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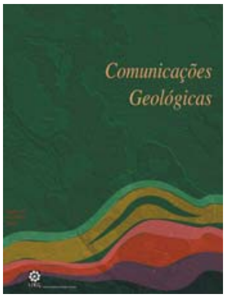
The Central Atlantic Magmatic Province (CAMP) volcanic sequences of Berrechid and Doukkala basins (Western Meseta, Morocco): volcanology and geochemistry



As sequências vulcânicas da Província Magmática do Atlântico Central (CAMP) das bacias de Berrechid e Doukkala (Meseta Ocidental de Marrocos): vulcanologia e geoquímica

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Abstract: The Late Triassic-Early Jurassic volcanic succession of the Berrechid and Doukkala basins (Western Meseta, Morocco) comprises two lava flow fields. At the base, the Sidi Mohamed Larbi-Sidi Saïd Mâachou Formation is composed of 1 to 5 flows, while the upper Aïn Bouhachad Formation presents 1 or 2 flows. Lavas are mainly compound pahoehoe flows showing evidence of endogenous growth by inflation, suggesting slow emplacement during sustained eruptive episodes. Textures vary vertically in each lobe (fine to medium-grained intergranular, subophitic to ophitic in the lava core, and aphanitic to glomeroporphyritic in the lava crust). The mineralogy is typical of continental tholeiites: plagioclase, clinopyroxene (augite and pigeonite), and minor amounts of olivine and ferro-titanium oxides. The major and trace element concentrations and/or ratios of the two formations match, respectively, the compositions described elsewhere for the Lower and Intermediate formations of the Central Atlantic Magmatic Province (CAMP) from the Central High Atlas and Argana basin.

Keywords: Physical Volcanology, Geochemistry, Central Atlantic Magmatic Province (CAMP), Morocco, Berrechid and Doukkala basins

Resumo: As sequências vulcânicas do Triásico Superior-Jurássico Inferior das bacias de Berrechid e Doukkala (Meseta Ocidental de Marrocos) constituem duas séries de escoadas. A inferior, Formação de Sidi Mohamed Larbi-Sidi Saïd Mâachou, é uma sucessão de 1 a 5 derrames, enquanto que a superior, Formação de Aïn Bouhachad, é composta por 1 ou 2 escoadas. Trata-se de derrames lávicos pahoehoe compostos apresentando características de espessamento por inflação, sugerindo implantação lenta durante erupções prolongadas. Os basaltos apresentam texturas intergranulares subofíticas a ofíticas finas a médias no núcleo e afaníticas a glomerofíricas na crosta. A mineralogia primária é típica de toleítos continentais: plagioclase, clinopiroxena (augite e pigeonite), alguma olivina e óxidos de ferro e titânio. Os basaltos das duas formações apresentam composições geoquímicas distintas, sendo as concentrações e/ou razões dos elementos maiores e traço equivalentes às que têm sido descritas para as formações Inferior e Intermédia das sequências da Província Magmática do Atlântico Central (CAMP) do Alto Atlas Central e da bacia de Argana.

Palavras-chave: Vulcanologia Física, Geoquímica, Província Magmática do Atlântico Central (CAMP), Marrocos, bacias de Berrechid e Doukkala.

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1. Introduction

The Late Triassic-Early Jurassic volcanic sequences of Morocco are a privileged window to the geodynamic evolution of the early Central Atlantic domain. Continental rifting of the Central Atlantic started during the Late Triassic, or even at the end of Late Permian, and progressed from South to North along the trend of the Late-Paleozoic Alleghanian-Hercynian orogenic belt (Manspeizer, 1988; Piqué & Laville, 1996; Withjack *et al.*, 1998). Mapping and dating magnetic anomaly pairs allowed precise reconstitutions of the different opening stages of the Central Atlantic Ocean (Olivet *et al.*, 1984) placing the beginning of the oceanic accretion at 170-175 Ma (Middle Jurassic, Klitgord & Schouten, 1986). Comparable ages (178-180 Ma) were obtained from xenoliths of metagabbros and metabasalts of MORB type affinity occurring in the Neogene-Quaternary volcanics of the Canary Islands, which are interpreted as fragments of underlying Mesozoic oceanic crust (Schmincke *et al.*, 1998; Hoernle, 1998). On the other hand, recent reconstructions of the opening of the Central Atlantic Ocean (Sahabi *et al.*, 2004), taking into account the African equivalent of the East Coast Magnetic Anomaly as well as the extension of the Triassic-Jurassic evaporite basins from Morocco and Nova

Scotia, place the age of the earliest oceanic crust at the end of the Sinemurian (189.6 to 196.5 Ma), i. e., 20 My earlier than the age proposed by Klitgord & Schouten (1986).

The Late Triassic-Early Jurassic volcanism of Morocco comprises NE-SW trending megadykes (Foum Zguid and Ighrem dykes) and associated sills swarms (Draa valley sills), as well as widespread lava flows scattered over the High Atlas, Middle Atlas and Meseta. Similar rocks are present in the Armorican Massif and Pyrenees (France), in Southern Portugal and Spain, in Algeria, and further south along the African continental margin (*e. g.*, Dalrymple *et al.*, 1975; Dupuy *et al.*, 1988; Bertrand, 1991; Sebaï *et al.*, 1991; Caroff *et al.*, 1995; Cebriá *et al.*, 2003; Martins *et al.*, 2008), and along the North and South American margins (*e. g.*, Whittington, 1988a, b; De Boer *et al.*, 1988; Puffer, 1992; Mchone, 1996, 2000; Deckart *et al.*, 1997; Marzoli *et al.*, 1999). These circum-Atlantic tholeiites spread over an area of more than 7000 km^2 from SW to NE and represent huge volumes of magma (2.3 to 4 x 10^6 km^3) erupted around 200 Ma ago (*e. g.*, Sebaï *et al.*, 1991; Deckart *et al.*, 1997; Marzoli *et al.*, 1999, 2004; Hames *et al.*, 2000; Verati *et al.*, 2007; Nomade *et al.*, 2007; Jourdan *et al.*, 2009). They are linked in time and space to the fragmentation of Pangaea and to the initial rifting stages of Central Atlantic, defining the Central Atlantic Magmatic Province (CAMP; Marzoli *et al.*, 1999) (Fig. 1a). The peak of magmatic activity was coeval with the Triassic-Jurassic boundary (Nomade *et al.*, 2007; Vérati *et al.*, 2007) and probably triggered the Tr-J mass extinction (Cohen & Coe, 2007; Cirilli *et al.*, 2009).

The extrusive successions of CAMP crop out in all structural domains of Morocco, except in the Anti-Atlas. In most basins, the total thickness of the volcanic pile is 100 to 200 m. However, it may be as thick as 350 m (southern flank of the Central High Atlas), or restricted to 8 to 50 m in inter-basins areas. The basaltic lava flow sequences are usually interstratified with red clastic, evaporitic or carbonated sediments or paleosols. The basaltic sequence is composed of one to several (up to 32; Knight *et al.*, 2004) lava flows with or without interbedded clastic or carbonated sedimentary layers. In the Central High Atlas, where CAMP basaltic sequence is more complete and better preserved, the volcanic pile has been subdivided into four lava flow units, separated by sedimentary levels, which were called Lower, Intermediate, Upper, and Recurrent formations (Bertrand *et al.*, 1982; Marzoli *et al.*, 2004).

In contrast to the widely investigated CAMP basalts from the High and Middle Atlas (Bertrand *et al.*, 1982 ; Sebaï *et al.*, 1991; Fiechtner *et al.*, 1992; Youbi *et al.*, 2003; Marzoli *et al.*, 2004; Knight *et al.*, 2004, Mahmoudi & Bertrand, 2007; El Hachimi *et al.*, 2011), just a few studies have dealt with the CAMP basaltic lava flows of the Berrechid and Doukkala basins (Peretsman, 1985; Girard, 1987; Peretsman & Holser, 1988; Girard *et al.*, 1989). Only a few whole-rock K-Ar ages and chemical data are available in the literature. K/Ar dating of Berrechid basin basalts yielded an age of 200 Ma (Peretsman, 1985; Peretsman & Holser, 1988), corresponding to the Triassic-Jurassic boundary (Gradstein *et al.*, 2004). Girard *et al.* (1989) obtained K/Ar ages ranging from 190 Ma to 105 Ma on the same CAMP basalts, which were interpreted as the result of isotopic resetting produced by younger hydrothermal episodes. In the nearby Khemisset basin, where the volcanic series are similar to those of the Berrechid and Doukkala basins, the whole rock K/Ar ages, ranging from 182 ± 13 to 191 ± 13 Ma (Manspeizer *et al.*, 1978), should also reflect later resetting. In the Doukkala basin, Westphal *et al.* (1979) obtained a plagioclase K/Ar age of 207±8 Ma from the Sidi Saïd Mâachou area. The only geochemical study available ascribed a tholeiitic intraplate affinity to those basalts (Girard, 1987; Girard *et al.*, 1989). No further attention was given to the physical volcanology of the volcanic pile in the Berrechid and Doukkala basins up to the present study.

The main objectives of this work are (i) to describe the stratigraphy and internal morphology of the CAMP basaltic lava flows of the Berrechid and Doukkala basins in order to define the process of lava flows emplacement and the formation of the associated structures, (ii) to determine the volcanological evolution of the sequence, (iii) to present new petrographic and geochemical data in order to better characterize the studied flows, and (iv) to compare the volcanological and geochemical data of the studied basalts with those of the Central High Atlas basin, where the CAMP volcanic succession is complete.

2. Geological setting

The Berrechid and Doukkala basins (or sub-basins) are Mesozoic sedimentary basins belonging to the northern part of the large El Jadida-Agadir basin (Medina, 1995 and references therein). During the first stages of basin formation, related to the rifting of the Central Atlantic Ocean, sediments and lava flows were deposited within large fault-bounded NNE-SSW and NE-SW trending graben structures, associated to a NW-SE extension (Salvan, 1984; Manspeizer, 1988; Medina, 1995, 2000; Hofmann *et al.*, 2000; Youbi *et al.*, 2003; Zühlke *et al.*, 2004; Hafid *et al.*, 2008). Both basins are separated from each other by the N-S trending Rehamna accommodation zone. To the North, the Berrechid basin is separated from the Middle-Atlas dependent Khemisset basin by the Cherrat horst, whereas to the south the Doukkala basin connects with the Essaouira basin in the Abda area.

The stratigraphic series of the Berrechid and Doukkala basins comprise (Permian?)-Late Triassic, some Jurassic (Doukkala only), Cretaceous and Quaternary deposits (Destombes & Jeannette 1966), overlying the deformed Cambrian to Carboniferous basement of the western Meseta (Fig. 1b, c, d). The Triassic deposits, which are best expressed by the series encountered in wells POM2 (Berrechid) and BHL1 (Doukkala), were initially subdivided by Salvan (1984) into four or five lithological units. In the Abda-Doukkala plain (Salvan, 1984), the series consists of: (i) a lower detrital formation (538 m), (ii) a lower salt formation (530 m), (iii) basalt flows (137 m), (iv) an upper salt formation (473 m) and, (v) an upper detrital formation (86 m). The basalt flows occur approximately in the middle of the column. The same lithologic succession is found in well POM2 drilled in the Berrechid basin (Destombes & Jeannette, 1966). At the basin margins, the formations are thinner, devoid of salt beds, and show a fluvial plain sandstone level at the base. Near Benslimane, a 500 m thick formation below the first mudstone levels (El Wartiti *et al.*, 1992) represents by its coarseness a particular facies in the Meseta area, similar to the Late Permian deposits of the Atlas chain.

On the basis of the most recent studies (Hamid, 2003; Lyazidi *et al.*, 2003), we suggest new local units consisting of three formal formations, in conformity with the international lithostratigraphic nomenclature. The lowermost formation, the Chaabat Al Hamira Formation, consists of two members: a lower member with fluvial conglomerates (Sidi Amar Member or M1) and an upper member (Ank Jmel Member or M2) formed by a sequence of sandstones and siltstones. The Berrechid (or M6) Formation consists of a sequence of lower red siltstones with gypsum, overlain by CAMP basalts and upper red siltstones (Fig. 2).

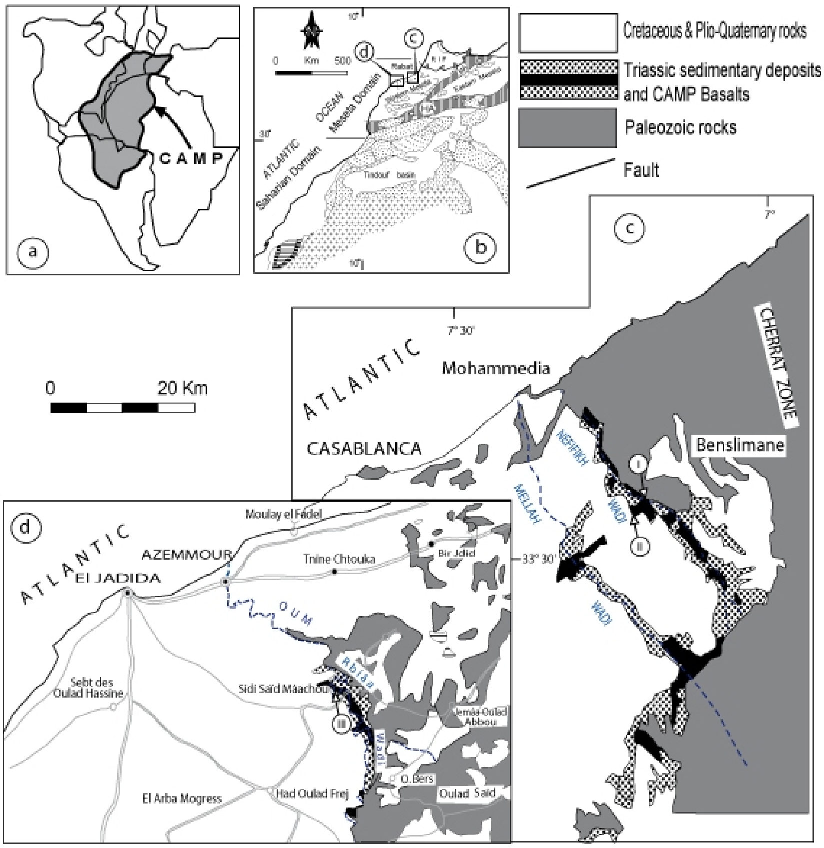

Fig. 1. (a) Reconstruction of Africa-South America-North America, Greenland and Europe at the time of CAMP emplacement and schematic extent of the CAMP LIP; (b) geographical location of Berrechid and Doukkala basins in the Western Meseta of Morocco; (c) simplified geological map of the Berrechid basin; (d) simplified geological map of the Doukkala basin (after Destombes & Jeannette, 1966; El Wartiti *et al.*, 1992; and Lyazidi *et al.*, 2003). Location of the studied sections in the CAMP volcanic pile of the Berrechid and Doukkala basins: I – Sidi Mohamed Larbi (N 33º40'38.95''; W 7º40'02.33''); II – Aïn Bouhachad (N 33º40'28.97''; W 7º18'10.41''); III – Sidi Saïd Mâachou (N 33º07'38.04''; W 8º07'36.84'').

Fig. 1. (a) Reconstrução da posição da África-América do Sul-América do Norte, Gronelândia e Europa na época do magmatismo da CAMP e sua extensão esquemática; (b) localização geográfica das bacias de Berrechid e Doukkala na Meseta Ocidental de Marrocos; (c) mapa geológico simplificado da bacia de Berrechid; (d) mapa geológico simplificado da bacia de Doukkala (segundo Destombes & Jeannette, 1966; El Wartiti *et al.*,1992; e Lyazidi *et al.*, 2003). Localização dos cortes estudados na sequência vulcânica da CAMP das bacias de Berrechid e Doukkala: I – Sidi Mohamed Larbi (N 33º40'38,95''; W 7º40'02,33''); II – Aïn Bouhachad (N 33º40'28,97''; W 7º18'10,41''); III – Sidi Saïd Mâachou (N 33º07'38,04''; W 8º07'36,84'').

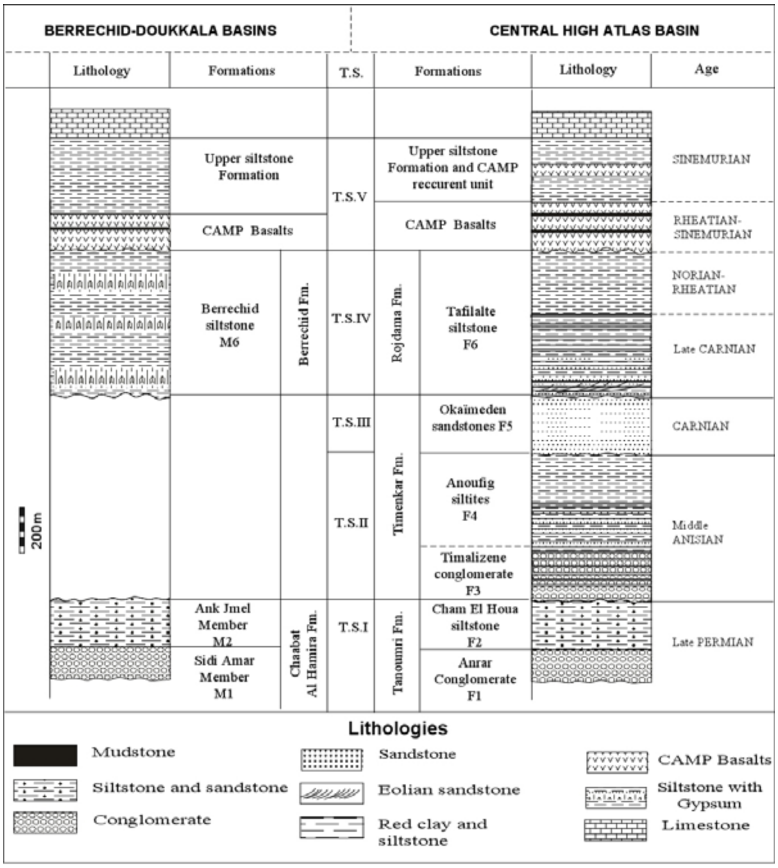

Fig. 2. Stratigraphical correlation between the Triassic-Jurassic series of the Berrechid and Doukkala basins and Central High Atlas basin (from Olsen *et al.*, 2000; El Arabi, 2007; and based on Destombes & Jeannette, 1966; El Wartiti *et al.*,1992; Hamid, 2003, and Lyazidi *et al.*, 2003).

Fig. 2. Correlação estratigráfica entre as sequências do Triásico-Jurássico das bacias de Berrechid e Doukkala e a bacia do Alto Atlas Central (segundo Olsen *et al.*, 2000; El Arabi, 2007; e baseado em Destombes & Jeannette, 1966; El Wartiti *et al.*,1992; Hamid, 2003, e Lyazidi *et al.*, 2003).

Comparison and correlation of the Mesozoic series in the studied basins with the thickest better preserved sequences of the Central High Atlas basins suggest that the Chaabat Al Hamira Formation may be of Permian age and could correspond to the Tanoumri Formation or to the tectonostratigraphic unit TSI (Olsen *et al*., 2000; El Arabi, 2007) which is conventionally composed of two members: the Anrar Member and the Cham El Houa Member (F1 and F2 of BIRON, 1983, respectively). The Berrechid Formation, which is rich in gypsiferous deposits, would be of Triassic age (Carnian to Norian-Rhaetian) and corresponds to the Rojdama Formation or to the tectonostratigraphic unit TSIV of Olsen *et al*., (2000), El Arabi (2007). The CAMP basaltic formation and the upper clay or siltstones would span in age from Triassic to Jurassic (Rhaetian-Sinemurian) and correspond to the tectonostratigraphic unit TSV of Olsen *et al*., (2000), El Arabi (2007) (Fig. 2).

3. Volcanology of the CAMP volcanic succession of Berrechid and Doukkala basins

The studied lavas present characteristics typical of inflated pahoehoe flows according to the terminology and methodology proposed by Self and co-workers (Self *et al.*, 1997, 1998; Thordarson & Self, 1998). In vertical section, each inflated pahoehoe flow show a three zones: a basal vesicular lava crust containing pipe vesicles, a central dense lava core with different segregation structures, and an upper lava crust, displaying alternating vesicular and massive layers.

Three detailed sections were studied on the volcanic pile of Berrechid and Doukkala basins. These sections are located along the margins of the two main rivers of these areas: Nefifikh Wadi and Oum Rbiaa Wadi. The most complete and representative sections are located at Sidi Mohammed Larbi and Ain Bou Hachad in the Berrechid basin, and at Sidi Saïd Mâachou in the Doukkala basin (Fig. 3).These sections show a succession of basaltic lava flows, 50 to 70 m thick.

The volcanic successions are subdivided in two formations. The lower Sidi Mohamed Larbi-Sidi Saïd Mâachou Fm. (15-45 m thick) consists of one lava flow in the Aïn Bouhachad section, three flows in the Sidi Saïd Mâachou section, and five individual lava flows in the Sidi Mohamed Larbi section. The upper Aïn Bouhachad Fm. (up to 30 m thick) generally consists of one or two flows (Sidi Mohamed Larbi and Aïn Bouhachad sections, respectively). These formations are separated by a thin silty horizon, up to 1 m thick. Important thickness variations from one section to another can be explained either by differential subsidence of the pre-volcanic basement during the emplacement of the lava flows (syn-rift series), or by the emplacement of the flows on a basement presenting an irregular paleotopography or a horst and graben structure. Sedimentological and structural data point towards a syn-rift context contemporaneous to the extrusion of the CAMP basalts in the Berrechid and Doukkala basins (EL Wartiti *et al.*, 1992; Hamid, 2003; Lyazidi *et al.*, 2003).

The lava flows of Berrechid and Doukkala basins present compound pahoehoe features (Walker, 1971; Jerram, 2002) and are composed of accumulations of thin anastomosing pahoehoe flow sheets and lobes, up to several meters thick. These compound flows are interpreted to represent lavas emplaced at low effusion rates.

The thickness of lava flow lobes ranges from 4 to 20 m, while lateral extent can exceed 100 m for each “sheet lobe”. However, several smaller lobes have a more limited lateral extent (10 m). The largest lobes as well as small lobes forming the studied basaltic flows are typically characterized by the threefold structure comprising a thin vesicular basal crust, a dense core, and a thick vesicular upper crust (Aubele *et al.*, 1988; Thordarson & Self, 1998). Flow lobe tops often show oxidized rinds, whereas centimetric silica-filled pipe vesicles are rarely present at the base. Two types of segregation structures can be observed in the core: vesicle cylinders (Goff, 1996) and vesicle sheets (Thordarson & Self, 1998). Vesicle cylinders (up to 0.50 m long) are observed in the lower and middle parts of the core, while vesicle sheets (5 to 20 cm thick) occur near the interface between the crust and the core.

On the studied sections there is evidence for a variable number of eruptions in each formation. The products of distinct eruptions can be separated by the presence of reddened flow surfaces (slightly weathered surfaces metamorphosed by overlying flows), development of more or less evolved red soils, or deposition of fine clastic sediments, indicating significant time intervals separating the emplacement of each package of lava flow-units.

The Sidi Mohamed Larbi-Sidi Saïd Mâachou Fm. was built up by 1 to 5 eruptions, each usually formed by flow fields composed of up to 5 flow units. The Aïn Bouhachad Fm., which is lacking in Doukkala basin, is the result of one or two eruptions. In the most complete CAMP lava sequences of the Central High Atlas, magnetostratigraphic data indicate the occurrence of five short magma pulses (Knight *et al.*, 2004).

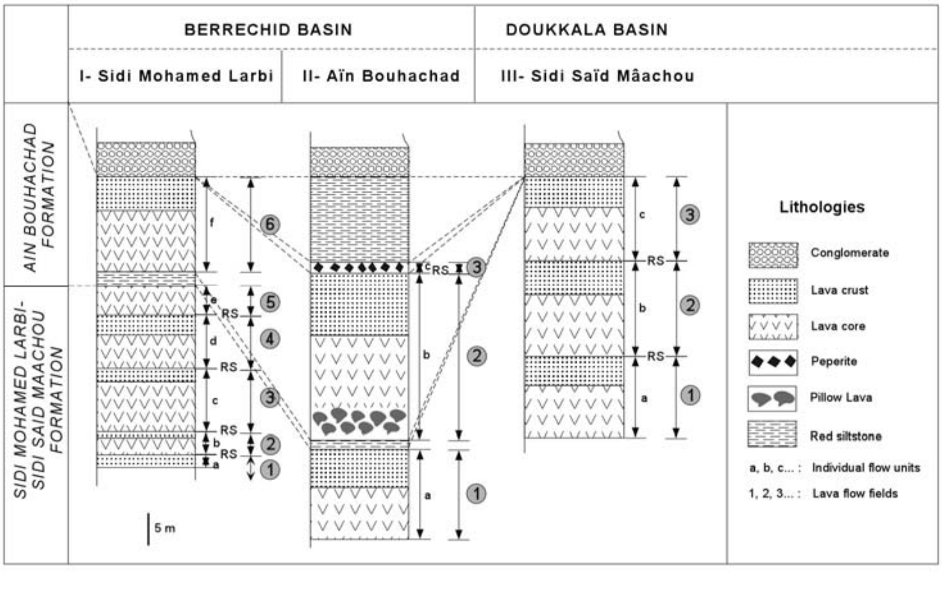

Fig. 3. Lithostratigraphic columns across the CAMP volcanic succession of Berrechid and Doukkala basins (CAMP Basalts in Fig. 2). RS indicates the presence of red soils separating products of separate eruptions.

Fig. 3. Colunas litoestratigráficas das sequências vulcânicas da CAMP nas bacias de Berrechid e Doukkala (CAMP Basalts na Fig. 2). RS indica a presença de solos vermelhos separando produtos de erupções distintas.

4. Petrography of the CAMP basalts of Berrechid and Doukkala basins

The lava flows of the Berrechid and Doukkala basins show different textures: (i) a fine- to medium-grained intergranular, subophitic to ophitic texture for the lava core; (ii) an aphanitic to glomeroporphyritic texture for the lava crust.

The dominant phenocryst phases are plagioclase showing albite twinning and rare sector zoning, augite and sometimes coexisting pigeonite. Olivine, which occurs rarely and in subordinate amount, is sometimes replaced by serpentine. With the exception of olivine, all these minerals are also part of the mesostasis together with accessory ferro-titanium oxides. The presence of pigeonite and the rarity of olivine, usually present as partially resorbed phenocrysts, point to a relatively high silica activity, typical of tholeiitic magmas. The secondary mineral assemblage, probably related to hydrothermal activity that affected these lavas, includes green chlorite scattered as patches in the mesostasis, silica filling veins and vesicles, calcite and iron oxides.

5. Whole rock geochemistry

5.1 Analytical procedures

Chemical analyses (major and trace elements including rare earth elements) of the CAMP basalts of Berrechid and Doukkala basins are listed in Table 1. After reducing the sample to centimeter-sized chips in a hydraulic press, the freshest pieces were selected and crushed using a jaw crusher and then powdered in an agate swing mill. A first set of major and trace elements analyses (MHW samples) was measured, except for Rb, by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) with an ISA Jobin-Yvon JY 70 Plus apparatus spectrometer at the Département des Sciences de la Terre de l'Université de Bretagne Occidentale, Brest in France. Rb was measured by flame atomic emission using a Perkin-Elmer 5000 spectrometer. International standards were used for calibrations tests (ACE, BEN, JB-2, PM-S and WS-E). Relative standard deviations are ± 1% for SiO_2 and ± 2% for other major elements except P_2O_5 and MnO (± 0.01%), and ca. 5% for trace elements. The analytical techniques were described in detail by Cotten *et al.* (1995). A second set of analyses (AN samples) were analysed at the Laboratoire des Sciences de la Terre, de l'Université de Lyon, France by XRF using Phillips PW-1404 spectrometer. The precision is 1–2% for major elements and 10–15% for trace elements (Sc, V, Cr, Co, Ni, Rb, Sr, Ba, Zr, Nb, Y, Ga and Pb).

5.2 Major and trace elements

The CAMP basalts of the studied basins show low to moderate values of loss on ignition (0.44 to 1.97%) reflecting moderate to weak degree of alteration of these rocks. The major element compositions of the studied rocks correspond to quartz-normative tholeiitic basalts (2.13% ≤ normative quartz ≤ 7.83%), with silica content ranging from 47.79 to 53.31 wt%. In the total alkali-silica (TAS) diagram (Fig. 4) of Le Bas *et al.*, (1986), the samples plot in the fields of basalt and basaltic andesite, and match the CAMP rocks domain compiled from data presented by Bertrand *et al.*, (1982), Mchone (2000) and Marzoli *et al.* (2004). In this diagram it is evident that rocks from the Sidi Mohamed Larbi-Sidi Saïd Mâachou Fm. (lower units of the Doukkala and Berrechid basins) present higher alkali content than those characterizing the Aïn Bouhachad Fm. (upper unit of the Berrechid basin). Such difference is also reflected by Y/Nb ratios, a proxy of magma alkalinity (*e. g.*, Pearce & Cann, 1973), which are > 3.17 in the, Aïn Bouhachad Fm. but < 2.47 in the Sidi Mohamed Larbi-Sidi Saïd Mâachou Fm. (see Table 1).

The studied rocks present TiO_2 content ranging from 1.14 to 1.59 wt% comparable to the low-Ti CAMP tholeiites (*e. g.*, Verati *et al.*, 2005; Chabou *et al.*, 2010) or to the low-Ti continental flood basalts (CFB) studied by Albarède (1992) (Fig. 5). The more alkali-rich rocks from the lower units are also characterized by higher TiO_2 contents (Fig. 5; Table 1).

Mg-numbers [#Mg defined as 100 x $Mg^{2+}/(Mg^{2+}+Fe^{2+})$, where FeO = Fe_2O_3t x 0.9], range between 53.52 and 63.18. These somewhat low #Mg coupled with moderate MgO (6.75–8.81 wt%) and Ni (84–112 ppm) contents show that these rocks represent magmas which have undergone significant fractional crystallization. Major and trace element variation in the studied rocks can be largely explained by crystal fractionation involving minor olivine, plagioclase and clinopyroxene (augite and pigeonite) (Fig. 6). The fractionation of olivine and pyroxene is shown by decreasing Cr and Ni with decreasing #Mg. In contrast, for the less evolved rocks, Fe_2O_3t and TiO_2 increase with decreasing #Mg, indicating that iron-titanium oxides do not crystallize at this stage of differentiation with the consequent iron-enrichment trend typical of tholeiitic series. The CaO and Al_2O_3 contents are relatively constant, with decreasing #Mg, which is interpreted as the result of the opposite effects of the olivine and pigeonite removal which, *per se*, would increase CaO and Al_2O_3 contents of the residual melts, and of the plagioclase and augite fractionation tending to deplete melts in those oxides. Nb, Zr and Y increase with decreasing #Mg, consistently with their incompatible character. The behaviour of Cu as an incompatible element during fractionation (not shown) is characteristic of continental tholeiites (Dupuy & Dostal, 1984).

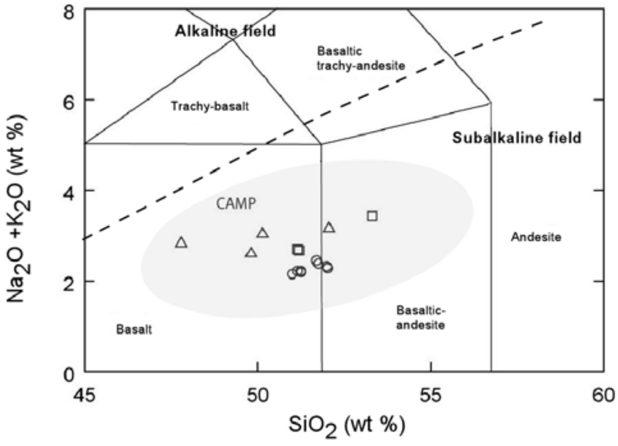

Fig. 4. Total alkali-silica classification diagram (Le Bas *et al.*, 1986) for CAMP basalts of Berrechid and Doukkala basins. CAMP domain (shaded area) after Bertrand *et al.* (1982), Mchone (2000) and Marzoli *et al.* (2004). Symbols: Sidi Mohamed Larbi-Sidi Saïd Mâachou Fm. - open triangles, lower unit of Doukkala basin; open squares, lower unit of Berrechid basin; Aïn Bouhachad Fm. - open circles, upper unit of Berrechid basin. The dashed line represents the compositional divider between alkaline and subalkaline fields proposed by Miyashiro, (1978).

Fig. 4. Diagrama alcalis total-sílica (Le Bas *et al.*, 1986) dos basaltos da CAMP das bacias de Berrechid e Doukkala. Domínios da CAMP (área sombreada) segundo Bertrand *et al.* (1982), Mchone (2000) e Marzoli *et al.* (2004). Símbolos: Formação de Sidi Mohamed Larbi-Sidi Saïd Mâachou - triângulos abertos, unidade inferior da bacia de Doukkala; quadrados abertos, unidade inferior da bacia de Berrechid; Formação de Aïn Bouhachad - círculos abertos, unidade superior da bacia de Berrechid. A linha a tracejado corresponde à divisória entre os campos alcalino e subalcalino (Miyashiro, 1978).

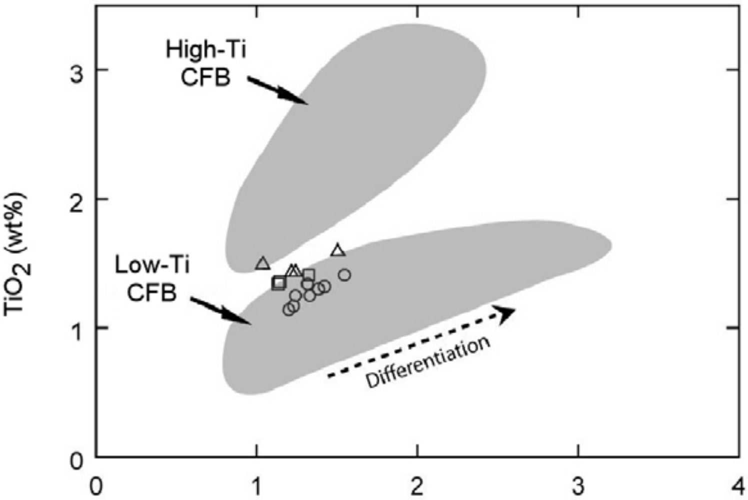

Fig. 5. TiO_2 versus FeOt/MgO diagram. Continental Flood Basalt (CFB) fields for comparison, from Albarède (1992). Reference data of low-Ti CAMP tholeiites in West Africa are from Marzoli *et al.* (2004), Deckart *et al.* (2005), Verati *et al.* (2005), Meddah *et al.* (2007), Mahmoudi & Bertrand (2007), and Chabou *et al.* (2010). Symbols as in Fig. 4.

Fig. 5. Diagrama TiO_2 contra FeOt/MgO. O campo dos Continental Flood Basalt (CFB), indicado para comparação, de Albarede (1992). Os dados de referência para os toleítos de baixo Ti da CAMP da África Ocidental de Marzoli *et al.* (2004), Deckart *et al.* (2005), Vérati *et al.* (2005), Meddah *et al.* (2007), Mahmoudi & Bertrand (2007), e Chabou *et al.* (2010). Símbolos como na Fig. 4.

Table 1. Major and trace element analyses of CAMP basalts from the Berrechid and Doukkala basins.

Tabela 1. Análises dos elementos maiores e traço dos basaltos da CAMP das bacias de Berrechid e Doukkala.

Basin	Doukkala	Doukkala	Doukkala	Doukkala	Berrechid	Berrechid	Berrechid	Berrechid	Berrechid	Berrechid	Berrechid	Berrechid	Berrechid	Berrechid	Berrechid
Formation	SIDI MOHAMED LARBI-SIDI SAÏD MÂACHOU Fm.							AÏN BOUHACHAD Fm.							
CAMP equivalent	Lower Fm.							Intermediate Fm.							
Locality	Sidi Saïd Maachou				Sidi Mohamed Larbi			Sidi Mohamed Larbi		Aïn Bouhachad					
Sample	AN401	AN402	AN403	AN404	AN405	AN406	AN407	AN408	AN409	MHW 9-1	MHW 9-2	MHW 9-3	MHW 9-5	MHW 9-6	MHW 9-7
Major Elements (wt%)															
SiO_2	47.79	49.81	52.06	50.14	51.15	51.2	53.31	52.02	51.25	51.75	51.25	52.00	51.00	51.15	51.7
TiO_2	1.49	1.43	1.59	1.43	1.36	1.34	1.41	1.17	1.14	1.32	1.25	1.3	1.25	1.34	1.41
Al_2O_3	14.06	13.71	13.43	13.63	13.48	13.32	13.58	13.76	13.77	13.8	13.5	13.7	13.3	13.3	13.85
Fe_2O_3	10.16	11.12	11.32	10.89	10.16	10.54	10.37	11.04	10.66	11.45	11.45	11.15	11.45	11.7	11.6
MnO	0.08	0.14	0.19	0.11	0.19	0.12	0.14	0.15	0.15	0.18	0.18	0.17	0.21	0.2	0.19
MgO	8.81	8.23	6.77	7.88	7.99	8.37	7.05	8.08	8.00	7.25	7.75	7.25	8.3	8.00	6.75
CaO	8.25	9.45	9.45	9.01	9.56	8.66	9.3	10.62	10.53	9.9	10.00	10.25	10.00	10.00	9.65
Na_2O	2.16	2.16	2.29	2.41	2.18	2.11	2.26	1.87	1.81	1.99	1.88	1.93	1.77	1.87	2.05
K_2O	0.66	0.44	0.86	0.62	0.52	0.56	1.17	0.41	0.38	0.39	0.34	0.39	0.38	0.35	0.4
P_2O_5	0.17	0.16	0.2	0.16	0.16	0.15	0.19	0.12	0.12	0.16	0.16	0.16	0.16	0.16	0.15
LOI	1.62	0.95	0.8	1.02	1.15	1.55	0.54	0.44	1.3	1.61	1.97	1.83	1.77	1.72	1.81
H_2O^-	4.67	2.58	1.24	2.81	1.9	2.32	0.94	0.85	1.42						
Total	99.92	100.18	100.2	100.11	99.8	100.24	100.26	100.63	100.53	99.8	99.73	100.13	99.59	99.79	99.56
# Mg	63.18	59.43	54.21	58.88	60.88	61.12	57.37	59.16	59.76	55.62	57.26	56.27	58.93	57.51	53.52
Trace Elements (ppm)															
Ba	180	188	282	177	171	186	297	132	120	150	150	137	154	163	150
Nb	11.7	11.7	13.7	11.9	12	10.2	12.9	6.9	7.2	8	7.6	7.8	7.3	7.7	8.1
Zr	143	134.8	162.2	140.5	132.3	124.2	152.8	104.7	103.6	120	116	118	110	116	120
Y	24.2	22.6	29.2	24.7	25.1	25.1	26.6	22.5	23.9	25.5	25	25.2	23.8	24.8	28
Sr	246	243	232	232	233	229	229	161	165	168	163	164	163	161	174
Rb	4.6	7.1	26.4	14.1	15	13.7	40	12.2	16.1	12.5	12.7	14.6	9.1	12.6	15.2
Th										2.35	2.3	2.55	2.3	2.25	2.7
Ni	87	79	69	93	85	82	74	95	87	84	102	84	112	108	75
Co	41	42	41	44	47	44	42	47	45	44	45	44	49	47	43
Cr	269	254	254	299	270	262	265	347	345	310	360	190	410	385	222
V	269	274	266	281	272	263	251	272	269	312	312	322	328	330	305
Sc	36	32	29	29	32	30	30	34	32	36	35	34	35	34	35
La										11.8	11.3	12	10.6	11.1	12.6
Ce										27	25	26.5	24	25	28
Nd										16	15.4	15.5	14	15	17
Sm										4.1	3.75	3.65	3.7	3.7	4.35
Eu										1.2	1.17	1.22	1.18	1.22	1.33
Gd										4.4	4.15	4.3	4.1	4.4	4.7
Dy										4.55	4.5	4.5	4.2	4.45	5.05
Er										2.6	2.35	2.6	2.3	2.35	2.7
Yb										2.48	2.35	2.38	2.21	2.34	2.55
Ga	19	18	19	18	18	17	19	18	17						
Cu	78	141	123	21	180	80	53	165	152						
Trace Elements Ratios															
Y/Nb	2.06	1.93	2.13	2.07	2.09	2.46	2.06	3.26	3.31	3.18	3.28	3.23	3.26	3.22	3.45
Zr/Nb	12.22	11.52	11.83	11.80	11.02	12.17	11.84	15.17	14.38	15	15.26	15.12	15.06	15.06	14.81
Zr/Y	5.90	5.96	5.55	5.68	5.27	4.94	5.74	4.65	4.33	4.70	4.64	4.68	4.62	4.67	4.28

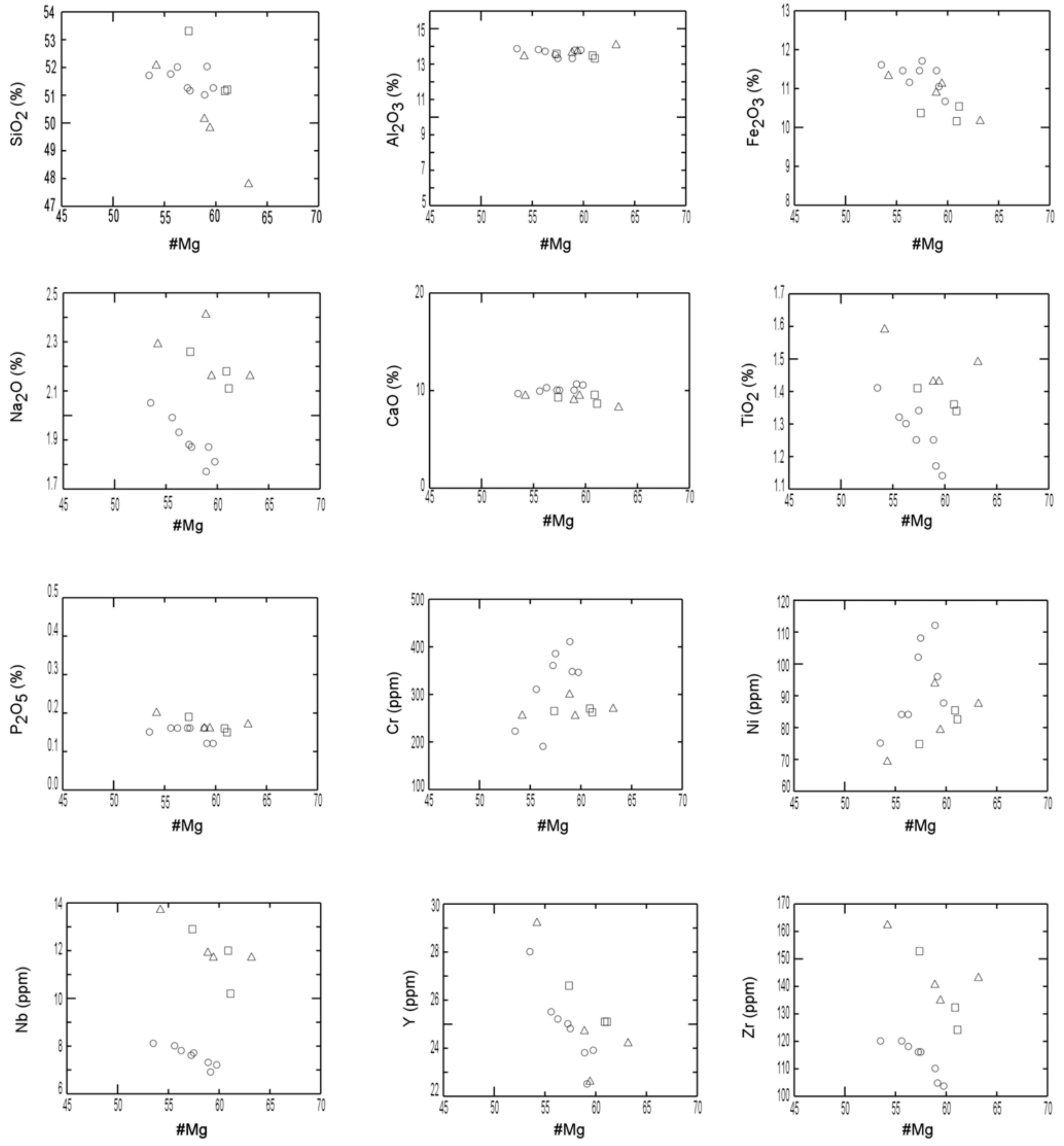

Fig. 6. Chemical variation diagrams for the CAMP basalts of Berrechid and Doukkala basins, showing major element oxides, and trace elements plotted against #Mg, defined as [100 X $Mg^{2+}/(Mg^{2+}+Fe^{2+})$, where FeO = Fe_2O_3t x 0.9]. Symbols as in Fig. 4.

Fig. 6. Diagramas de variação química para os basaltos da CAMP das bacias de Berrechid e Doukkala, incluindo os principais óxidos e elementos-traço projectados contra #Mg definido como [100 X $Mg^{2+}/(Mg^{2+} + Fe^{2+})$, onde FeO = Fe_2O_3t x 0,9]. Símbolos como na Fig. 4.

The chondrite-normalized rare-earth element (REE) patterns of the studied rocks display moderate REE enrichment and light/heavy REE (LREE/HREE) fractionation (Fig. 7), with the $(La/Yb)_N$ ratio ranging from 3.40 to 3.61.

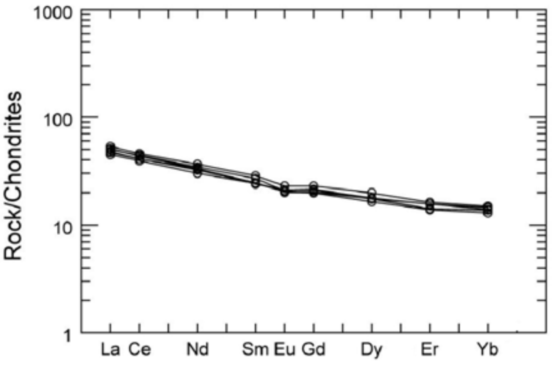

Fig. 7. Chondrite-normalized REE patterns (Sun & McDonough, 1989). Symbols as in Fig. 4.

Fig. 7. Padrões dos REE normalizados para condritos (Sun & McDonough, 1989). Símbolos como na Fig. 4.

The primitive mantle-normalized multi-trace element patterns also show moderate enrichment either in large ion lithophile elements (LILE), or in high field strength elements (HFSE). The relative degree of enrichment, for the majority of elements, is similar to those reported by Sun & McDonough (1989) for oceanic basalts. However, in opposition to oceanic basalts, small Nb and P negative anomalies are sometimes observed (Fig. 8a, b).

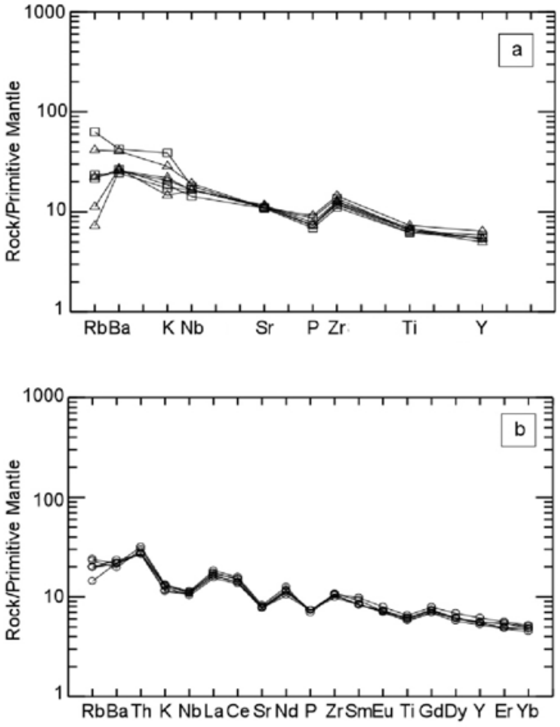

Fig. 8. Primitive mantle-normalized trace element patterns (Sun & McDonough, 1989). Symbols as in Fig. 4.

Fig. 8. Padrões dos elementos-traço normalizados para o manto primitivo (Sun & McDonough, 1989). Símbolos como na Fig. 4.

The causes for such anomalies can be variable (Nb: contamination by continental crust or involvement of a subduction-modified lithospheric mantle source - Dupuy & Dostal, 1984; Coish & Sinton, 1992; P: magma contamination by continental crust, apatite fractionation or apatite as melting residual phase, Taylor & Mc Lennan, 1985; Rudnick & Fountain, 1995; O'Reilly & Griffin, 2000). However, we emphasize that these patterns are similar to those of many other low-Ti CAMP tholeiites identified in West Africa (*e. g.*, Verati *et al.*, 2005; Chabou *et al.*, 2010).

It is interesting to note that, when comparing lavas with similar #Mg, i. e., with similar degree of evolution, the Sidi Mohamed Larbi-Sidi Saïd Mâachou Fm. is richer in incompatible elements, like Zr and Nb, than their counterparts of the Aïn Bouhachad Fm. (Fig. 6). This also translates into distinct incompatible trace-element ratios (Sidi Mohamed Larbi-Sidi Saïd Mâachou Fm.: $Zr/Nb < 12.23$, $Y/Nb < 2.47$, $Zr/Y > 4.93$; Aïn Bouhachad Fm. $Zr/Nb > 14.37$, $Y/Nb > 3.17$, $Zr/Y < 4.71$). Differences like these imply distinct mantle sources.

6. Discussion

6.1 Emplacement mechanisms of the CAMP lava flows of Berrechid and Doukkala basins

The studied CAMP flows show clear evidence of endogenous growth or inflation in the acceptation of Self *et al.* (1997; 1998). They are very similar to inflated pahoehoe flows found in Hawaii (Hon *et al.*, 1994), Columbia River Basalt Province (Thordarson & Self, 1998), Cenozoic volcanic Province of North Queensland in Australia (Whitehead & Stephenson, 1998), Deccan Traps (Keszthelyi *et al.*, 1999; Bondre *et al.*, 2004a, b; Jay & Widdowson, 2008), Paraná-Etendeka CFB (Waichel *et al.*, 2006; Jerram *et al.*, 1999a, b), and the CAMP flows of Fundy, Canada (Kontak, 2008), Argana basin (El Hachimi *et al.*, 2011), and Algarve basins, Portugal (Martins *et al.*, 2008).

The features indicating endogenous growth are: (i) the three-part structural division of sheet lobes displaying vesicular basal crust, massive lava core, and vesicular upper crust, which when thick, tends to show layering of alternating dense and vesicular levels; and (ii) the vertical distribution of vesicles and the presence of segregation structures (spherical vesicles, pipe vesicles, vesicle cylinders and vesicle sheets).

6.2. Correlation with the High Atlas basin of Morocco

The thickest, best preserved and most complete basaltic lava flow sequences of the Moroccan CAMP are exposed in the Central High Atlas basin. Four lava flow fields, emplaced in subaerial environment, are recognized and designated Lower, Intermediate, Upper and Recurrent Formations (De Pachtere, 1983; Bertrand *et al*., 1982; Bertrand, 1991; Youbi *et al*., 2003; Marzoli *et al*., 2004). The Lower Fm. is a 55-173 m thick succession of 2 to 9 individual flows. The Intermediate Fm. (up to 130 m) is composed of 2 to 9 individual flows. The Upper Fm. (15-76 m thick) is formed of one or two lava flow units. The Recurrent Fm. is formed of one 5-50 m thick flow. These formations are separated by thin sedimentary units (siltstones, sandstones, stromatolitic limestones) and paleosols that represent minor periods of volcanic quiescence. Compound pahoehoe flows are almost exclusively present in the Lower and Intermediate Fms., while simple flows dominate the Upper and Recurrent Fms. (El Hachimi *et al*., 2010; El Hachimi *et al*., 2011).

The comparison of volcanological data of the Berrechid and Doukkala basins (Fig. 9) with those of the Central High Atlas basins shows that the Upper and Recurrent units are lacking in the studied basins. In the Berrechid basin, we recognized the Lower and Intermediate Fms. while only the Lower Fm occurs in the Doukkala basin. Indeed, the lack of pillow lavas, which often occupy a specific stratigraphic position at the base of the Intermediate Fm. and at the top of the Upper Fm. in the CAMP volcanic successions of the High Atlas basin, and the higher number of lava flows in this formation (between 3 and 4), indicate that the Sidi Mohamed Larbi-Sidi Saïd Mâachou Fm. is correlated with the Lower Fm. of the High Atlas basin. The existence of a silty sedimentary level sometimes overlain by pillow lavas suggests that the Aïn Bouhachad Fm. is the equivalent to the Intermediate Fm. of the High Atlas basin.

The CAMP lava sequence of the Central High Atlas basin of Morocco is characterized by chemostratigraphic variations in major element contents (e.g. SiO_2 and TiO_2), and upward decrease of incompatible element contents and of LREE/HREE ratios (e.g. La/Yb). These time-related variations suggest that the basalts from the four units differentiated from distinct mantle-derived parental magmas (Bertrand *et al.*, 1982; Bertrand, 1991; Marzoli *et al.*, 2004; Marzoli *et al.*, 2006).

Major and trace element concentrations and ratios of basalts from Sidi Mohamed Larbi-Sidi Saïd Mâachou Fm. (Berrechid and Doukkala basins) and Aïn Bouhachad Fm. (Berrechid basin) respectively match the composition of the Lower and Intermediate Formation from the Central High Atlas basin (Fig. 10) confirming what was inferred from volcanological data (see above). The reported differences on incompatible trace-element ratios (see above; Table 1) also support the need of distinct parental magmas and mantle sources to explain part of the chemical variability of the studied rocks.

6.3. Mantle source and geodynamic model

A key feature of the studied rocks, regarding their trace element patterns, is the occurrence of small Nb negative anomalies which contrast with the composition of mid ocean ridge basalts (MORB) and ocean island basalts (OIB). Although these chemical characteristics, typical of CAMP low-Ti tholeiites, may have been interpreted in terms of crustal contamination (Dupuy & Dostal, 1984), they are more commonly considered to reflect a subcontinental lithospheric mantle (SCLM) source, previously enriched by metasomatic event(s) related to ancient subduction process(es) (Bertrand *et al.*, 1982; Alibert, 1985; Pegram, 1990; Bertrand, 1991; Montes-Lauar *et al.*, 1994; Demant & Morata, 1996; Puffer, 2003; Cebriá *et al.*, 2003; Demin *et al.*, 2003; Deckart *et al.*, 2005).

The involvement of a subduction modified SCLM source is consistent with the isotopic data available for the other Moroccan CAMP volcanic successions, and is inferred from Nd isotopic signatures characterized by time-integrated enrichment (ε_{Nd} down to -1) or only marginally depleted (ε_{Nd} up to +0.3) (Marzoli *et al.*, 2006). The progressive depletion in the incompatible elements, upward in the sequence, referred by these authors and also depicted by the studied rocks, is explained by the progressive exhaustion of the most fertile and probably lower solidus, domains of the SCLM.

The triggering mechanism for partial melting associated with the generation of CAMP magmas is still the locus of an intense debate. The magmas may have been generated (i) in response to mantle warming underneath the insulating Pangea supercontinent (*e. g.*, Yale & Carpenter, 1998; Doblas *et al.*, 2002; Coltice *et al.*, 2007, 2009); (ii) by adiabatic melting in response to plate margin lithospheric extension linked to the Central Atlantic opening: passive rifting (*e. g.*, Withjack *et al.*, 1998; Medina, 2000); and/or (iii) by the activity of a thermally and chemically

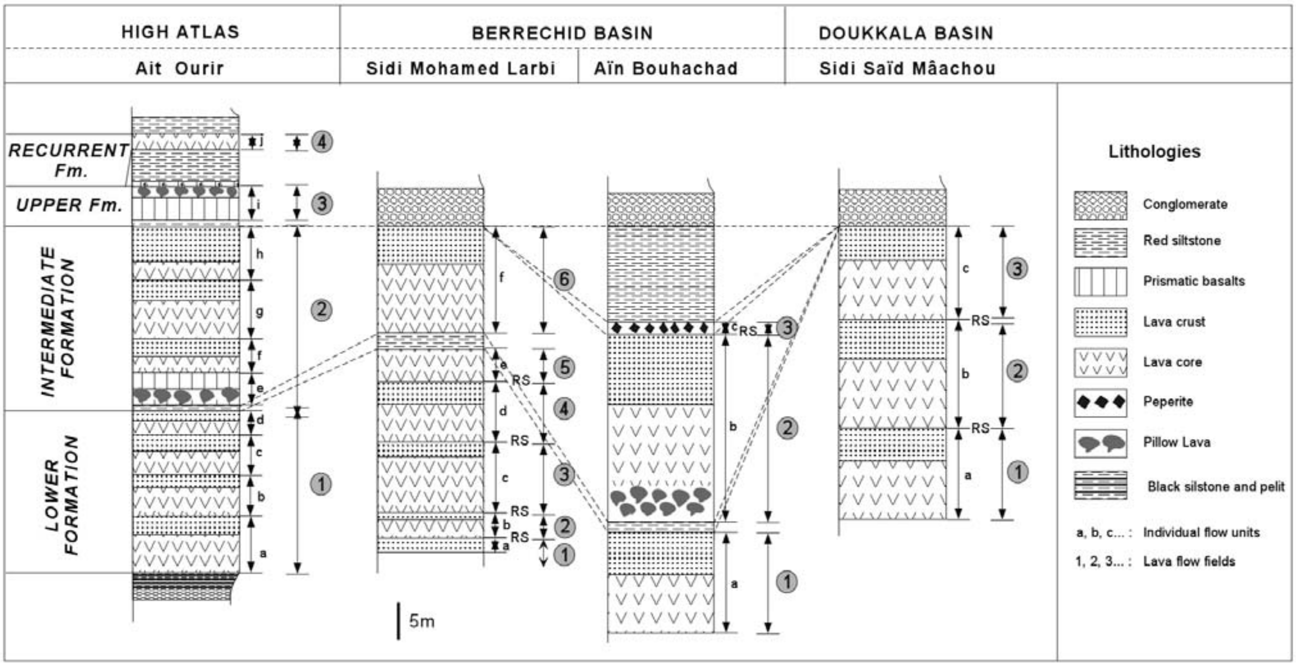

Fig. 9. Lithostratigraphic comparison of the CAMP volcanic succession of Berrechid and Doukkala basins with those of the Central High Atlas.

Fig. 9. Comparação da lito-estratigrafia das sequências vulcânicas da CAMP das bacias de Berrechid e Doukkala com as das bacia do Alto Atlas Central.

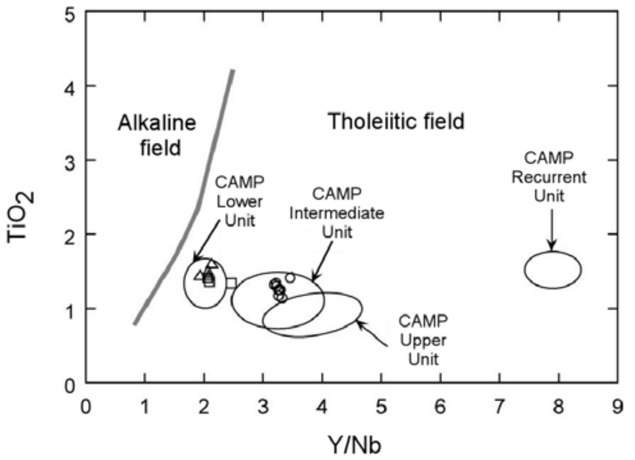

Fig. 10. TiO_2 versus Y/Nb plot (Winchester & Floyd, 1977) showing the tholeiitic affinity of CAMP basalts from the Berrechid and Doukkala basins. Symbols as in Fig. 4. The encircled areas represent the average compositions of the Lower, Intermediate, Upper and Recurrent Formations of the High Atlas (fields taken from Marzoli *et al.*, 2004).

Fig. 10. Diagrama TiO_2 contra Y/Nb (Winchester & Floyd, 1977) mostrando a afinidade toleítica dos basaltos da CAMP das bacias de Berrechid e Doukkala. Símbolos como na Fig. 4. As áreas envolvidas em elipses representam as composições médias das formações Inferior, Intermédia, Superior e Recorrente do Alto Atlas (campos retirados de Marzoli *et al.*, 2004).

anomalous mantle plume (superplume), which has been considered the precursor of the opening of Central Atlantic and break-away of Africa and Europe at 195 Ma: active rifting (*e. g.*, Oyarzun *et al.*, 1997; Wilson, 1997; Thompson, 1998; Janney & Castillo, 2001; Ernst & Bleeker, 2010). The option by one of these models is beyond the scope of this study.

7. Concluding remarks

In this study we presented volcanological and geochemical data from the extrusive sequence of Berrechid and Doukkala basins (Morocco) in order to contribute to the knowledge of the CAMP volcanology and geochemistry in the Moroccan Meseta, and to compare it with the High Atlas and Middle Atlas domains.

(i) The CAMP volcanic pile of Berrechid and Doukkala basins was formed during one (Doukkala) to two pulses (Berrechid) of volcanic activity, represented by the Sidi Mohamed Larbi-Sidi Saïd Mâachou and the Aïn Bouhachad Formations. These are geochemically correlative to the Lower and Intermediate Formations of the Moroccan High Atlas. The Sidi Mohamed Larbi-Sidi Saïd Mâachou Fm. (Doukkala and Berrechid basins) was produced by 1 to 5 eruptions, and usually comprise flow fields composed of up to 5 flow units. The Aïn Bouhachad Fm., which is lacking in Doukkala basin, is the result of up to 2 eruptions.

(ii) Sidi Mohamed Larbi-Sidi Saïd Mâachou and the Aïn Bouhachad Formations are characterized by distinct incompatible trace element ratios implying different mantle sources.

(iii) The studied CAMP basalts are low-Ti continental tholeiites, moderately enriched in LILE and LREE relative to HREE and HFSE, also displaying small negative Nb and P anomalies. Their compositional range is similar to that of other low-Ti CAMP tholeiites, in particular those of the neighbouring CAMP outcrops of Morocco, Algeria and Mali. The major and trace element concentration and ratios of the Sidi Mohamed Larbi-Sidi Saïd Mâachou Fm. and the the Aïn Bouhachad Fm. match, respectively the composition of the Lower and Intermediate Formations from the Central High Atlas basin. In the Berrechid basin, we recognized the chemical fingerprint the Lower and Intermediate Fms. while only the Lower Fm. occurs in the Doukkala basin.

(iv) The primitive mantle-normalized multi-trace element patterns are similar to many other low-Ti CAMP tholeiites identified in West Africa. The negative Nb anomaly is interpreted as indicating the involvement of subduction-modified subcontinental mantle (*e. g.*, Demin *et al.*, 2003; Deckart *et al.*, 2005). The involvement of a modified SCLM source is consistent with the isotopic data available (Marzoli *et al*., 2006), while the stratigraphic upward progressive depletion in the incompatible elements, is explained by the progressive exhaustion of the most fertile, and probably lower solidus, domains of the modified SCLM.

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