

# Environmental implication of subaqueous lava flows from a continental Large Igneous Province: Examples from the Moroccan Central Atlantic Magmatic Province (CAMP)



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## ABSTRACT

The Late Triassic–Early Jurassic volcanic sequence of the Central Atlantic Magmatic Province (CAMP) of Morocco is classically subdivided into four stratigraphic units: the Lower, Middle, Upper and Recurrent Formations separated by intercalated sediments deposited during short hiatuses in volcanic activity. Although corresponding to a Large Igneous Province formed in continental environment, it contains subaqueous lava flows, including dominant pillowed flows but also occasional sheet flows. We present a study of the morphology, structure and morphometry of subaqueous lava flows from three sections located at the Marrakech High-Atlas (regions of Ait-Ouir, Jbel Imzar and Oued Lhar-Herissane), as well as an analysis of the sediments, in order to characterize them and to understand their environmental meaning.

The analysis of clays by the diffraction method X-ray revealed the presence of illite, mica, phengite, celadonite, talc and small amounts of quartz, hematite, calcite and feldspar, as well as two pairs of interbedded irregular (chlorite Smectite/chlorite-Mica). Fibrous minerals such as sepiolite and palygorskite were not detected.

The peperite of Herissane region (Central High Atlas) provided an excellent overview on the factors favoring the magma-sediment interaction. These are the products of a mixture of unconsolidated or poorly consolidated sediments, low permeability with a low viscosity magma. The attempt of dating palynology proved unfortunately without results.

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## 1. Introduction

Earth history is punctuated with occasional emissions of large volumes of basaltic magma, termed to Large Igneous Provinces (LIP's), (Sheth Hetu, 2007; Coffin and Eldholm, 1994; Ernst and Buchan, 2001; Bryan and Ernst, 2007). They have induced drastic climate changes and mass extinctions. One of the largest LIP is the Central Atlantic Magmatic Province (CAMP), which was emplaced around 201 My ago, during the initial stages of Pangea supercontinent break-up that gave rise to the Central Atlantic opening (Olsen et al., 2004; Marzoli et al., 2004).

Although corresponding to a continental volcanic event, CAMP volcanism presents evidence for interaction of the eruptive activity with water (e.g., Manspeizer, 1980; Olsen et al., 2003). In southern Portugal this interaction is mostly the result of subterranean water leading to an abundance of phreato-magmatic pyroclastic deposits (Martins et al., 2008). These are absent in Morocco, but in the other hand there are frequent examples of subaqueous lava morphologies that include pillow lavas (Foye, 1924; Olsen et al., 2005; Greenberger et al., 2015) and subaquatic sheet flows indicating the presence of sufficiently deep surface water bodies into which the lavas flowed (Youbi et al., 2003). The present work aims at contributing to the physical and environmental characterization of the CAMP subaqueous basaltic successions of the Marrakech High-Atlas regions of Ait-Ouir (N31 32 59.2 & W7 40 2.26), Jbel Imzar (N31 35 46.9 & W7 25 49.3), and Oued Lhar-Herissane (N31 36 44.7

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& W7 22 48.8). These areas exhibit some of the best exposed pillow-lavas and volcano-sedimentary successions in Morocco, which contribute to characterize the paleo-environmental conditions prevalent at this area of Pangea during the volcanic activity.

## 2. Geodynamic and geological setting

Intracontinental rifting, leading to Pangea break-up and Central Atlantic opening, initiated during latest Permian-earliest Triassic times and propagated northward along the trend of the Variscan orogen (Ruellan, 1985; Ruellan et al., 1985; Medina, 1995, 2000; El Arabi et al., 2006). Pangea rifting was accompanied by CAMP extrusion (Marzoli et al., 1999) a LIP mostly composed of low-titanium tholeiitic basalts. CAMP magmatism is represented by the remains of intrusive rocks (crustal underplating, layered intrusions, sills and dykes) and less abundant extrusive rocks, mostly lava flows but also pyroclastic deposits (Youbi et al., 2003; Martins et al., 2008; Kontak Daniel, 2008). The CAMP is associated with the fragmentation of pangea (Alibert, 1985; Pegram, 1990; Bertrand, 1991; Sebai et al., 1991; Deckart et al., 1997; McHone, 2000; Hames et al., 2000; Cebria et al., 2003; De Min et al., 2003). It is genetically linked with the activity of a thermally and chemically anomalous mantle plume or “super-plume”, and with the initiation and production of a new oceanic crust during the Jurassic (Oyarzun et al., 1997; Wilson, 1997; Tompson, 1998; Janney and Castillo, 2001; Ernst and Bleeker, 2010).

The areas now studied are located within the Mesozoic (Triassic–Jurassic) outcrops from the High-Atlas, some 60 km SE of Marrakech. In this region the CAMP formations are represented by

successions of basaltic lava flows including well preserved pillow lavas (Fig. 1).

The lava flow sequences of the Moroccan CAMP are classically subdivided into four formations based on field and geochemical criteria. The presence of intercalated sediments within the volcanic succession marks the occurrence of short hiatus (De Pachtere, 1983) in volcanic activity and allows an easy field separation of the four formations that correspond to four volcanic stages whose products are included in the Lower, Middle, Upper and Recurrent Formations, respectively (De Pachtere, 1983) (Fig. 2). They correspond to four lava flow fields, each composed of lava flows from several eruptions, with the flow fields separated by red shales, silts, paleosols or carbonated sediments (Fig. 3D). Most flows are subaerial corresponding to simple or composite pahoehoe (El Hachimi et al., 2011). However, in the Middle and Upper Formations subaqueous lava flows are common (De Pachtere, 1983). These correspond to pillow lava piles or to sheet flows presenting characteristic thin undulating columnar jointing.

The field analysis of these volcanic sequences in the High-Atlas of Marrakesh (Aït-Ouir, Jbel Imzar and Oued Lhar – Herrissane; Figs. 1 and 2), the morphology, the internal structure of the basaltic flows, and the presence of reddened surfaces marking the separation of lava flows allow describing the composition of each of the four formations. The Lower Formation is composed of 3–6 composite pahoehoe flows (Fig. 3B), occasionally presenting a brecciated base; the Middle Formation is composed of 4–8 lava flows, including pillow lavas (Fig. 3A–J–H), columnar jointed subaqueous flows (Fig. 3C) and composite pahoehoe flows; the Upper Formation is formed by 1–5 lava flows, including pillow lavas, columnar

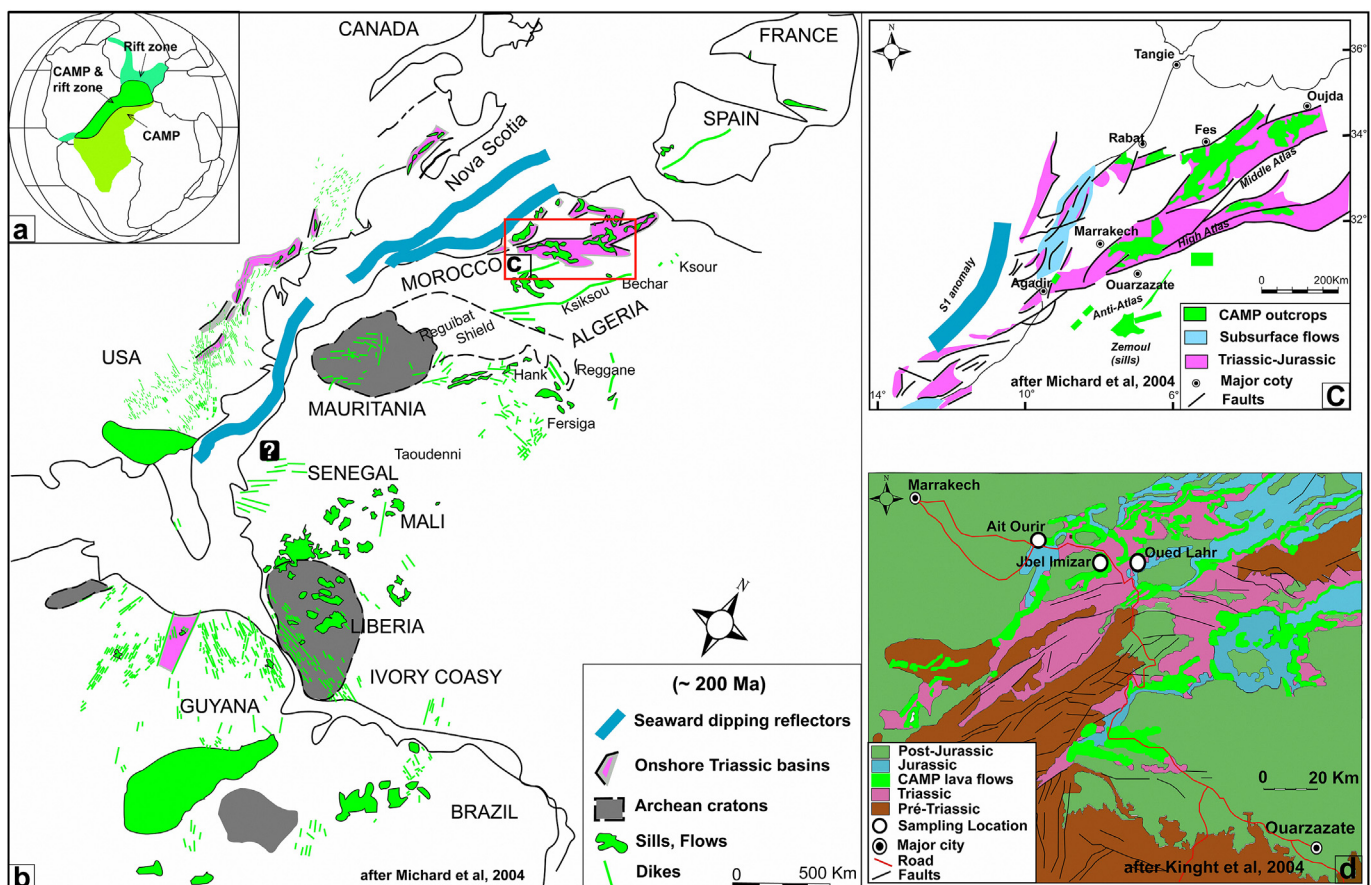


Fig. 1. Location and geological setting of the study area (Knight et al., 2004): a, b. Pangea reconstruction and distribution of CAMP products in North America, South America, Europe and North Africa; c. simplified geology of North Morocco; d. geology of the region SE of Marrakech and location of the studied outcrops.

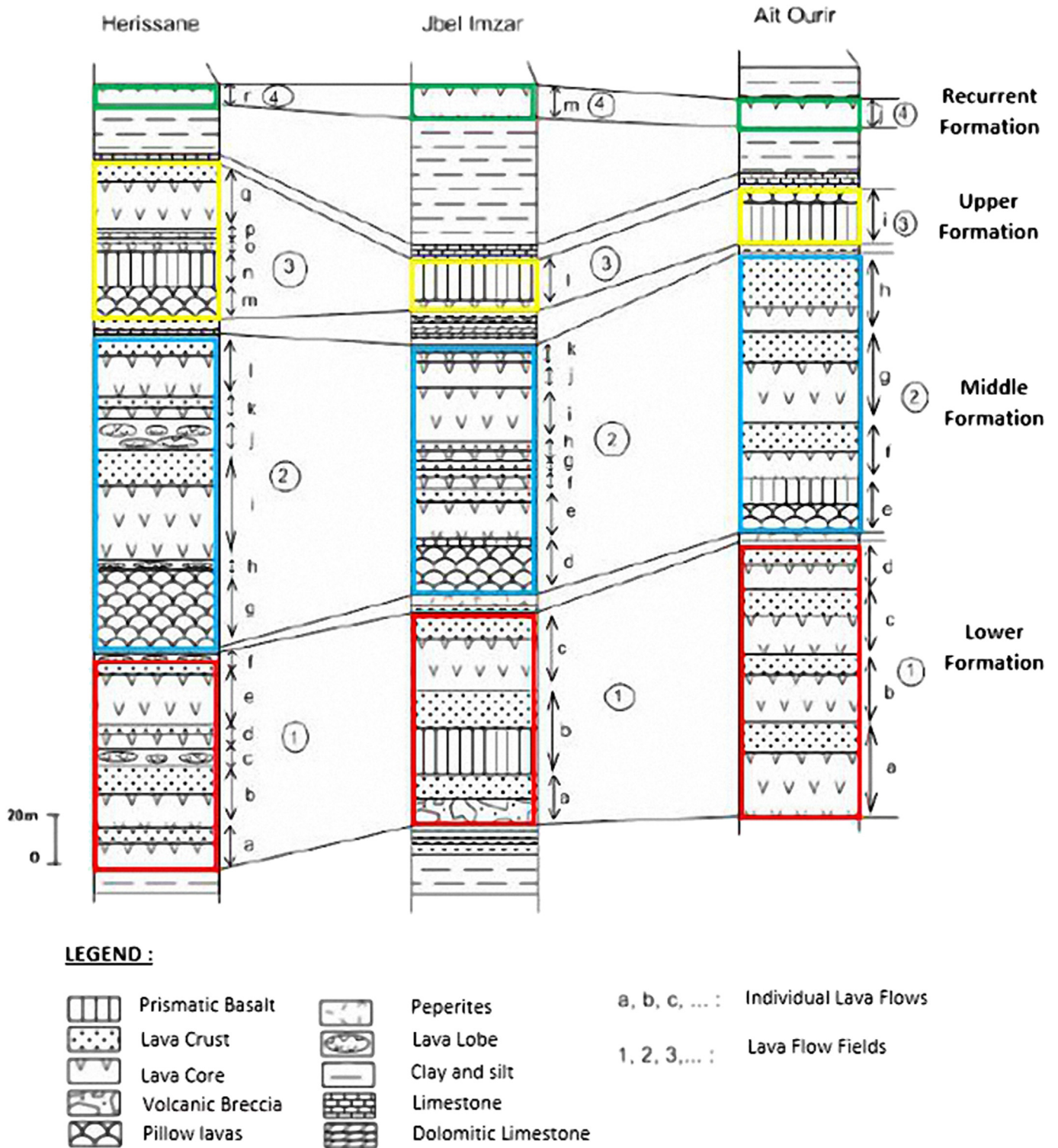


Fig. 2. Lithostratigraphic logs through the volcanic pile of the CAMP at the studied locations.

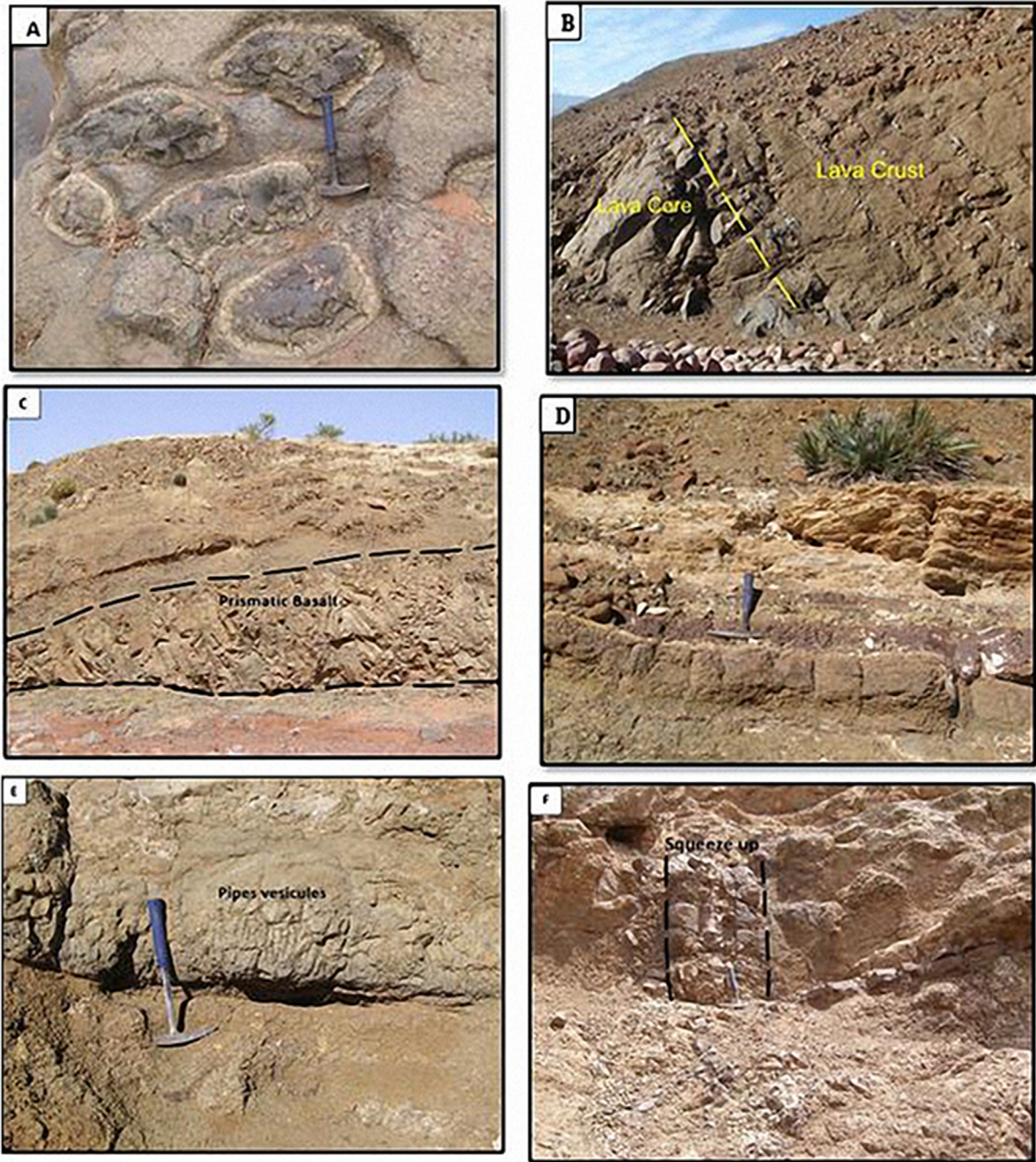
jointed flows and composite pahoehoe flows; finally, the Recurrent Formation corresponds to a single simple pahoehoe flow.

Locally, pahoehoe flows display structures such as tumuli, squeeze ups (Fig. 3F) and horizontal squeezes as well as segregation structures such as pipe vesicles (Thordarson and Self, 1998; Self et al., 1998) (Fig. 3E) indicating the occurrence of inflation processes. Peperitic interaction is frequently observed where lava flowed over unconsolidated sediment (Fig. 3I–L).

### 3. The structure of subaqueous flows

The subaqueous lava flows in the High Atlas region present variable aspects. They may locally correspond to densely packed pillows, to pillows dispersed into more or less abundant hyaloclastite matrix, and more or less extended sheet flows presenting well-developed undulated and thin columnar jointing. Pillow lavas and hyaloclastite containing pillows may pass laterally into sheet flows.





**Fig. 3.** A: Pillow lavas of the Middle Formation at Herissane; B: Lava core-Lava crust limit in a pahoehoe flow; C: subaqueous sheet flow presenting thin undulated columnar jointing from the Middle Formation of Aït-Ouir flow purposes prisms; D: Red silty horizon separating Middle and Upper Formation at Jbel Imzar; E: vesicle pipes at the base of a pahoehoe flow the Middle Formation at Jbel Imzar; F: Squeeze up from the Lower Formation at Herissane; J: Pillow lavas from Aït-Ouir section; H: Pillow lavas from Jbel Imzar section; I and G: Macroscopic aspect of peperites at the Herissane area; K and L: Microscopic aspect of peperites at the Herissane area.

At the Middle Fm. of Aït-Ouir and Oued Lhar, the subaquatic sequence starts with densely packed pillows, passing upwards into pillows dispersed in hyaloclastite and finally into subaerial flows. At Oued Lhar the base of the subaerial flow is marked by a pillowed structure before passing into a massive thick pahoehoe flow with 2 m-thick columns.

At Aït-Ouir section, the subaquatic sequences of the Middle and Upper Formations (Table 1.) has a total thickness of about 15 m (Fig. 4, picture 5 & 6), that of Oued Lhar section is much thicker with a total thickness of about 30 m (Fig. 4, picture 1, 2, 3 & 4).

#### 4. Pillow lavas morphometry

A morphometry of the pillow lavas was performed by measuring the horizontal (H) and vertical (V) diameters of individual pillows. Whenever possible the measures were obtained on sections as perpendicular as possible to the axis of the pillow. This task was extremely difficult in outcrops where the pillows were intensely weathered and observed in a 2D surface; at Oued Lhar, however, the outcrop allows a 3D observation of the subaquatic sequence. At all locations (Aït-Ouir, Jbel Imzar and Oued Lhar or



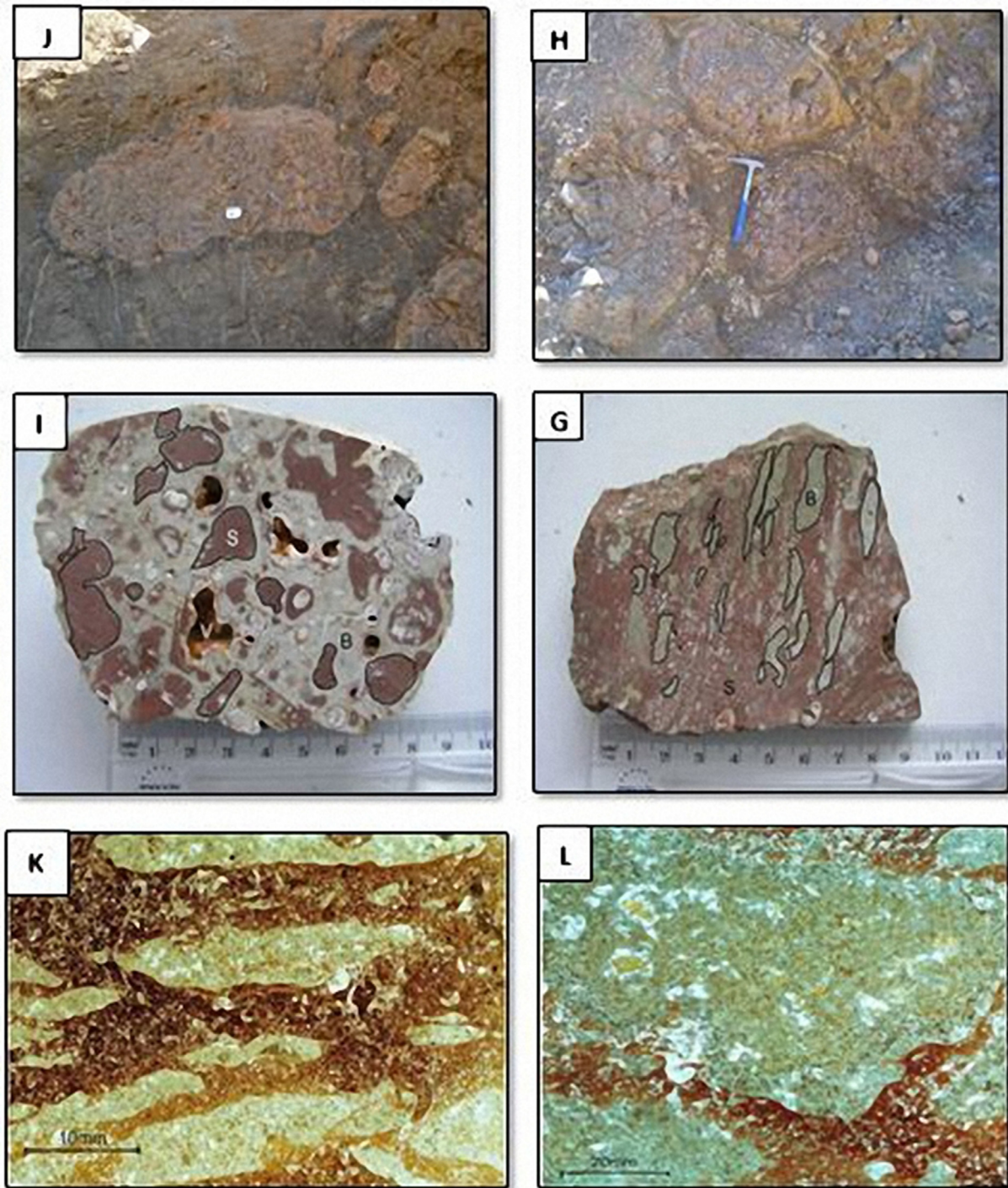


Fig. 3. (continued).

Herissane) an effort was made to measure all pillow lavas, and not only the smaller ones, which are easier to measure, in order to obtain the most representative sample, although in places the largest pillows were not totally exposed at the outcrop. The measurements performed at the three locations at the Middle and Upper Fms. amount to a total of 178 measurements (Fig. 5).

The median sizes of pillow from the studied sections are larger than those obtained in Iceland by Walker (1992) (Fig. 6).

The pillows from the Middle Formation at Jbel Imzar section present  $V > H$ . Pillow-lavas sizes from the Middle Formation at

Aït-Ouir, Jbel Imzar and Herissane, as well as those from the Upper Formation from Aït-Ouir, are relatively small (Fig. 5).

### 5. Mineralogy of sedimentary beds and peperites

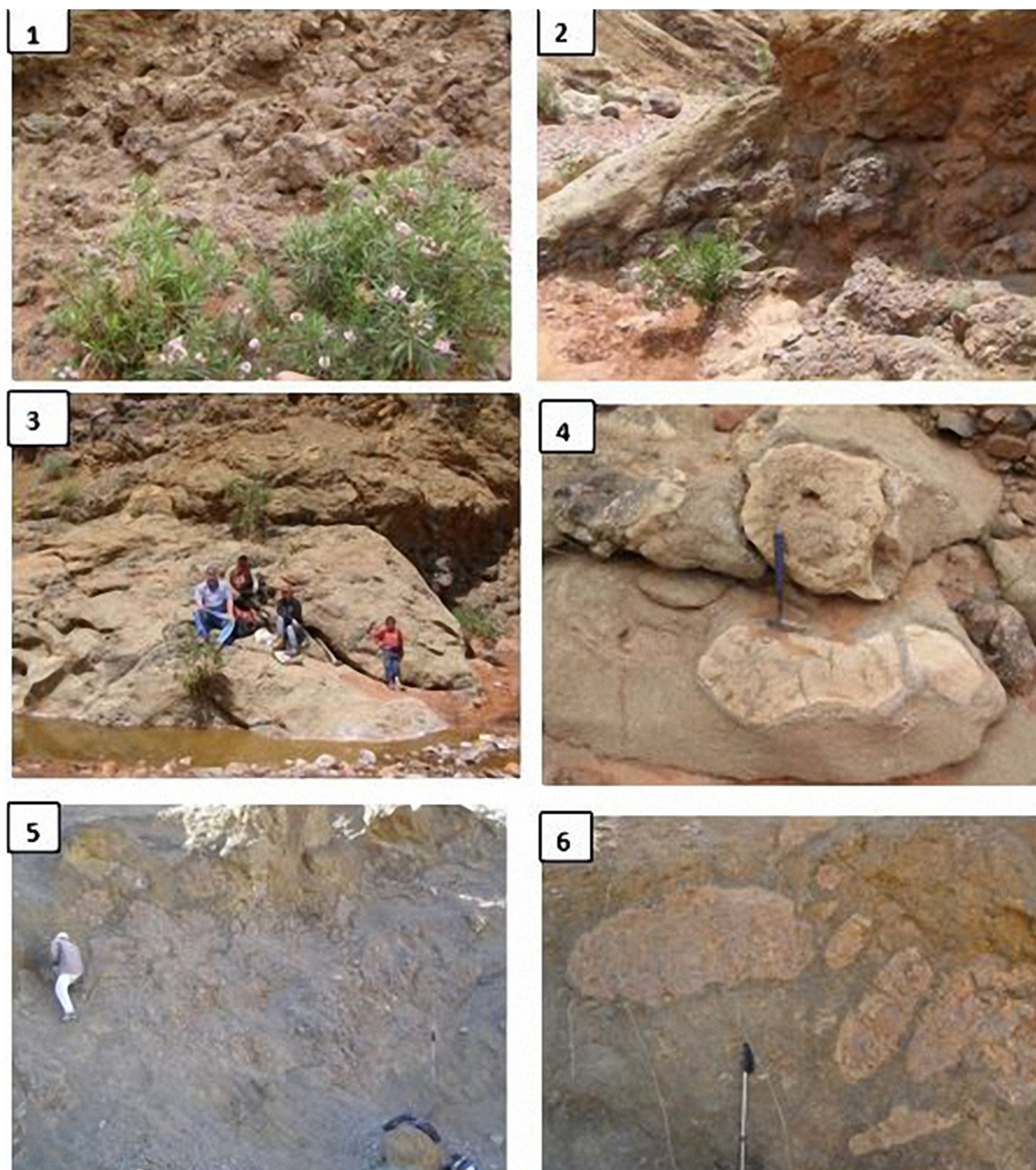
Sediments were sampled along the Jbel Imzar (Fig. 7) and Sidi Rahal (Fig. 8) sections and analysed by X-Ray diffraction at Instituto Andaluz de Ciencias de la Tierra (Granada, Spain).

The lithostratigraphic analysis of the volcanic succession at Jbel Imzar revealed 14 superimposed flows, organized into four



**Table 1**  
Attitude of intrusive pillow lavas at Ait-Ourir section.

Pillow lavas of Ait Ourir section	Size of individual pillows		Glass crust thickness (cm)	Observations
	H(cm)	V(cm)		
1	63	49	2.5–4	Absence of pipe vesicles, massive core with a finely vesicular area surrounding the pillow.
2	19	16	0.5	Vesicular finely area of about 3–4 cm
3	270	180	4–10	Massive flow with some vesicles distributed within.
4	47	50	3–5	Massive flow/absence of vesicles
5	290	290	8–14	Tubular vesicles with random orientation/double crust with invagination at the second crust
6	43	15	3–8	Empty heart filled with hyaloclastites
7	213	55	–	Pipe vesicles on the banks, base and top.
8	49	18	–	Completely vesicular pillow
9	85	76	4–6	Absence of pipe vesicles/vesicular heart
10	51	42	6–15	Vesicular nucleus/outdoor dense area more or less vesicular



**Fig. 4.** 1: Closed-packed pillows of level 1 of the Middle Formation at Herissane section; 2: Dispersed pillows with a hyaloclastic matrix of level 2 at Herissane section; 3: Dispersed pillows of level 3 at Herissane section; 4: Completely vesicular pillow of level 3 at Herissane section; 5: Closed-packed pillows of level 1 at Ait-Ourir section; 6: Dispersed pillows of level 2 at Ait-Ourir section.

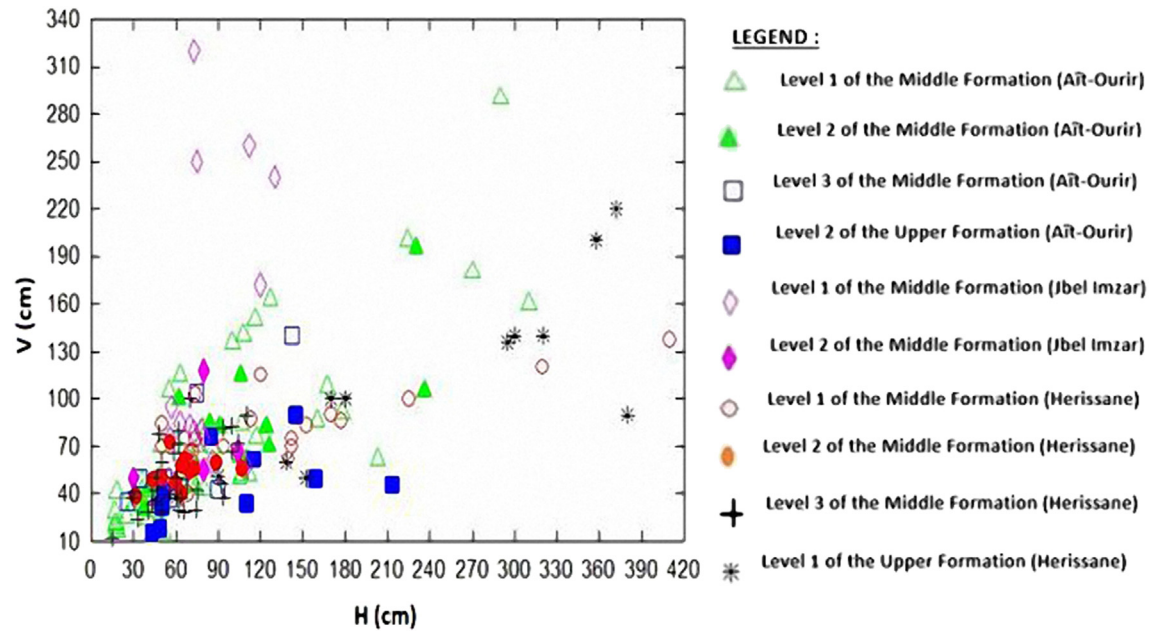


Fig. 5. Cloud of points of H and V dimensions of pillows from the Ait-Ouir, Jbel Imzar and Herissane or Oued Lhar sections.

formations and separated by sediments. Three sedimentary intervals were sampled: E1—red and black-shales beneath the lavas from the Lower Fm.; E2—peperitic sediment (White et al., 2000; Skilling et al., 2002) between the Lower and the Middle Fms.; and E3—black and green clays at the base of the Upper Fm. At the Sidi Rahal section only the Lower and Middle Fms. are present and the intercalated clay sediments were sampled (E0). X-Ray diffraction results of the analysis of the samples are given in Table 2.

Mineralogy of the analysed sedimentary intervals is very diverse.

Sedimentary interval E1 is mostly made of a set of clay and other silicate minerals. Type 1:1 phyllosilicates: mica, illite, phengite, celadonite, associated with chlorite, quartz and little feldspar and

interstratified chlorite-smectite. In samples Jm2a and Jm2b, which are correlated to samples Sr2a, Sr2b and Sr3 of Sidi Rahal section, another irregular interstratified chlorite-mica and small amounts of hematite are also present.

Sedimentary interval E2 is made of greenish shales interbedded with fine sandstone. Clay minerals consist of type 1:1 phyllosilicates, characterized by illite and irregular interstratified type chlorite-smectite, associated with quartz, mica, phengite, celadonite and small amounts of hematite.

Sedimentary interval E3 is localized just below the basalts of the Recurrent formation, mostly consists of shales of greenish, black and red colors, interbedded with finely sandy, reddish shales, and two carbonate beds (dolomite and stromatolite limestone). This is

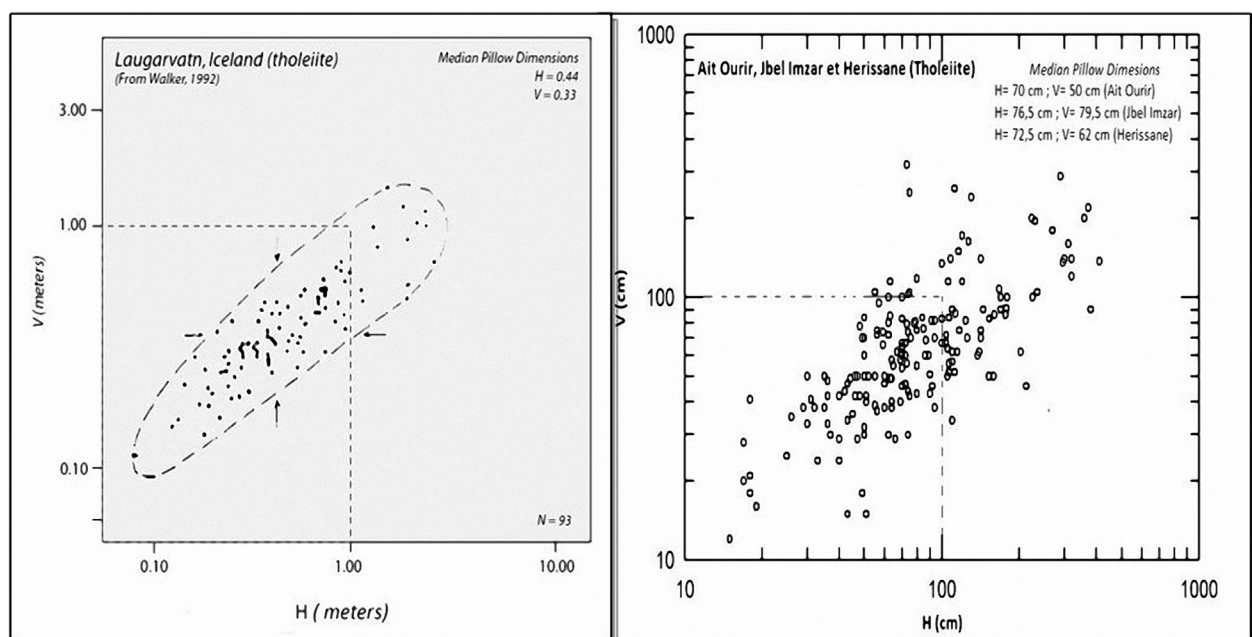


Fig. 6. Comparison of the size spectra between tholeiitic pillows from Iceland (Walker, 1992) and those of the present work.



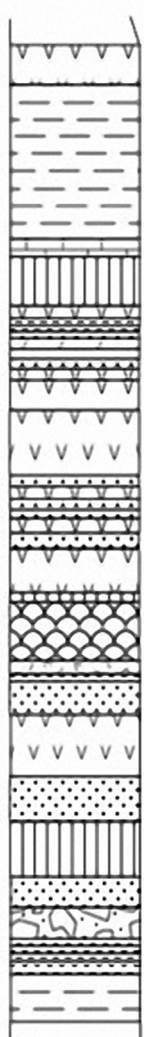
Formation	Lithology	Description	Samples
Recurrent Formation		Basalt	
Upper Formation		Clays and silts	
		Stromatolitic Limestone	
		Basalt	
E3		Black and green clays Sandstone Dolomitic Limestone	JM4 et JM5
Middle Formation		Basalt	
		Pillow lavas	
		Peperites	
E2		Basalt (Lava core and lava crust)	JM2a et JM2b
Lower Formation		Columnar Basalt	
		Lava crust	
		Volcanic Breccia	
		Red and black clays	
		Clay with gypsum	
E1		JM1a et JM1b	

Fig. 7. Stratigraphy of the Jbel Imzar section with the sediment sampling sites.

finally overlain by a millimeter thick ferruginous crust.

At Herissane section peperites occur at the base of pillow lavas from the Middle Formation (Fig. 9, Fig. 3L) overlying a sedimentary bed of silty or sandy shales.

At the three localities of the present study, the natures of the host sediment in peperites indicate that the environment was subaerial and the immaturity of the host sediment suggests that the transport has been limited.

## 6. Discussions and conclusions

The succession of lava flow is subdivided into the Lower, Middle, Upper and Recurrent Formations. The emplacement of basalts may induce an important thermal effect onto the adjacent sediments; therefore train an effect on the clay and mineral assemblages.

The pillow lavas and some silty and sandy sediment indicate subaquatic environment.

Some sediment between basalt flows have been affected by hydrothermal fluids circulation, resulting into interactions at the basalt-sediment interface. This is further confirmed by the occurrence of talc that witnesses hydrothermal activity (Daoudi and Pot de Vin, 2002). The initial smectite would therefore have become unstable under the new thermal conditions, and would have been transformed into corrensite, then into chlorite (Hower et al., 1976; Kisch, 1983). This transformation usually occurs at temperatures of 200 °C (Velde, 1985; Lindqvist et al., 1991; Inoue et al., 1991).

The lack of fibrous clay minerals such as sepiolite and palygorskite make the reconstitution of Trias-Jurassic paleoclimate impossible with the clay mineral assemblages found in the Sidi Rahal (N31 64 56.7 & W7 47 31.6) and Jbel Imzar sections.

Unfortunately, the samples studied did not yield palynoflora (Prof. Anne de Vernal, Geotop-UQAM, Canada, per. com).

The interaction of pillow lavas from the Middle Formation with reddish, unconsolidated or poorly lithified, fine, low permeability



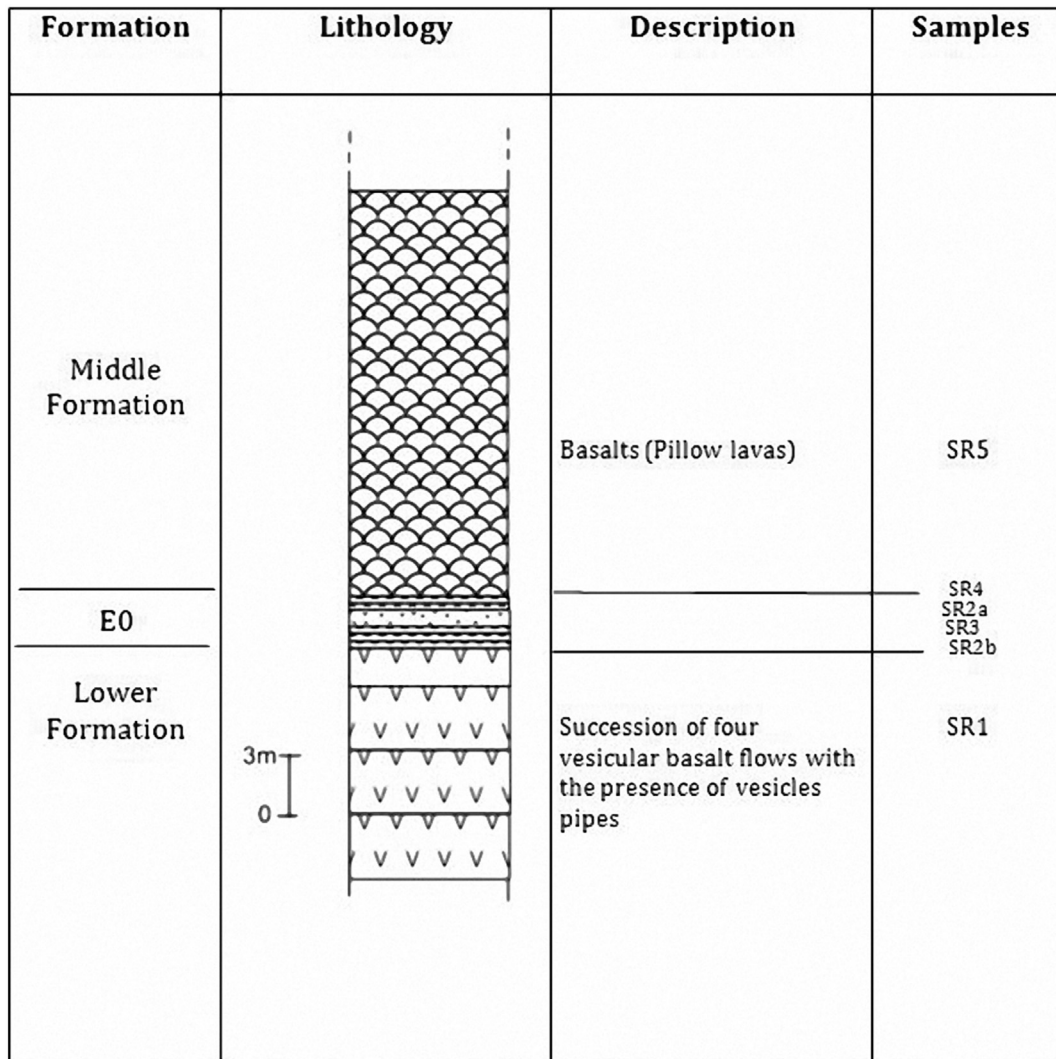


Fig. 8. Stratigraphy of the Sidi Rahal section with the location of the sampled sediments.

sediments has enhanced the phenomenon of lava fluidity, which is responsible for the development of fluidals peperites (Brooks et al., 1982; Kokelaar, 1982) at the Herissane section.

According to our observations, the alteration that affects the internal part of basalt fragments, maybe related to the temperature contrast between basalt fragments and the surrounding sediment. The sediment facies suggest a subaerial environment and its immature character suggest limited transport.

The relatively small size of level 2 pillow lava from the Middle Formation found in Herissane, Jbel Imzar and Ait-Ourir sections indicate a high effusion rate and low viscosity for the lavas. A

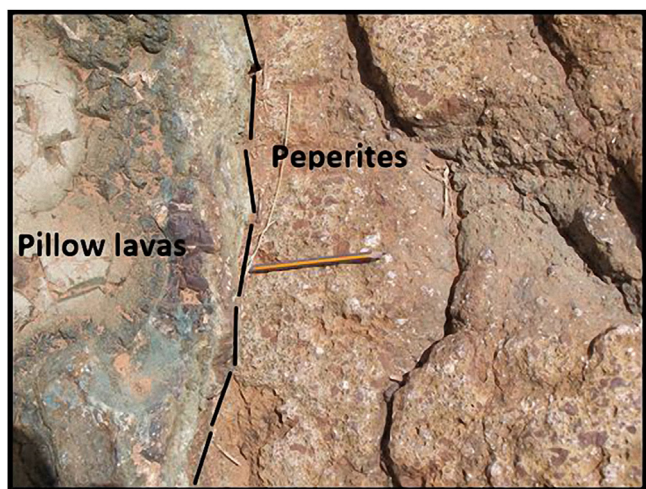
steeper slope was responsible for their smaller size and for their rounded, rather than flattened, shape. Occurrence and proportion of inter pillow lava matrix provides additional information on the slope:

- In Oued Lhar or Herissane section, the absence of matrix in the closely-packed pillow lavas of level 1 of Middle Formation suggest a horizontal slope.
- Those of level 2 and 3 include an important and increasing upward proportion of hyaloclastite matrix (it becomes

Table 2

Clay content of the sediments from the Jbel Imzar and Sidi Rahal sections.

Sample	Clay minerals content
Jm1a	Illite-Mica-Phengite-Celadonite and irregular interstratified Chlorite-Smectite
Jm1b	Mica-Illite-Phengite-Celadonite, Quartz, Chlorite and a little of Feldspar and interstratified Chlorite-Smectite
Jm2a et b	Mica-Illite-Phengite-Celadonite, Quartz and a little of Interstratified Chlorite-Mica, and Chlorite-Smectite, a little of Feldspar and Hematite.
Jm4	Talc, Chlorite and the Phyllosilicates type 1:1 (Mica-Illite-Phengite-Celadonite)
Sr2a	Phyllosilicates type 1:1 (Mica-Illite-Phengite-Celadonite), Quartz and a little of Interstratified Chlorite-Mica
Sr2b	Phyllosilicates type 1:1 (Mica-Illite-Phengite-Celadonite), Quartz and a little of Interstratified of Chlorite-Mica
Sr3	Phyllosilicates type 1:1 (Mica-Illite-Phengite-Celadonite), Quartz and irregular Interstratified Chlorite-Smectite, a little of Feldspar and Hematite
Sr4	Phyllosilicates type 1:1 (Mica-Illite-Phengite-Celadonite), Quartz, Interstratified Chlorite-Mica, a little of Feldspar and Calcite



**Fig. 9.** Contact between a pillow from the Middle Formation and sediments showing peperite interaction.

dominant in level 3) which indicates an increase of the slope during emplacement of the middle formation in this locality.

Increase of the proportion of inter pillow lava matrix indicates high effusion rate as well as a fast cooling (examples of Oued Lhar and Aït-Ouir sections).

The environmental depositions in this areas still a matter of debate. The morphology, structure and morphometry studies suggest that:

At the Herissane section the pillow lava of the Middle Formation have a hyaloclastic matrix whose percentage grow from level 1 to level 3 and this indicates that the slope has to be almost horizontal inclined weakly and became highly inclined.

The relatively small sizes of pillow lava level 2 of the Middle Formation of the three area indicates high effusion rate or a low viscosity.

In Herissane and Aït-Ouir, the percentage of inter-pillow matrix suggests a high effusion rate and fast cooling rates.

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