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Some aspects of current State of Knowledge on Triassic series on both sides of the Central Atlantic Margin / *Quelques aspects de l'état des connaissances des séries triasiques de part et d'autre de la Marge Atlantique*

Physical volcanology and emplacement mechanism of the Central Atlantic Magmatic Province (CAMP) lava flows from the Central High Atlas, Morocco

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Abstract. The best preserved and most complete lava flow sequences of the Central Atlantic Magmatic Province (CAMP) in Morocco are exposed in the Central High Atlas and can reach up to 300 m in thickness. Four distinct formations, emplaced in subaerial environments, are classically recognized: the

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Lower, Intermediate, Upper and Recurrent formations. These formations are separated by paleosoils and sedimentary sequences (mudstones, siltstones, sandstones, limestones), that are in general less than two meter-thick and may exceptionally reach a thickness of 80 m, representing minor periods of volcanic quiescence. CAMP lava flows of the Central High Atlas can be grouped into two main categories: subaerial compound pahoehoe flows and simple flows. The former type is exclusively confined to the Lower and Intermediate Formations, while simple flows occur in the Upper and Recurrent Formations. The dominance of compound flows in the two lowermost units of the CAMP suggests a slow emplacement during successive sustained eruptive episodes. Instead the thick single flows characterizing the Upper and Recurrent units indicate higher effusive rates. Basaltic pillow lavas (always of short lateral extent: 10 to 100 m), showing radial jointing and vitreous rinds, identical to those found in the Western Meseta, are occasionally associated with hyaloclastites in the base of the Intermediate Formation, immediately above clastic sediments, or in the Upper Formation. The occurrence of pillow lavas does not imply a generalized subaqueous environment at the time of the lava emission. Instead, they represent subaerial flows that entered small lakes occupying depressions on the volcanic topography of the Lower and Intermediate Formations. The short lateral extent of the pillow lavas and their constant stratigraphic position, the existence of lava flows with unequivocal subaerial characteristics associated to sediments containing fossilized wood, clearly indicate onshore emplacement.

Keywords. Large igneous province (LIP), Central Atlantic Magmatic Province (CAMP), Pahoehoe flows, Simple flows, High Atlas, Morocco.

1. Introduction

The Central Atlantic Magmatic Province (CAMP) is one of the largest continental flood basalt (CFB) provinces on Earth [Marzoli et al., 1999] (Figure 1a, b). This Large Igneous Province (LIP) extends for more than 7500 km from north to south. It may have covered over 10 million km^2, with a total volume of magma exceeding 3 million km^3 [Marzoli et al., 2018]. The CAMP was emplaced during the early stages of breakup of the Pangean supercontinent that led to the opening of the Central Atlantic Ocean. Pangean intracontinental rifting began in the Late Permian–Early Triassic [El Arabi et al., 2006, Medina, 1995, 2000, Ruellan, 1985, Youbi et al., 2003] and progressed northwards, following the direction of the late Palaeozoic Alleghenian–Hercynian orogenic belt. The oldest identified magnetic anomalies on conjugate margins from the Central Atlantic (ECMA in North America and S1 in Morocco) were initially dated as Middle Jurassic [Klitgord and Schouten, 1987], but later reconstructions of the opening of the Central Atlantic Ocean (e.g. Sahabi et al. 2004) suggest that the age of the earliest oceanic crust is Sinemurian (196.5 to 189.6 Ma). The peak activity of the CAMP straddled the Triassic–Jurassic boundary, at ca. 201 Ma [Blackburn et al., 2013, Davies et al., 2017, Marzoli et al., 1999], and probably lasted less than 1 million years, while the late activity reached the Sinemurian [Marzoli et al., 2018].

CAMP magmatism is represented by extrusive rocks (mostly lava flows and very minor pyroclastics) and remnants of intrusive (layered intrusions, sill complexes and dike structures) (Figure 1b) that occurred in once-contiguous parts of north-western Africa, south-western Europe, North and South America (e.g., De Min et al. 2003, Hames et al. 2003, Knight et al. 2004, McHone and Puffer 2003, Martins et al. 2008, Marzoli et al. 2004, 2019, Tegner et al. 2019, Verati et al. 2007, Youbi et al. 2003). Lava flow sequences are thicker in Morocco and North America (total thickness up to about 300 m and 500 m, respectively; Kontak [2008], Marzoli et al. [2019], Merle et al. [2014]) than in Portugal, and South America (up to 130–170 m, Bertrand et al. [2014], Martins et al. [2008], Merle et al. [2011]). In Algeria, only 10–15 m are preserved in the western Saharan Atlas [Meddah et al., 2017]. Most CAMP rocks are low-Ti tholeiitic Continental Flood Basalts (CFBs), whereas high-Ti CFBs are restricted to a narrow zone in the southern margin of the West African Craton (Liberia, Sierra Leone) and north-eastern South America (Surinam, French Guyana and northern Brazil; e.g., Callegaro et al. [2017], Deckart et al. [2005], Merle et al. [2011]).

In Morocco, CAMP lava flows can be found in all structural domains (Figure 1c) north of the South Atlas Fault. In the Anti-Atlas, the CAMP is represented by intrusions such as the Foum Zguid dike and the Draa sills (e.g., Salvan 1984, Van Houten 1977). The volcanic pile overlies a Late Triassic clastic and evaporitic sedimentary sequence. The total thickness of the Moroccan CAMP lava flow piles ranges normally from 100 to 300 m. However, it may be as thin as

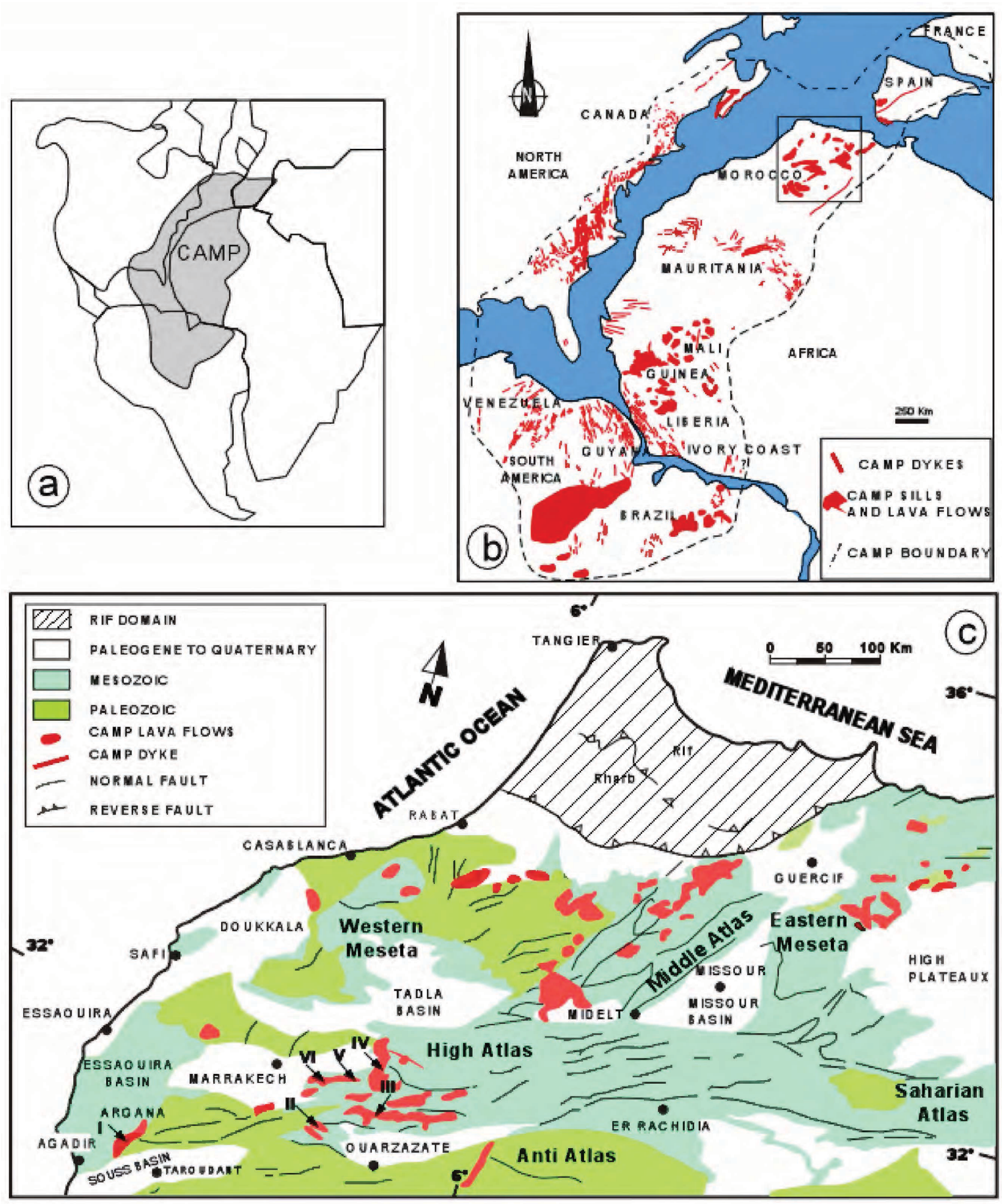

Figure 1. (a) Reconstruction of the Pangea supercontinent at time of CAMP emplacement and schematic extent of the CAMP. (b) Distribution of CAMP lava flows, sills and dikes. The dashed line shows the estimated global surface area of the CAMP. (c) Simplified geological map of the northern part of Morocco showing the distribution of CAMP products and the location of the studied sections: I – Argana (Latitude: 30° 43′ 21″ N; Longitude: 9° 14′ 03″ W); II – Tiourjdal (Latitude: 31° 07′ 74″ N; Longitude: 7° 22′ 70″ W); III – Telouet (Latitude: 31° 15′ 83″ N; Longitude: 7° 17′ 29″ W); IV – Oued Lahr (Latitude: 31° 36′ 45″ N; Longitude: 7° 22′ 53″ W); V – Jbel Imzar (Latitude: 31° 35′ 48″ N; Longitude: 7° 25′ 46″ W); VI – Ait Ourir (Latitude: 31° 32′ 50″ N; Longitude: 7° 40′ 20″ W).

8 m, or even absent on uplifted and eroded interbasin blocks on the interior of the Moroccan Meseta. The difference in thickness from one area to another (from 8 to ca 300 m) can be explained either by dif-

ferential subsidence of a pre-volcanic basement during the emplacement of the lava flows (syn-rift series), or by the emplacement of the flows on an irregular paleotopography related to horst and graben structures. The most-studied area is the Central High Atlas, where the CAMP is best preserved and the most complete basaltic lava piles are exposed. Although the CAMP volcanism is mainly subaerial, subaquatic volcanic products also occur locally in relation with the presence of lakes of probable tectonic origin [El Ghilani et al., 2017].

The main objectives of this paper are: (i) to describe the stratigraphy, morphology and internal structures of the CAMP basalt lava flows of the Triassic–Jurassic basins of Morocco, (ii) to define lava flow emplacement mechanisms, and (iii) to discuss implications on the evolution of the CAMP and other Large Igneous Provinces.

2. Terminology and methodology

Based on their surface morphology and internal structure, basaltic lava flows have been subdivided into pillow, pahoehoe, and aa flows (e.g., Macdonald 1953, 1967, White et al. 2009). Pahoehoe flows are characterised by a smooth, billowy or ropy surface and exhibit a typical three-tiered structure [Aubele et al., 1988], comprising: (i) a basal lava crust; (ii) a lava core; and (iii) an upper lava crust. Aa flows are characterized by angular, spinose clinkers at both the flow top and bottom and tend to be usually thicker when compared to pahoehoe flows. A wide range of intermediate flow types occur between these two end-member types such as rubbly pahoehoe, slab pahoehoe, and toothpaste pahoehoe [Keszthelyi and Thordarson, 2000, Keszthelyi, 2002, Macdonald, 1953, 1967, Rowland and Walker, 1987] . These transitional lavas show some of the characteristics of both aa and pahoehoe lavas. For example, the rubbly pahoehoe has been suggested for a lava type that has a flow top composed of broken pieces of smaller pahoehoe lobes rather than spinose aa clinker [Keszthelyi and Thordarson, 2000].

According to Self et al. [1997, 1998] and Thordarson and Self [1998] the products of an effusive eruption can be subdivided into three hierarchic levels, *flow lobe*, *lava flow*, and *lava flow field*, respectively:

(i) a *flow lobe* is an individual unit of lava enclosed in a chilled crust, varying in length from decimetres to several kilometres and up to 60 m in thickness [Wilmoth and Walker, 1993]. Lobes can be classified in two types: S-type ("spongy") lobes and P-type lobes ("pipe amygdale-bearing") Wilmoth and Walker [1993]. S-type lobes lack pipe vesicles and are vesicular throughout their thickness. P-type lobes are characterized by pipe vesicles and display a typical internal structure with a vesicular base and top, and a relatively vesicle poor core;

(ii) a *lava flow* is a regional subunit formed during a continuous effusive event (during a single eruption), which may consist of several flow lobes. If a lava flow consists of a single flow lobe it is referred to as a *simple lava flow* [Walker, 1971] and if the lobe has a sheet-like or tabular geometry it is classified as a *sheet lobe*; conversely, the term *compound lava flow* [Walker, 1971] describes a lava flow composed of multiple lobes and toes;

(iii) a *lava flow field* is a complex body that may consist of several lava flows and is usually identified on the basis of mineralogy and chemistry (or of stratigraphic criteria) as the product of a single eruption.

We also use the terminology of Fisher [1961, 1966] to describe volcaniclastic (e.g., peperite, hyaloclastite) and epiclastic deposits (e.g., mudstone, siltstone, sandstone, limestone) that has been used by other authors for the description of primary volcaniclastic rocks (e.g., Manville et al. 2009, White and Houghton 2006). Fisher's pioneering classification [Fisher, 1961, 1966] subdivided volcaniclastic rocks into pyroclastic, hyaloclastic, autoclastic and epiclastic classes based on the particle forming processes. Pyroclastic fragments (produced by explosive fragmentation), hyaloclastic (quench fragmentation), and autoclastic (mechanical self-fragmentation) can be applied to both individual grains and their deposits [Fisher and Schmincke, 1984]. Epiclastic is restricted to fragments derived from weathering and erosion of "preexisting rocks", and excludes reworking of particles from non-welded or unconsolidated volcanic materials.

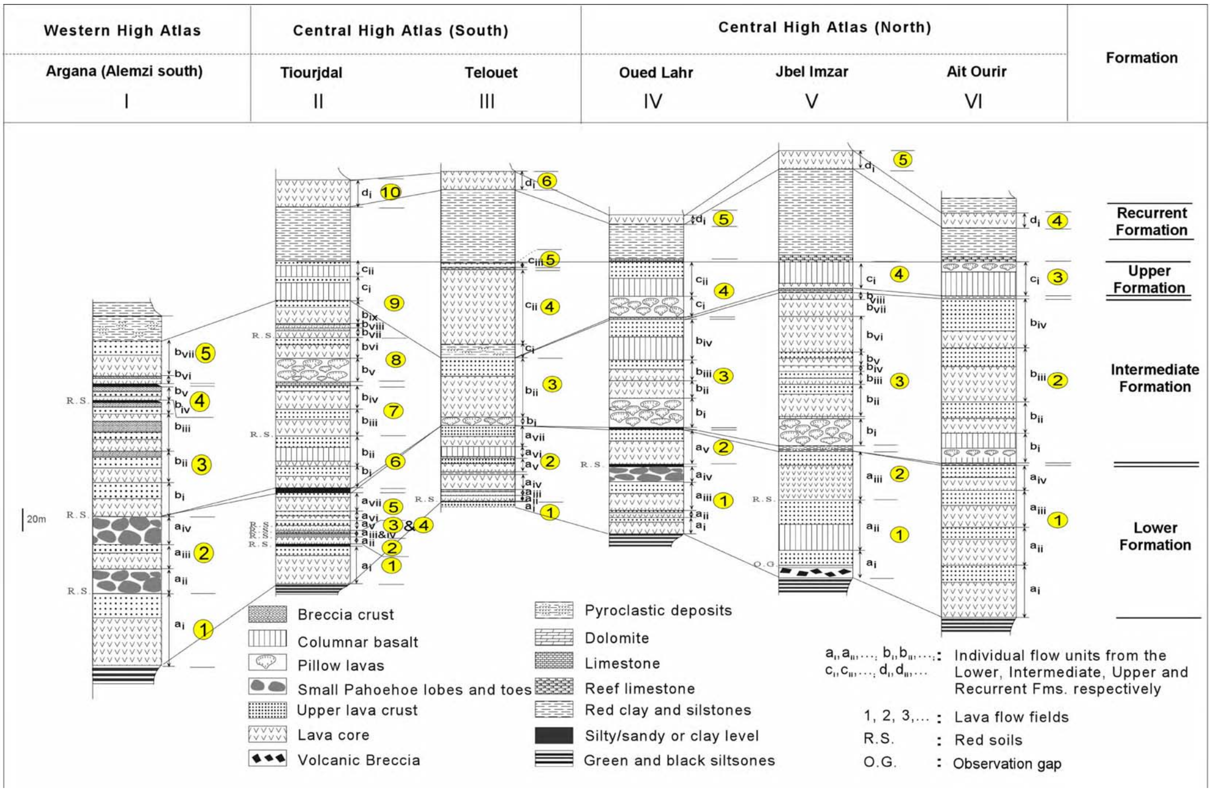

Figure 2. Lithostratigraphic columns across the CAMP volcanic succession of Morocco at the studied sections. See Figure 1 for the location of sections.

Detailed sections were investigated in six areas of the CAMP volcanic piles of Morocco (Figure 1), recording the morphology, internal structure and stratigraphy of the lava flows. The correlation between the studied sections has been performed following our field-work observations and the published petrographic and geochemical data [Bertrand, 1991, Bertrand et al., 1982, Deenen et al., 2010, Knight et al., 2004, Marzoli et al., 2004, 2019, Youbi et al., 2003]. For the first criterion, the correlation was made based on the epiclastic levels separating the different units, which may attest for significant time intervals between volcanic episodes. For the latter, we used the pioneering work of Bertrand et al. [1982] who recognized systematic geochemical changes in the stratigraphy of the Moroccan CAMP lava piles. Indeed, based on major and trace element analyses and on field-work observations, Bertrand et al. [1982] have subdivided the lava piles into four main formations (fms), the Lower, Intermediate, Upper and Recurrent fms (Figure 2). The Lower and Intermediate fms represent about 90% of the preserved lava volume, whereas the Upper and Recurrent fms hardly exceed 10%.

Individual eruptions were identified based on the presence of reddened flow surfaces (slightly weathered surfaces thermally metamorphosed by overlying flows), development of incipient or more or less evolved red and grey soils, or deposition of thin layers of fine epiclastic sediments between lava flows, representing time intervals separating the emplacement of each package of lava flow-units. Individual flow units are identified on the basis of their morphology and internal structure especially the presence of upper/lower crusts, changes in vesiculation, jointing style and volcanic textures. The identification of pahoehoe flow lobes in the field is based on the recognition of a three-partite internal structure, consisting of a basal lava crust, a lava core and an upper lava crust, and absence of a clinker envelope. The subdivision into a three-partite structure considers the variations of three groups of internal features: (i) the vesiculation pattern, which is defined by distribution, mode, shape, size of vesicles and other degassing features (ii) the jointing style which refers to the arrangement and morphology of cooling joints; and (iii) the petrographic texture in terms of crystallinity and crystal size, properties that are controlled by a number of parameters, such as cooling rate, volatile content, and crystal nucleation rate.

3. Results

The six sections were investigated in detail from SW to NE across the volcanic pile cropping out in the northern and southern flanks of the High Atlas Basin (Figures 1, 2). Subaerial lava flows from the Moroccan CAMP can be grouped into two main categories: compound pahoehoe flows and simple flows. The former type is exclusively confined to the Lower and Intermediate fms while only simple flows occur in the Upper and Recurrent fms. According to Keszthelyi's (2002) classification, some transitional types between pahoehoe compound flows and aa flows, such as "rubbly pahoehoe flows", have also been observed in the Western High Atlas CAMP sequences of Morocco (e.g., Argana Basin; El Hachimi et al. 2011). Besides the subaerial flows, pillow lavas, displaying radial jointing and glassy rinds, subaquatic sheet flows and hyaloclastites are frequently found in the lower part of the Intermediate and Upper fms. In the following sections, we describe the characteristics of the volcanic lava piles for each formation at the studied areas.

3.1. *Lower formation*

The base of the Lower Formation (Fm) is usually sharp and overlies a 2 to 10 cm-thick pale grey to black silty-sandy soil or a slightly to strongly weathered surface at the top of a thick red clay-to-sand sedimentary sequence (Figure 3A) dated as Rhaetian by Panfili et al. [2019]. In the Tiourjdal section, the basalt–sediment contact is characterized by "injections" of basalt into the underlying sediment ("load casts"; Dal Corso et al. 2014, Marzoli et al. 2004). These load casts form as a result of the rapid deposition of basalt onto a water-saturated sediment and indicate that the underlying deposits were still soft or only slightly consolidated at the time of emplacement of the volcanic rock, further suggesting that the first lava flows were almost contemporaneous with the deposition of the Upper Triassic sediments. In this case, water would have played an important role by quickly cooling the basalt and reducing its thermal effect on the sediment. Furthermore, in the Oued Lahr section, the basalt–sediment contact is characterized by a volcanic breccia, typical of the base of pahoehoe-like lava flows [Self et al., 1997], which has acted as an insulator between basalt and sediment.

The Lower Fm is a 55 to 173 m-thick succession composed of 3 to 7 individual flows resulting from 1 to 5 eruptions (Figures 2, 3B). It makes up to c. 30–50% of the total preserved lava thickness in the Central and Western High Atlas. These basaltic lava flows show external and internal features typical of inflated pahoehoe flows such as a three-tiered structure with vesicle zonation, presence of tumuli, and grain size variations. They display morphological characteristics similar to those described for inflated pahoehoe flows in other CFB provinces [Aubele et al., 1988, El Hachimi et al., 2011, Kontak, 2008, Self et al., 1997, 1998, Thordarson and Self, 1998, Waichel et al., 2006].

Pahoehoe lava flows of the Lower Fm are of the compound type, 2 to 40 m thick, composed of several stacked lava lobes (Figure 3C, D). The lateral extent of the flows usually exceeds hundreds of meters. As described in Aubele et al. [1988], Thordarson and Self [1998], and Self et al. [1998], lava flows of the Lower Fm display a three-tiered structure with (i) a thin "basal lava crust" which is vesicular, often with pipe vesicles (Figure 3E), (ii) a dense "lava core" usually not vesiculated or presenting few cm-sized spherical or irregular vesicles, and (iii) an "upper lava crust" showing increased vesicularity towards the top and horizontal vesicle concentration zones. This "three-tiered structure" is a clear evidence of endogenous growth by inflation, suggesting a slow emplacement during sustained eruptive episodes.

In the Central High Atlas, epiclastic sediments intercalated in the volcanic sequence are clearly baked by the overlying lavas. An example can be observed at Oued Lahr, where lava flows contain injections of red sediment ("clastic dikes" and "sills" of baked red silt; Figure 3F). The clastic dikes rise from the base of the lavas without reaching the top of the flows and, in some cases, display upward flow structures and, thus, they cannot be interpreted as the filling of fractures from above. This magma/sediment mingling can be interpreted as a peperite (see Skilling et al. 2002 for

Plate 1

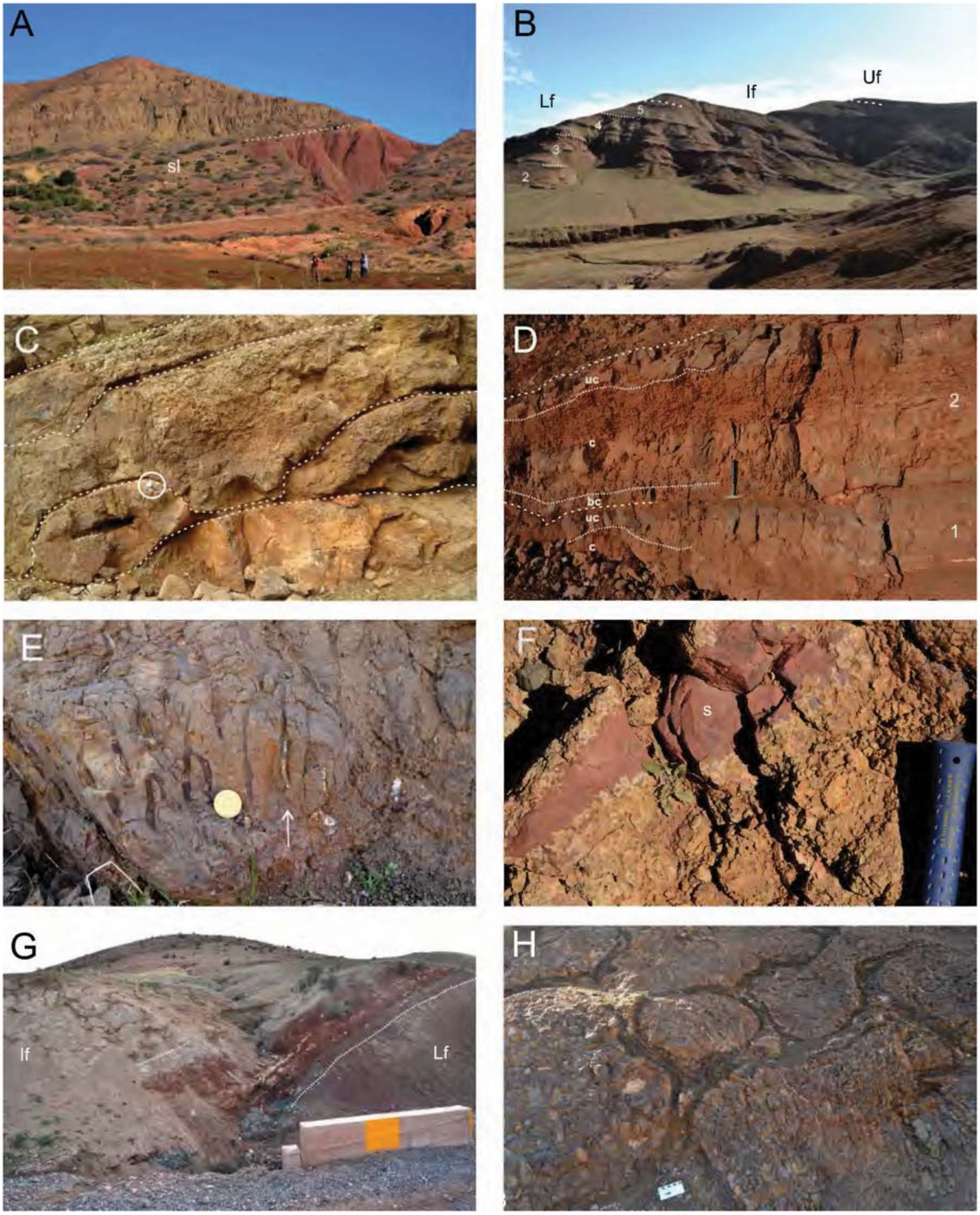

Figure 3. A-H (see captions below).

Plate 2

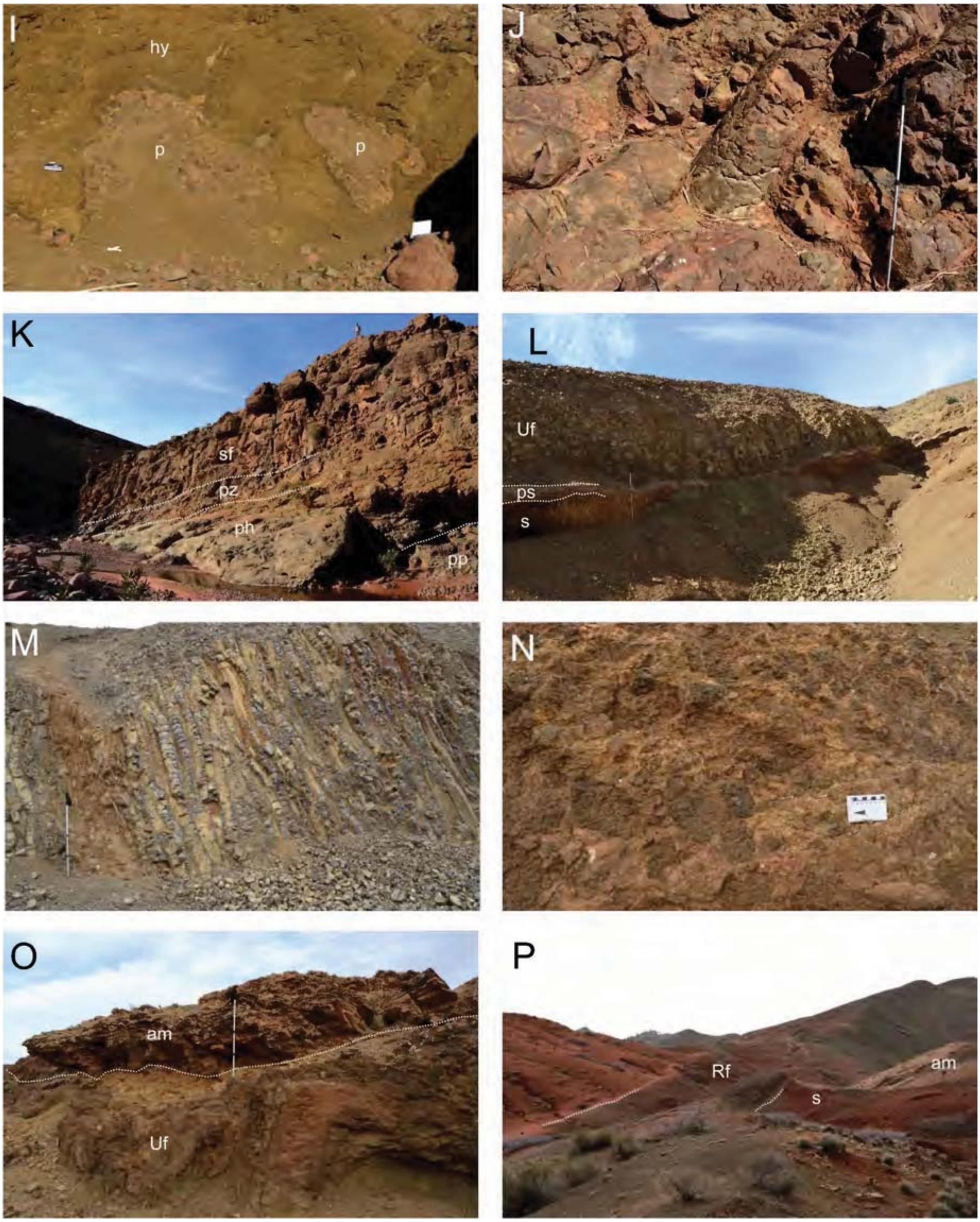

Figure 3. I-P (see captions below).

Figure 3. Field photographs illustrating some of the most characteristic aspects of the Moroccan CAMP volcanic sequences: (A) Contact (dotted white line) between the Lower Fm. lava pile and the underlying Rhaetian red silts at the Oued Lahr section. The top of the sediments is a pale grey layer. The central part of the lower half of the slope is slumped (sl). (B) General view looking SE of the Ait Ourir section. The contacts between the Lower (Lf), Intermediate (If), and Upper (Uf) formations are marked by dashed white lines. In the Lower Fm. successive lava flows (numbers and dotted white lines) are separated by reddened surfaces (the lowermost lava flow 1, is not visible in the photograph). (C) Aspect of a compound lava flow of the Lower Fm. at the Oued Lahr section, corresponding to a pile of superposed thin pahoehoe toes (highlighted by dashed white lines). Wrist watch for scale encircled. (D) Compound lava flow of the Lower Fm. lava sequence at the Oued Lahr section, composed of several superposed pahoehoe lobes (two of which – 1, 2 – are shown separated by dashed white lines) presenting chilled dense basal (bc) and upper (uc) crusts enveloping a variably vesiculated lava core (c) (contacts highlighted by dotted white lines). Hammer for scale. (E) Pipe vesicles perpendicular to the base of a subaerial pahoehoe lava flow from the Lower Fm. from the Ait Ourir section. Pipes start about 4–5 cm above the base and extend upwards some 25 cm. Coin as scale is 2.7 cm in diameter. (F) Red silt lens injected into the core of an inflated pahoehoe flow from the Lower Fm. at the Oued Lahr section. Note the peperitic interaction at the edge of the injected sediment, meaning that the lava core was still partially molten, although the sharp contacts of the feeder sediment dike (not shown) suggest that the base of the lava was already brittle when the sediment injection occurred. Hammer handle for scale. (G) Sedimentary sequence separating the Lower (Lf) and Intermediate (If) formations at the Sidi-Rahal section. The 3 m-thick sediments include, from base to top, grey, green and red mudstones, red sandstones, red mudstones, limestones, red sandstones, red and light-grey mudstones. The volcanic rocks are extremely weathered, but the densely packed pillows of the Intermediate Fm. above the sediments are clearly defined by their darker glassy rind. (H) Weathered densely packed pillow of the base of the subaquatic lava flow from the base of the Intermediate Fm. at the Ait Ourir section. The pillows present cm-thick glassy rinds, and the few spaces between them are filled by hyaloclastite. Ruler as scale is 8 cm-long. (I) The same lava flow of photo H passes upwards into hyaloclastites (hy) with dispersed large pillows (p). Note frequent invaginations of the glassy rind of the pillows. Field book at the left is 16 cm long. (J) Aspect of densely packed, well-preserved pillows, from the base of a partially subaquatic lava flow from the base of the Intermediate Fm. at the Oued Lahr section. The pillows can be seen in three dimensions with some of them exposed in longitudinal view and others in transversal section. Once removed the ~15° northwards tilt of the whole sequence, the pillows still dip 30°–45° to the north, thus suggesting a northwards prograding lava delta. Walking stick for scale is 1.3 m long. (K) General view of the same lava flow dipping ~15° to the north: the lava flow is composed of densely packed pillows (pp) at the base (shown in photo J), followed by isolated pillows in hyaloclastite (ph), a transition zone of mixed subaquatic-subaerial facies (pz), and the 8 m-thick upper, columnar-jointed, subaerial part of the lava flow (sf). The thickness of the subaquatic part of the flow (25–30 m) corresponds to the depth of the lake. The underlying Lf lavas are subaerial and the two units are separated by a thin discontinuous red clay layer. Dotted white lines mark the transition between different zones of the flow. Shephard and flock on top of the cliff give scale. L. Sediments (s) and paleosoil (ps) separating the Intermediate (If) and Upper (Uf) formations at the Ait Ourir section. The base of the Uf corresponds to a subaquatic sheet flow presenting well-developed columnar jointing (see also photo M). Walking stick for scale is 1.3 m long. (M) Subaquatic sheet flow from the base of the Upper Fm. at the Ait Ourir section displaying typical thin undulating columns. Walking stick for scale is 1.3 m long. (N) Outcrop of pillow breccia in a matrix of hyaloclastites from the top of the uppermost lava flow of the Upper Fm. (Ait Ourir section). Ruler for scale is 8 cm long. (O) Top of the Upper Fm. (Uf) at the Ait Ourir section, overlain by a 2 m-thick algal mat limestone (am). The upper part of the Uf sequence at this location corresponds to hyaloclastites with intrusive pillows and pillow breccias. Walking stick for scale is 1.3 m long; (P) South (left) dipping upper part of the Ait Ourir volcanic sequence composed of algal mat limestones (am), red silty mudstones (s), the 5 m-thick simple flow of the Recurrent Fm. (Rf), which is covered by several meters of red silty mudstones.

more details). These occurrences indicate the interaction between lava flows and unlithified wet sediments (clay to sand), suggesting that volcanism and sedimentation were coeval (see Skilling et al. 2002). Thus, peperites observed in the lava flows of the Lower Fm show that the underlying or intercalated red siltites were still soft or poorly consolidated when the lava flows were emplaced. Similar structures have been observed in the Argana basin (Western High Atlas; El Hachimi et al. 2011) and in the Algarve (Portugal) CAMP sequences [Martins et al., 2008]. They have also been described at the base of a large pahoehoe lobe in the Western Ghats of the Deccan Volcanic Province [Duraiswami et al., 2003], in the Neo-Proterozoic volcanic sequence of the Anti-Atlas (in lava flows and ignimbrites), and, even in carbonatitic tuffs in ocean island volcanoes (e.g. Santiago, in Cape Verde) (J. Madeira unpublished data). Thus, although their genesis is not yet fully understood, these sedimentary intrusions seem to be relatively common features.

Coalescence of lobes and toes is another relatively common feature often found at the top of some compound pahoehoe flows from the Oued Lahr and Argana sections. The smallest lobes are sometimes elongated lenses trending NE-SW. The glassy contacts between lobes are often thermally oxidized. P-type lobes are more frequent than S-type lobes.

Tumuli and breakout structures characteristic of the compound pahoehoe flow type have been observed at three of the studied localities: Tiourjdal section in the southern Central High Atlas, the Argana section in the western High Atlas and the Ait Ourir section in the northern Central High Atlas (Figure 1C). Tumuli are found within pahoehoe lava flow fields containing multiple lobes and flows. The flows are often up to 5 m thick, and show the classic internal three-tiered structure described above. In the Tiourjdal area, the upper crust of the lower lava flow is marked by a thick squeeze-up, which is 70 cm wide, oriented N50, and that can be followed horizontally over 20 m. Its length suggests that it may have been extruded through an axial cleft of a pressure ridge. The squeeze-up contains vesicles that increase in size inwards. It presents a chilled margin indicating the contact with the colder upper crust of the host lava flow. In the Argana basin, some pahoehoe lava flows display thick squeeze-ups breaking through the upper crust and sometimes forming small pahoehoe toes on top of the feeder lava flow (see El Hachimi et al. 2011 for details).

At the Ait Ourir section, fault planes offset the basal compound pahoehoe flows but are fossilized by the overlying flows, indicating the occurrence of synvolcanic extensional tectonics.

3.2. *Intermediate formation*

The Lower and Intermediate fms are separated by silt-to-sand sediments of variable thicknesses, locally also including limestones (Figure 3G), or by 0.15 to 2 m-thick red paleosoils. The paleosoils are structureless (sometimes faintly bedded, suggesting a pedogenized sedimentary nature) and usually contain rounded volcanic clasts embedded in a clay to silty matrix. The Intermediate Fm is up to 130 m-thick, and is composed of 2 to 9 flows corresponding to up to 4 eruptions. Lava flows present typical pahoehoe features (cf. Cas and Wright 1987, Francis and Oppenheimer 2004, Macdonald 1967, 1972, Self et al. 1998, Wilmoth and Walker 1993). They are almost always compound in nature [Walker, 1971]. Pahoehoe lava flows display the three-tiered structure previously described. Each lava flow is defined by chilled tops and bottoms and the boundaries of the internal sub-divisions are clearly defined by marked changes in the vesiculation pattern, jointing style, and petrographic texture [Thordarson and Self, 1998]. Segregation structures, characteristic of the compound pahoehoe flows type, such as pipes vesicles, cylinder vesicles [Goff, 1996], and horizontal vesicular sheets [Thordarson and Self, 1998] are common. Sometimes, the pipe axes are inclined, thus recording the lava movement and are reliable markers of the flow direction (e.g., Walker 1987). Walker [1987] relates the pipe vesicles to the rise of bubbles through the lower part of cooling lava flow when it has acquired yield strength of the order of 50 $N{\cdot}m^2$, and a flow rate equivalent or smaller than the rate of bubble rise, a condition that is favoured by lava flowing on very low angle slopes. Vesicle cylinders are observed in the core of compound pahoehoe flows. They are almost always rootless and not connected with the pipe vesicles in the basal crust. Cylinders in thick lobes can be up to 0.50 m long. They are sometimes connected with vesicle sheets. Horizontal vesicular sheets occur near the interface between the upper crust and the core. The sheets thickness is 10 cm in average, but can reach up to 30 cm. The vesicle sheets display irregular shapes and branching patterns, which suggests that they have filled joints that formed at the early stages of cooling. In the Tiourjdal section (southern Central High Atlas), compound pahoehoe flows are composed of coalescing well-defined toes producing irregular upper surfaces of the flow field.

The lower flows of the Intermediate Fm often present subaquatic facies represented by densely packed pillows (Figure 3H), pillows in a hyaloclastite matrix (Figure 3I), and subaquatic sheet flows. Pillow-lavas vary in diameter from 10 cm to 2.5 m. The internal structure of the basaltic pillows is characterized by two concentric layers: an outer cortex and the core. The cortex corresponds to a 0.1 to 14 cm thick glassy envelope. At the Oued Lahr section, the first lava flow of the Intermediate Fm entered an approximately 25–30 m-deep lake, as suggested by the thickness between the transition zone (separating the subaquatic and subaerial facies) and the base of the flow (see Ramalho et al. 2010, 2017 for examples of the use of this type of markers). It corresponds to a lava delta consisting of prograding foresets of pillow lavas and hyaloclastites passing upwards into an 8 m-thick subaerial pahoehoe flow (Figure 3J, K). Pillow lavas from this section present horizontal and vertical diameters ranging from 0.2 to 1.6 m and 0.18 to 1.18 m, respectively. At other locations, where the transition zone is not exposed or the sequence is entirely composed of subaquatic volcanics, only a minimum water depth can be determined.

In some areas of the Central High Atlas, the subaerial lava flows of the Intermediate Fm show well-developed columnar jointing. In one outcrop from the Tiourjdal section a 15 m-thick lava flow displays radial jointing in its lower half, indicating that the lava entered a 6–7 m deep body of water (river, lake?).

In the Tiourjdal section, the Intermediate Fm is marked by the presence of thin layers of lacustrine limestone (~1 m thick) interbedded within the volcanic sequence.

3.3. *Upper formation*

The Upper Fm sequence is 15 to 76 m thick, representing a volume of 5 to 8% of the preserved lava piles. It is separated from the uppermost flows of the Intermediate Fm by a thin level (0.5 to 1 m) of red to greyish siltstones, laminated limestones, or red-green mottled paleosoils (Figure 3L). The Upper Fm is composed of one or two lava flows representing one or two eruptions.

The subaerial lava flows of the Upper Fm usually display well-developed prismatic jointing, sometimes corresponding to laterally extensive simple flows, usually ranging in thickness from 5 to 30 m. The thickest simple flow (~40 m) is observed in the Telouet section. Simple flows are clearly separated from underlying flows by weathering surfaces or paleosoils several centimetres thick. They appear as dense and massive flows, but can be subdivided, as compound pahoehoe flows, into a three-tiered structure [Aubele et al., 1988, El Hachimi et al., 2011, Thordarson and Self, 1998] with a thin basal crust, a dense lava core and an upper crust, indicating thickening by inflation. The lower crust of the simple flows is 0.25 to 0.5 m thick, representing 2 to 3% of the total thickness of the flow. Although vesicles may be numerous, pipe vesicles were not observed. The lava core is the thickest part of the flow, up to 30 m in the Telouet section. It usually appears as a poorly vesiculated zone with respect to the upper crust. The upper crusts are 4–20 m thick and strongly vesiculated. Lobes, layering of vesicle-poor ("dense") and vesicle-rich ("vesicular") bands, tumuli and squeeze-up structures which are characteristic of the compound pahoehoe flows type have not been observed within the upper crust of these simple flows.

Subaquatic flows also occur at the base of the unit where they may reach 4 to 20 m in thickness. At the Ait Ourir section, the facies of subaquatic flows varies laterally or vertically from sheet flows, presenting thin, undulating columnar jointing (10 to 15 cm in diameter; Figure 3M), to pillow lavas intruded into hyaloclastite, or pillow breccias (Figure 3N).

In the Telouet section (Central High Atlas), the lowermost lava flow of the Upper Fm displays injections of brownish red siltstone forming irregular sedimentary bodies (4 cm–1 m long) randomly dispersed in the core of the lava flow, indicating peperitic interaction.

3.4. *Recurrent formation*

The Recurrent Fm is limited to the Central High Atlas lava piles and is absent in the Argana basin. It is separated from the Upper Fm by a sedimentary unit which may reach 80 m such as in the south flank of the Central High Atlas. The sediments are composed of red silty-mudstones, locally overlying algal mat limestones (Figure 3O, P). The base of the Recurrent Fm lava flow frequently displays load casts into the underlying mudstones, indicating that the sediments were still soft.

The Recurrent Fm is the result of a single eruption and is composed of a 5–50 m thick simple lava flow. This lava flow has a dense and massive texture. Segregation structures characteristic of compound pahoehoe flows such as pipe vesicles, cylinder vesicles and vesicular sheet are absent.

This late unit represents a small volume eruption (<5% of the CAMP total). The Recurrent Fm is covered by Early Jurassic silt-to-clay and carbonated sediments and it is found only in the northern and southern flanks of Central High Atlas basins. A similar formation has been described from the Newark and Hartford basins in North America [Olsen et al., 2003], but was not found in Iberia.

4. Discussion: *emplacement mechanisms of the CAMP lava flows of Morocco*

Once considered to be composed by monotonous stacks of basaltic lava, continental flood basalt (CFB) provinces are now known to display considerable diversity in lava flow morphology. Whereas most initial studies of flood basalt morphology and emplacement focused on younger provinces such as the Miocene Columbia River Basalt (e.g., Self et al. 1996, Thordarson and Self 1998), subsequent investigations targeted older provinces such as the ca. 201 Ma Central Atlantic Magmatic Province (CAMP, e.g., El Hachimi et al. 2011, Kontak 2008, Martins et al. 2008), the ca. 132 Ma Paraná-Etendeka [Jerram et al., 999a,b, Rossetti et al., 2014, Waichel et al., 2006, 2012], and the ca. 66 Ma Deccan Volcanic Province (DVP, e.g., Bondre et al. 004a,b, Duraiswami et al. 2001, 2003, 2014, Keszthelyi et al. 1999, Sheth 2006, Sheth et al. 2011). The morphology of lava flow lobes in CFB provinces can help understanding the mechanisms involved in their emplacement as shown by Self et al. [1997].

The CAMP lava flows of Morocco show clear evidence of endogenous growth or inflation in the sense of Self et al. [1997, 1998]. The features indicating endogenous growth are: (i) the three-partite structural division of sheet lobes in a thin basal crust, a dense lava core, and a vesicular upper crust, which, when thick, tends to show layering of alternating massive and vesicular levels; (ii) the vertical distribution of vesicles and the presence of segregation structures such as spherical vesicles, pipe vesicles, vesicle cylinders and vesicle sheets, and (iii) the occurrence of tumuli and squeeze-ups. In this sense, they are similar to other inflated pahoehoe flows found in Hawaii [Hon et al., 1994], Columbia River Basalt Province [Thordarson and Self, 1998], in the Cenozoic volcanic Province of North Queensland in Australia [Whitehead and Stephenson, 1998], Deccan Traps [Bondre et al., 004a,b, Keszthelyi et al., 1999, Jay and Widdowson, 2008], Paraná-Etendeka CFB [Jerram et al., 999a,b, Waichel et al., 2006], the CAMP flows of the Fundy basin, Canada [Kontak, 2008], and the CAMP basins of Argana [El Hachimi et al., 2011], Berrechid and Doukkala, Morocco [Bensalah et al., 2011], and Algarve, Portugal [Martins et al., 2008]. The predominance of P-type lobes in compound flows can be related to breakouts emerged from larger inflated sheet flows [Hon et al., 1994, 2003]. According to Wilmoth and Walker [1993], these lobes can be found almost anywhere in the pahoehoe flow field, but are more common in areas with shallow slopes (<4°). Lava flows with subaquatic facies represent subaerial lavas that flowed into ponds or lakes occupying depressions on the pre-volcanic topography. Most of these depressions probably correspond to asymmetric graben structures, as suggested by the occurrence of syn-volcanic tectonism, common in Morocco. At odds with what is stated by Mattis [1977] and Lorenz [1988], the presence of subaquatic lava flows does not require a widespread subaquatic environment at the time of eruption. Indeed, the limited lateral continuity of pillow lavas and their almost constant stratigraphic position, the existence of lava flows with subaerial characteristics associated to sediments containing fossilized wood, clearly support a generally subaerial emplacement of CAMP basalts. These subaquatic volcanic sequences can also be used to determine the depth (or minimum depth) of these water bodies, based on the thickness of the subaquatic portion of the lava flow, and suggest that these lakes could be as deep as 20 m and, probably, were not temporary ponds.

The emplacement of the CAMP occurred in an extensional tectonic setting, related to the break-up of the megacontinent Pangea and subsequent opening of the Central Atlantic Ocean [Sahabi et al., 2004, Labails et al., 2010, Marzoli et al., 2017]. The magmatic activity was syn-to slightly post-extensional, with lava flows emplaced in progressively subsiding grabens or sealing them [Hafid, 2006, Marzoli et al., 2019]. Thordarson and Self [1998] show that the emplacement of the Roza lavas (Colombia River Basalt Province) was produced by one long single eruption. In contrast to this, the morphologic, textural and stratigraphic features of the Moroccan CAMP volcanic pile favour an emplacement during several sustained eruptions. Significant time breaks within the volcanic sequence are marked by the presence of red oxidized surfaces, paleosoils between pahoehoe compound and simple flows produced by individual eruptions within each formation, or by the presence of epiclastic sedimentary sequences separating the four classical formations. These imply significant volcanic quiescence periods between the emplacement of successive simple lava flows or flow fields. According to Marzoli et al. [2019], Lower to Upper CAMP flows in Morocco were erupted in four pulses each lasting about 400 years [Font et al., 2011, Knight et al., 2004], with an eruption rate during the pulses of 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 and Self, 1993].

Based on the physical volcanology, the comparison of the CAMP basaltic succession in Morocco with the Deccan volcanic Province (India), Paraná (Brazil), Columbia River Basalt Province (USA) and other CFBs indicates that these Large Igneous Provinces (LIP) do not have a simple, "layer-cake stratigraphy", but present complex architectures. Such architectures are governed by the volume of individual eruption events, the location and abundance of volcanic centers, and the evolution of these centers through time [Jerram, 2002, Jerram and Widdowson, 2005, White et al., 2009]. The architecture of the Moroccan CAMP and of most, if not all, CFB provinces reveals that the production of compound pahoehoe flows was followed by flows with a simpler sheet-like geometry, indicating a fundamental temporal change in the emplacement process of lava flows. Accordingly, it appears that flood basalt volcanism starts by sustained eruptions with relatively low effusion rates [Jerram, 2002, Walker, 1971], and gradually accelerates to high effusion rates leading to high-volume but short-lived eruptions [Shaw and Swanson, 1970, Walker, 1971]. This worldwide similarity suggests that the magma genesis and/or magma ascension processes are essentially similar in all CFB provinces [Duraiswami et al., 2014, El Hachimi et al., 2011, Jerram, 2002, Jerram and Widdowson, 2005, Jerram et al., 999a,b, Martins et al., 2008, Planke et al., 2000, Rossetti et al., 2014, Waichel et al., 2012, White et al., 2009], although local conditions (such as regional topography, surface and underground water availability) may constrain the details of the internal architecture of each province [El Ghilani et al., 2017, Luchetti et al., 2014].

5. Summary and conclusions

The data presented here indicate that the CAMP volcanic pile of Morocco formed during four phases of geochemically distinct volcanic activity, represented by the Lower, Intermediate, Upper and Recurrent fms. Epiclastic sediments, intercalated or separating the Lower, Intermediate and Upper fms are rare and usually thin.

The studied sections display evidence for a variable number of eruptions in each formation (1 to 5 eruptions in the Lower Fm, 1 to 3 eruptions in the Intermediate Fm, 1 or 2 eruptions in the Upper Fm, and a single eruption in the Recurrent Fm). The products of the distinct eruptions can be separated by the presence of reddened top surfaces, development of incipient or more evolved soils, or deposition of thin layers of fine epiclastic sediments, representing time intervals separating the emplacement of each package of lava flows.

Except for the Recurrent Fm, each of the remaining formations shows thick successions of individual flows. The older formations (Lower and Intermediate fms) are composed of compound pahoehoe flows that display the entire range of pahoehoe morphology including inflated lobes, the three-partite structure of sheet lobes, vertical distribution of vesicles, presence of segregation structures and tumuli structures, while the younger formations (Upper and Recurrent fms) are constituted by simple flows forming extensive thick sheets capped by highly vesicular, weathered crusts, or flow-top breccias, and exhibiting a three-tiered structure. Pillow lavas are common in the Intermediate fm. throughout Morocco, but are absent or rarer in the other units.

The architecture of most, if not all, CFB provinces reveals that the production of compound pahoehoe flows was followed by flows with a simpler sheet-like geometry indicating a fundamental temporal change in the emplacement of flows. Accordingly, the morphology of CAMP lava volcanic sequence of Morocco suggests an increase in effusion rate of eruptions from the first to the last pulse of volcanism.

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