and depleted in Ca and Al compared to Upper basalts. These differences may reflect melting at lower degrees and a shallower depth of melting. However, a shallower melting depth for Lower vs Upper basalts is apparently not consistent with incompatible trace element modeling, which suggests a more significant garnet- vs spinel-peridotite signature for the Lower magmas (see below; Fig. 21). Alternatively, the Lower magmas may originate from hydrous peridotite, yielding melts richer in Si compared to anhydrous ones (e.g. Kushiro, 1996).

We calculated the REE and Nb contents of mantle melts generated by non-modal batch melting of spinel and garnet peridotites with a primitive-mantle or slightly enriched REE abundances, the latter being consistent with the enriched Sr–Nd isotopic compositions of the Moroccan CAMP (Fig. 21). The enriched peridotite composition is calculated by adding 2% of upper crust (average continental crust composition after Rudnick & Gao, 2003). Notably, the effects of closed-system fractional crystallization are quite small for the La/Sm and Sm/Yb ratios and in particular for La/Nb (fractional crystallization trends are shown by a solid black arrow in Fig. 21a). Therefore, measured values can be compared to calculated mantle melt compositions even if the samples are not primary (with the caveat that ‘real’ melting degrees are probably slightly higher than those apparent from direct comparison of calculated and measured trace element ratios in Fig. 21). However, crustal assimilation may induce a shift towards slightly higher La/Sm, and significantly higher Sm/Yb and La/Nb (dashed black curves in Fig. 21) are EC-AFC trends starting from an Upper basalt) as previously discussed (Fig. 12).

Taking into account open- or closed-system fractional crystallization, the trace element ratios of the basalts and basaltic andesites can be reproduced by various possible mantle melting models (see caption of Fig. 21 for details on the parameters used; the parameters are also reported in Supplementary Data Table S10; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org). This modelling assumes a simple melting event occurring either in the presence of garnet or of spinel. We are aware that melting may occur over a relatively large depth range in a melting column, possibly starting within the garnet stability field and then achieving shallower depths where spinel is stable. The REE modelling we performed here is mainly intended to test if the CAMP magmas issued dominantly from the garnet or from the spinel stability depth. The relatively high LREE/HREE ratios of Lower to Upper basalts require the presence of residual garnet in their mantle source. Lower basaltic andesites would be consistent with about 3–4% melting of a garnet
peridotite with a primitive-mantle composition, or with 5–6% melting of a more fertile (enriched) garnet peridotite.

The Upper basalts yield generally lower La/Sm and Sm/Yb, pointing to a reduced garnet and more significant spinel signature. The Upper basalts could correspond to 8–9% melting of an enriched garnet peridotite or to c.7–8% melting of a primitive mantle peridotite. However, at such high melting degrees garnet would be entirely exhausted in the mantle source, not accounting for the high Al contents of the Upper basalts. This could suggest a significant contribution of a spinel peridotite source and the gap between observed and calculated compositions could be explained at least in part by fractional crystallization process (black arrow in Fig. 21a). This would suggest a shallower average melting region for the Upper basalts, possibly straddling the garnet-spinel transition. A progressively rising melting region would be consistent with CAMP magmatism occurring in an extensional tectonic regime leading to the observed progressive subsidence of the basins and probably to progressive thinning of the continental lithosphere (Labails et al., 2010).

Recurrent basalts would require about 10% melting of a spinel peridotite source with primitive or even slightly depleted (not shown in the figure) REE abundances. We favour this latter hypothesis as it would be consistent with the slightly depleted Sr–Nd isotopic composition of the Recurrent basalts compared to the older magmas. We note also that melts calculated from augite compositions for the Recurrent basalts show REE patterns that resemble those of enriched MORB, highlighting the peculiar geochemical features of the Recurrent basalts within the CAMP.

Modelling of mantle melting also shows that the relatively low Nb and high La/Nb of the Moroccan CAMP basalts require a mantle source slightly enriched compared to the primitive mantle. As noted above, the enriched peridotite source shown in Fig. 21 was obtained by adding 2% upper continental crust (Rudnick & Gao, 2003) to a primitive mantle composition. Melts from such enriched peridotite fit the observed La/Nb compositions quite well. This suggests that the HFSE depletion characteristic of CAMP basalts (and of many LIP basalts, in general) can at least in part be explained by mantle source enrichment, i.e. by the presence of recycled crustal components within the mantle. Interestingly, the Moroccan CAMP basalts show ΔNb values close to zero (0.1 to 0.07; Fig. 12). Such values overlap those of MORB and of some virtually uncontaminated, primitive LIP basalts. In particular, picrites from the southern Karoo are interpreted as being derived from a subduction-influenced upper mantle (Luttinen, 2018) and plot quite close to the Moroccan basalts in terms of HFSE ratios (Fig. 12i and j). On the contrary, Atlantic OIB show significantly higher ΔNb compared to the Moroccan CAMP basalts, arguing against a common origin.

Mantle source, isotopic constraints
Moroccan CAMP samples have Sr-Nd-Pb isotopic compositions falling generally within the field of low-Ti basalts from throughout the huge aerial extent of the CAMP. The main characteristics of the CAMP rocks are relatively high 87Sr/86Sr and low 143Nd/144Nd values, combined with high 207Pb/204Pb and 208Pb/204Pb at only moderately high 206Pb/204Pb (i.e. they have high Δ7/4 and Δ8/4 as defined by Hart, 1984). These isotopic characteristics of the CAMP low-Ti basalts point to a common, enriched source which is different from those of central Atlantic MORB (local asthenosphere; e.g. Janney & Castillo, 2001) and from neighbouring OIB (e.g. Cabo Verde, Canary Islands; e.g. Holm et al., 2006; Klügel et al., 2017). Indeed, these oceanic basalts have compositions plotting along the NHRL (Northern Hemisphere Reference Line), whereas this is not the case for CAMP. Although, as previously discussed, some crustal assimilation en-route to the surface plausibly contributed to these enriched compositions, this process offers only a partial explanation. As shown for example in Fig. 16, EC-AFC trends starting from parental MORB compositions do indeed intersect the Sr–Nd–Pb isotopic values of the Moroccan CAMP basalts, but only for large degrees of assimilation (>20% assimilation, e.g. Pan African granite). However, such high degrees of assimilation are not compatible with the unradiogenic Os isotopic compositions, with the relatively low incompatible trace element concentrations and with the basic composition of the CAMP samples. Therefore, the mantle source of CAMP magmas must have had an enriched signature. The origin of this enriched component has been largely discussed in previous publications dealing with the North American and European regions of the CAMP (Puffer, 2001; Callegaro et al., 2013, 2014a; Merle et al., 2014; Whalen et al., 2015; Shellnutt et al., 2018) and the interpretation proposed therein probably applies to the Moroccan CAMP as well. Accordingly, involvement of lower and upper continental crustal materials subducted during the late Proterozoic or early Paleozoic (see Merle et al., 2014) and stored below the Pangea mega-continent is modelled in Fig. 22. Unlike previous studies, we tried here to explore the possibility that the dominant mantle component is not represented by the DMM, but rather by a prevalent-mantle (PREMA-type mantle) similar to that defined in Jackson & Carlson (2011). This mantle source could be represented by the following isotopic compositions: 87Sr/86Sr = 0.7030, 143Nd/144Nd = 0.5127, 206Pb/204Pb = 18.0 at 201 Ma (Zindler & Hart, 1986). As modelled in previous studies, only about 5% of recycled crustal materials with compositions similar to circum-Atlantic Late Proterozoic to Paleozoic crustal rocks are required to attain the enriched isotopic compositions of low-Ti CAMP basalts starting from the DMM (e.g. Callegaro et al., 2013, 2014; Merle et al., 2014). By contrast, because of its higher incompatible element abundances, the PREMA end-
member would require about 10% of such recycled crustal components to fit the observed composition of the Moroccan CAMP basalts. As shown for other LIPs (Jackson & Carlson, 2011), the PREMA end-member could represent 90% of the mantle source of the CAMP basalts (Fig. 22).

Isotopic compositions of Lower to Upper basalts are instead clearly different from any known OIB from the Central Atlantic (e.g. Cape Verde, Canary Islands; e.g. Holm et al., 2006; Klügel et al., 2017). Thus, any possible contribution from an Atlantic-type mantle-plume component is not supported by the very different and enriched geochemical composition of CAMP magmas. This is also consistent with trace element contents and ratios (e.g. Fig. 12i). Only the Recurrent basalts have relatively high $^{143}$Nd/$^{144}$Nd (positive $e_{Nd}$), relatively low $^{87}$Sr/$^{86}$Sr and radiogenic Pb isotopes trending towards the composition of Atlantic OIB or of Moroccan alkaline and peridotitic rocks. In Fig. 22, we show a mixing curve between the possible mantle source of Moroccan Upper basalts (i.e. 93% PREMA plus 7% recycled crustal components) and a mantle similar to the source of Atlantic OIB, i.e. close to the C or FOZO component (Hanan & Graham, 1996). In this model, Recurrent basalts could issue from a source plotting along this mixing curve at about 20–30% of the Atlantic OIB (or C) component, while the remaining 70–80% would correspond to a mixture of PREMA (or DMM) plus recycled crustal rocks. However, it should be noted that Recurrent basalts are fairly evolved (MgO $\sim$4 wt %) and possibly contaminated by the continental crust. This makes recognition of any mantle component quite problematic.

One peculiar characteristic of the Moroccan Lower to Upper magmas is their generally low Os isotopic composition (Fig. 17). In particular, some Upper and Intermediate samples yield among the lowest $^{187}$Os/$^{188}$Os$_{201Ma}$ of all CAMP rocks so far analysed and plot at lower values than the Primitive Upper Mantle (PUM; Meisel et al., 2001), i.e. at lower values than most oceanic basalts or sub-lithospheric mantle components. As emphasized above, caution must be used when

---

**Fig. 22.** Isotopic compositions of Moroccan CAMP basalts and basaltic andesites (same symbols as Fig. 16) compared to calculated compositions resulting from mixing of the PREMA (Prevalent Mantle; Zindler & Hart, 1986; Jackson & Carlson, 2011) with recycled upper and lower continental crust (UC and LC; Callegaro et al., 2013). Red lines show 90% (dotted), 80% (dashed) and 0% (continuous) PREMA in the mixture; black lines show the UC/LC ratio (0, 20, 40, 60, 80, 100%) among crustal components. The green line is a mixing curve between the mantle source of the Upper basalts and an OIB mantle source similar to that of Atlantic OIB (e.g. Cape Verde, Canary Islands; Holm et al., 2006; Klügel et al., 2017). Tick marks (crosses) show 10% increments in the mixture. Compositions of the considered mantle components are reported in Supplementary Data Table S10; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org.
interpreting these unradiogenic initial isotopic ratios because they are found only in samples for which a large correction for radiogenic ingrowth was necessary and other samples with similar corrections show surprisingly high initial \(^{187}\text{Os}/^{188}\text{Os}\). Nevertheless, if taken at face value, the low \(^{187}\text{Os}/^{188}\text{Os}_{201\text{Ma}}\) of several of the Moroccan CAMP basalts are comparable to those of Middle Atlas mantle xenoliths \((^{187}\text{Os}/^{188}\text{Os}_{201\text{Ma}} = 0.116-0.126; \text{Wittig et al., 2010a})\), of the nearby peridotite massifs of Beni Bousera and Ronda \((c.0.11-0.125; \text{Reisberg et al., 1991, Reisberg & Lorand, 1995; Pearson & Nowell, 2004})\) and in general, of worldwide cratonic \(^{187}\text{Os}/^{188}\text{Os}\) about 0.105–0.125 and off-cratonic Subcontinental Lithospheric Mantle (SCLM) \((0.115–0.135; \text{Carlson, 2005})\). This might support a contribution from the local SCLM to the source of the Moroccan CAMP basalts. However, Moroccan mantle xenoliths as well as alkaline and ultra-alkaline rocks that possibly issued from this SCLM \((\text{e.g. carbonatites and lamproites; Wagner et al., 2003; Bouabdellah et al., 2010; Wittig et al., 2010b; Bosch et al., 2014})\) have Sr–Nd–Pb isotopic compositions distinct from CAMP and similar instead to compositions of OIB from the Cape Verde or the Canary Islands \((\text{Holm et al., 2006; Klügel et al., 2017})\). An apparent decoupling between lithophile element isotopes, yielding a signature distinct from the Moroccan lithospheric mantle xenoliths and Os isotopes, showing a significant SCLM signature is thus observed. This may be explained by the fact that, relative to abundances in typical mafic magmas, Os concentrations are high in the SCLM, while Sr, Nd and Pb concentrations are low, favouring perturbation of the Os isotope compositions of the magmas relative to those of the lithophile elements during passage of the asthenosphere-derived melts through the lithosphere. Alternatively, a selective assimilation process \((\text{Heinonen et al., 2016})\) could be proposed. In this scenario, melts percolating through the relatively refractory and depleted SCLM are contaminated by Os-rich and low \(^{187}\text{Os}/^{188}\text{Os}\) material, possibly sulfides stored within the cratonic SCLM \((\text{cf. Guex et al., 2016})\). According to Guex et al. (2016) sulfides or sulphur-rich veins may remain stable at the base of the lithosphere during continental thinning, assuming that heat transfer from the asthenospheric mantle is low and the temperature within the SCLM does not exceed the sulfide solidus \((>1200\degree \text{C at pressure} >2 \text{GPa for monosulfide solid solution; Bockrath et al., 2004})\). Only enhanced thermal erosion and thinning of the SCLM may lead to melting and assimilation of the sulfides by the relatively hot, tholeiitic CAMP melts on their way to the surface. The contamination by old sulfides with low \(^{187}\text{Os}/^{188}\text{Os}\) seems to increase from Lower to Upper basalts, possibly as a consequence of progressively increased heating, erosion and thinning of the SCLM, as the mantle upwelling rises. Moreover, it should be considered that the most refractory and isotopically depleted sulfides in the SCLM may be those entrained within silicate minerals, while interstitial sulfides may have less depleted Os isotopic signatures and can melt more readily \((\text{Harvey et al., 2011})\).

**A MODEL FOR THE GENESIS OF THE MOROCCAN CAMP**

The main phase of CAMP magmatism occurred between 201.6 and 201.3 Ma. High volumes of Lower and Intermediate basaltic andesites erupted close to 201.5 Ma, while only minor volumes of Recurrent basalts erupted slightly later and were restricted to the Central High Atlas basins. CAMP basaltic or basaltic andesitic magmas of the main phase were emplaced throughout Morocco in a series of 4–5 main pulses. Such pulses were probably of short duration, with eruption rates exceeding that of any present-day volcanic district and in line with the eruption rates \((10–100 \text{km}^3/\text{yr})\) calculated from other continental flood basalt piles related to LIP activity. The pulsed eruption mechanism and high eruption rates reinforce the possibility that CAMP magmatism triggered end-Triassic climate change and mass extinction. The pulsed mechanism requires a rapid tapping of the magmatic plumbing system, which is likely to be associated with volatile fluxing from the magmatic plumbing system \((\text{Caricchi et al., 2018})\) and may have caused widespread and intense seismicity. Notably, end-Triassic sedimentary strata with the abundant presence of seismites have been recently discovered in northern Europe and linked to CAMP volcanism and tectonism \((\text{Lindström et al., 2015})\).

The magmatic activity was syn-extensional, with lava flows emplaced in progressively subsiding grabens \((\text{Fig. 23})\). Sills and feeder dykes crop out mainly in the Paleozoic basin of the Anti Atlas and yield geochemical compositions comparable to Intermediate, Upper and Recurrent flows, while only one sill and one dyke sample from central-western Morocco yielded compositions similar to Lower flows.

Volcanic sequences from throughout the country show similar time-related evolution, with generally abrupt compositional shifts among the four magmatic units \((\text{Lower to Recurrent})\). Some of the magmas were contaminated by the continental crust in shallow-level AFC processes, as suggested by the isotopic systematics and by augite trace element contents. According to this interpretation, Intermediate magmas were derived from parental melts similar to Upper basalts, but experienced more contamination, while Lower basaltic andesites evolved from a distinct, more enriched parental magma without significant amounts of crustal contamination. The highest rates of assimilation during the middle and main phase of volcanism \((\text{Intermediate unit for which distinct crustal contaminants are required in the Central High Atlas and in the Middle Atlas, respectively})\) may be related to a progressive heating of the crust intruded by the rising magmas. The lack of significant contamination for the Upper basalts may be due to a reduced magma flux, to a reduced fertility of
The crustal rocks, or to armouring of the conduit systems.

The presence of at least three parental magma types is required, i.e. Lower, Upper and Recurrent. The melting mantle source of the Moroccan CAMP becomes progressively shallower from Lower to Recurrent basalts (Fig. 23). While a significant contribution from a garnet peridotite source is required to account for the geochemical features of the Lower magmas, Upper magmas likely issued from a mantle zone straddling the garnet-spinel transition and Recurrent basalts may result from melting of a prevailing spinel peridotite source. Such evolution is consistent with formation of the CAMP during progressive extension and consequent lithospheric thinning.

The four magmatic units share a common enriched isotopic and trace element signature similar to that of most other low-Ti CAMP basalts from throughout the province. This enriched signature might result from mixing between a dominant DMM- or PREMA-type mantle with subducted and recycled continental material, in accordance with many previous studies on the CAMP (see Callegaro et al., 2013, 2014a; Merle et al., 2014; Whalen et al., 2015; Shellnutt et al., 2018, for the most recent studies). However, each of the four Moroccan units also displays peculiar features. Lower unit magmas are slightly enriched compared to the Upper basalts in terms of their trace element contents and ratios as well as in Sr–Nd–Pb isotopic compositions. An enriched source is proposed for this magmatic unit. Notably, among all the CAMP relics, other rocks with geochemical compositions similar to those of the Moroccan Lower basaltic andesites (rocks forming the Tiourjdal group; Marzoli et al., 2018) are only known from a relatively restricted area in northwestern Africa at the northern margin of the West African craton (Morocco, Algeria and Mali; Verati et al., 2005; Chabou et al., 2010; Marzoli et al., 2018). Our hypothesis is that the Tiourjdal group magmas (including the Moroccan Lower unit) are probably the CAMP basalts with the strongest garnet-peridotite signature. They are produced by relatively low degree partial melting of a source in which the recycled component plays a more important role. This scenario would justify the enriched incompatible trace element contents and ratios of this magmatic group as well as their slightly more enriched Sr and Pb isotopic composition compared to the Upper basalts. The deeper melting region of the Tiourjdal group basalts may be possibly related to their location close to the West African Craton (Figs 1 and 23), where the lithosphere was thicker at least during the early stages of CAMP magmatism (cf. also Tegner et al., in press).

Several Upper and Intermediate basalts, which probably derive from common parental magmas, are characterized by fairly low initial Os isotopic compositions. Despite the large corrections applied for radiogenic ingrowth, these data may point to the involvement of an old, possibly cratonic SCLM component. While...
whole-melt melting of such probably refractory and depleted mantle rocks is unlikely and not supported by the isotopic and trace element compositions of CAMP basalts, we envisage that only the Os isotopic system might fingerprint the cratonic SCLM signature, possibly due to assimilation of sulfides or sulfur-rich veins present locally along the margin of the West African craton.

Only the late and volumetrically minor Recurrent basalts yield compositions that might support involvement of a mantle component tapped also by Atlantic OIB. This is suggested by REE patterns and concentrations for Recurrent basalts and their augites, similar to those of enriched-MORB, as well as by Sr–Nd–Pb isotopic compositions distinct from those of other Moroccan CAMP rocks and trending towards a C or FOZO-type composition. A rapid decline of the magmatic activity after emplacement of the Upper and then of the Recurrent unit would be consistent with an exhaustion of the fertile components within the mantle-source, as suggested by Puffer (2003).

ACKNOWLEDGMENTS

D. Pasqual and R. Carampin (Padova) provided technical assistance during X-ray fluorescence and electron microprobe analyses, while C. Zimmermann aided with the Re-Os analyses. Valuable help during field-work was provided by C. Rapaille, K. Allenbach, R. Neuwrth, R. Martini, L. Zaninetti, S. Nomade, K. Knight, C. Verati, A.M Fioretti, H. Ibouh. K. Knight kindly provided TEL, OL R. Martini, L. Zaninetti, S. Nomade, K. Knight, C. Verati, A.M Fioretti, H. Ibouh. K. Knight kindly provided TEL, OL and TJ samples, originally collected for magnetostratigraphy. John Puffer, Jussi Heinonen and Leo Melluso and the editor Simon Turner are thanked for detailed and constructive reviews.

SUPPLEMENTARY DATA

Supplementary data are available at Journal of Petrology online.

FUNDING

We acknowledge financial support from CARIPARO (Eccellenza-2008), PRIN (PRIN 20178LPCP), Padova University (CPDA132295/13) to A.M; CNRi (Italy)-CNRST (Morocco) to A.M and N.Y.; PICS CNRS (France)-CNRST (Morocco) to H.B. and N.Y.

REFERENCES


Jourdan, F., Sharp, W. D. & Renne, P. R. (2012). \(^{40}\)Ar\(^{39}\)Ar ages for deep (~3.3 km) samples from the Hawaii Scientific Drilling Project, Mauna Kea volcano, Hawaii. Geochemistry, Geophysics, Geosystems 13, Q05004.


May, P. R. (1971). Pattern of Triassic-Jurassic diabase dikes around the North Atlantic in the context of pre-drift position.


