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Chapter

Study of Monogenic Volcanism in a Karstic System: Case of the Maar of Lechmine n'Aït el Haj (Middle Atlas, Morocco)

Sara Mountaj, Hassan Mhiyaoui, Toufik Remmal, Samira Makhoukhi and Fouad El Kamel

Abstract

The Lechmine n'Aït el Haj maar (LNH) is a mixed phreatomagmatic-strombolian vent located in the Causse of the Middle Atlas. The application of tephrostratigraphic, and geophysical studies to the volcaniclastic deposits allowed interpreting the volcanic dynamics of this volcano set up during the Quaternary. Pyroclastic deposits allow us to understand the chronology of the eruptions. These are organized in four eruptive phases. The basal sequences are phreatomagmatic, followed by a strombolian unit. The last activity of LNH is phreatomagmatic. The structural analysis revealed a localized distension signed by fracture geometry, the mixed nature of the volcanism, tectonic markers, and the mechanisms of syn-eruptive tectonics. This subsidence, controlled by the NW-SE to WNW-ESE directions tends towards a strike-slip regime fault NE–SW during the phreatomagmatic-strombolian transition. The latter is favored by the position of the LNH volcano on the path of faults of cryptokarstic origin. The LNH maar is one of numerous well preserved monogenic volcanoes of the Causse of the Middle Atlas. The appropriation of this geoheritage is very important for tourism and territorial development of the region.

Keywords: Lechmine n'Aït el Haj, maar, karst, monogenetic volcanoes, geoheritage, Middle Atlas

1. Introduction

Monogenetic volcanic provinces have recently attracted the interest of volcanologists especially in intracontinental settings [1, 2]. The Middle Atlas Volcanic Province (MAVP) is an example of those small volcanic systems with dispersed magmatic plumbing systems that erupt predominantly basaltic magmas [3, 4].

In the last thirty years, many studies have concerned the volcanism of the Middle Atlas. A hundred of cones and maars have been listed and mapped over an area of almost 1000 km^2 [5, 6]. The distribution of volcanoes is controlled by the tectonic context of the region [7, 8]. The petrological study of eruptive vents allowed distinguishing four lava types dominated by under-saturated alkali basaltic flows (68.5%). The basanites cover 22.5% of the plateau surface, the subalkaline basalts cover 7,8%, and finally the nephelinite with the smallest proportion

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(1,2%). The three first types are exclusively Plio-Quaternary (3.77–0.60 Ma), the K-Ar age of the last one is Middle Miocene (16.25–5.87 Ma), and Plio-Quaternary (3.92–0.67 Ma) [9]. This magmatism results from a partial melting that occurred at around 2 GPa, i.e. near the lithosphere–asthenosphere boundary beneath the Middle Atlas (60–80 km) [10]. The analysis of the Middle Atlas aeromagnetic data allowed the characterization of the regional magnetic anomalies, their location and delimitation corresponding to the major accidents of the Middle Atlas [11, 12].

30% of MAVP volcanoes are represented by maar-diatreme-type volcanic systems [6]. They have a negative shape forming a crater that intersects the pre-eruptive surface. Lechmine n'Aït el Haj is the first maar ever studied in this region. After a previous work on the analysis of the eruptive sequence of the maar [13], the aim of this chapter is to understand the structural context of the formation of this maar and its eruptive dynamic.

2. General features of monogenic volcanism

Magma system volumes can occur in an intraplate context devoid of a mantle plume [14]. This type of volcanism is characterized by "small" volcanoes with magmatic system often basaltic [4–6], derived mostly from a mantle that stays in the crust just the time to allow a minor fractional crystallization [15]. These monogenic volcanic fields occur in any tectonic setting [2, 16–18], not only on Earth but also on other planets such as Mars [19].

Much research has been done on monogenic volcanoes, focusing on their nature from source to surface [15, 20]. The rapid ascent of magma and the short eruptive history of volcanoes allow to understand, for example, the magmatic evolution of the systems that fed several small volcanoes over long periods of time (millions of years) [21, 22].

In many cases, the eruptive style is controlled not only by the internal properties of the magma but also by the external environmental conditions to which it has been exposed. The resulting morphology is often related to the mechanism of the dominant eruptive style, making it important criteria in the study and especially in the classification. The estimated time for the formation of these volcanoes is in the order of a few days to a decade [23].

Monogenic volcanoes are referred to as the product of a single eruption [24], however, a magma ascent is not always related to a single magma influx, which usually involves several episodes producing a geochemical evolution even over a single eruption [15, 20, 25]. This magma may come directly from the mantle or from a volume of magma trapped in a zone of contrasting density, such as the upper mantle/crustal boundary [25]. The magma ascension begins with an inter-connectivity between the small volumes of magma in the mantle and their vertical migration forming dykes [26, 27]. These dykes generally follow pre-existing structures such as faults of the basement rocks as they move towards the surface [28].

The magma of monogenic volcanoes is often primitive. It rarely expresses itself individually; it tends to form several monogenic volcanoes in a volcanic field, where there may be tens or even thousands of individual volcanoes [29]. However, a monogenic volcanic field could experience repeated monogenic eruptions across a broad area over millions of years [30].

Once a batch (or batches) of magma begins its ascent to the surface, it faces continuous outgassing and interactions with the host environment. Once at the surface, this magma can produce a volcanic eruption that can be explosive or effusive. This is controlled by the characteristics of the eruption which are determined at a superficial depth (≤1–2 km) by the balance between internal and external factors [4].

3. The Middle Atlas Volcanic Province (MAVP)

The Atlas mountain chain is the result of the Oligocene compression induced by the Europe-Africa convergence and continent-continent collision. Its basement is structured during the Hercynian orogeny [307,5 ± 6,8–364,0 ± 8,2] [31]. It is continental and outcrops only at a few inlier [32]. The cover consists mainly of Jurassic deposits. It is deformed in the folded Middle Atlas, whereas it is sub-tabular in the Causse of the Middle Atlas [32]. This latter zone is distinguished with a simple structural style of inclined blocks, manifesting itself in the topography by a succession of subhorizontal layers (Tabular Middle Atlas). It is the area where the Plio-Quaternary volcanism occurred with a hundred of eruptive centers aligned in a sub-meridian direction (**Figure 1**). It is crossed by the Tizi n'Tritten Fault (TTF) and a network of faults between the North Middle Atlas Fault NMAF and TTF. All these accidents, which are at least Hercynian, from direction N45 to N70, affect the recent Quaternary deposits [8].

The emission points located between Azrou and Timahdite have an NNW–SSE orientation along 50 km. The basalt flow covers the ancient Quaternary formations up to the Saïs plain in the north (**Figure 1**). They are channeled to the East by the

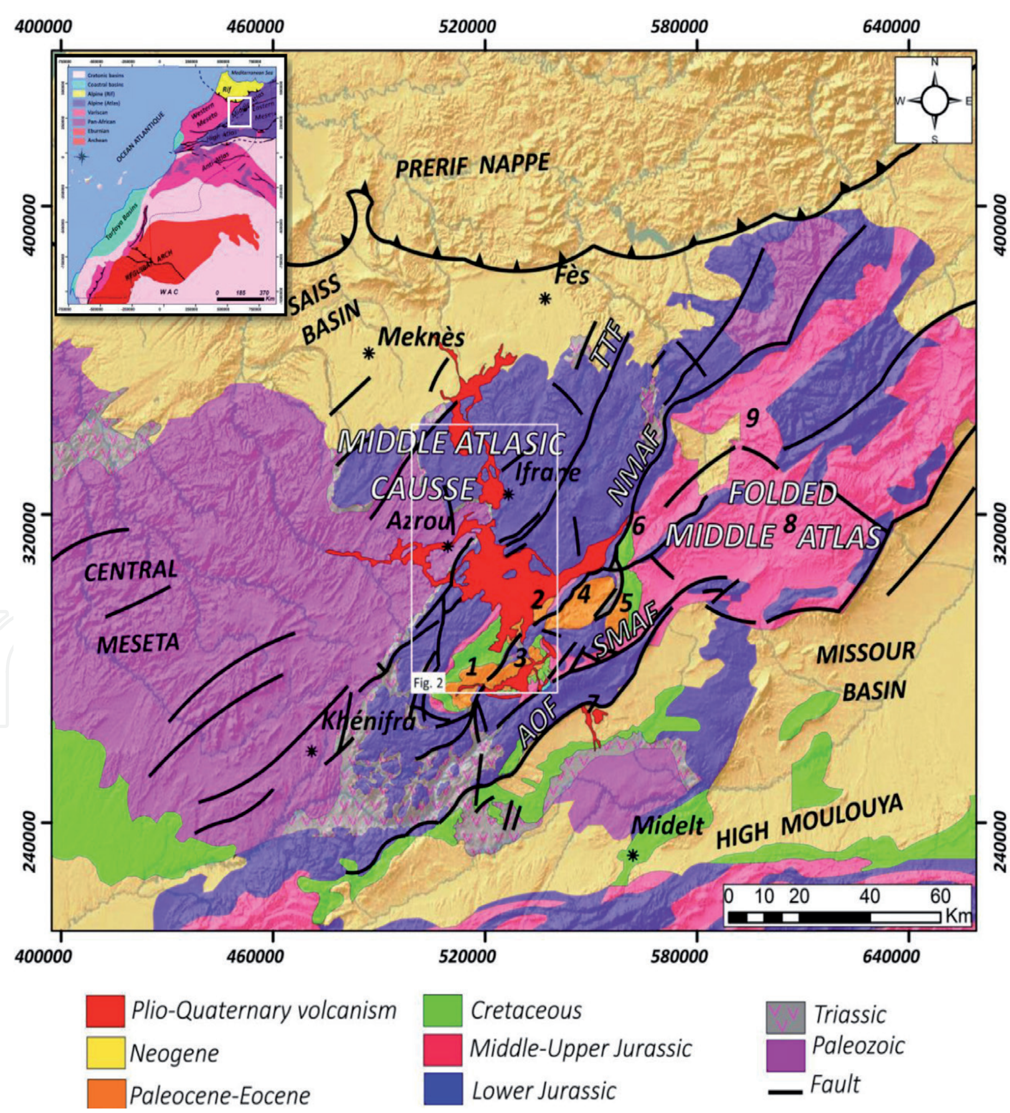

Figure 1.
Structural map of the Middle Atlas with the location of the volcanic field [33]. SMAF: South Middle Atlas fault, AOF: Ait Oufella fault, NMAF: North Middle Atlas fault, TTF: Tizi n'Tretten fault. Jurassic, cretaceous, and Paleogene synclines: 1: Bekrite, 2: Timahdite, 3: Bou-Anguer, 4: Aïn-Nokra, 5: Oudiskou, 6: Tirhboula, 7: Ait Oufella, 8: El-Mers, 9: Guigou.

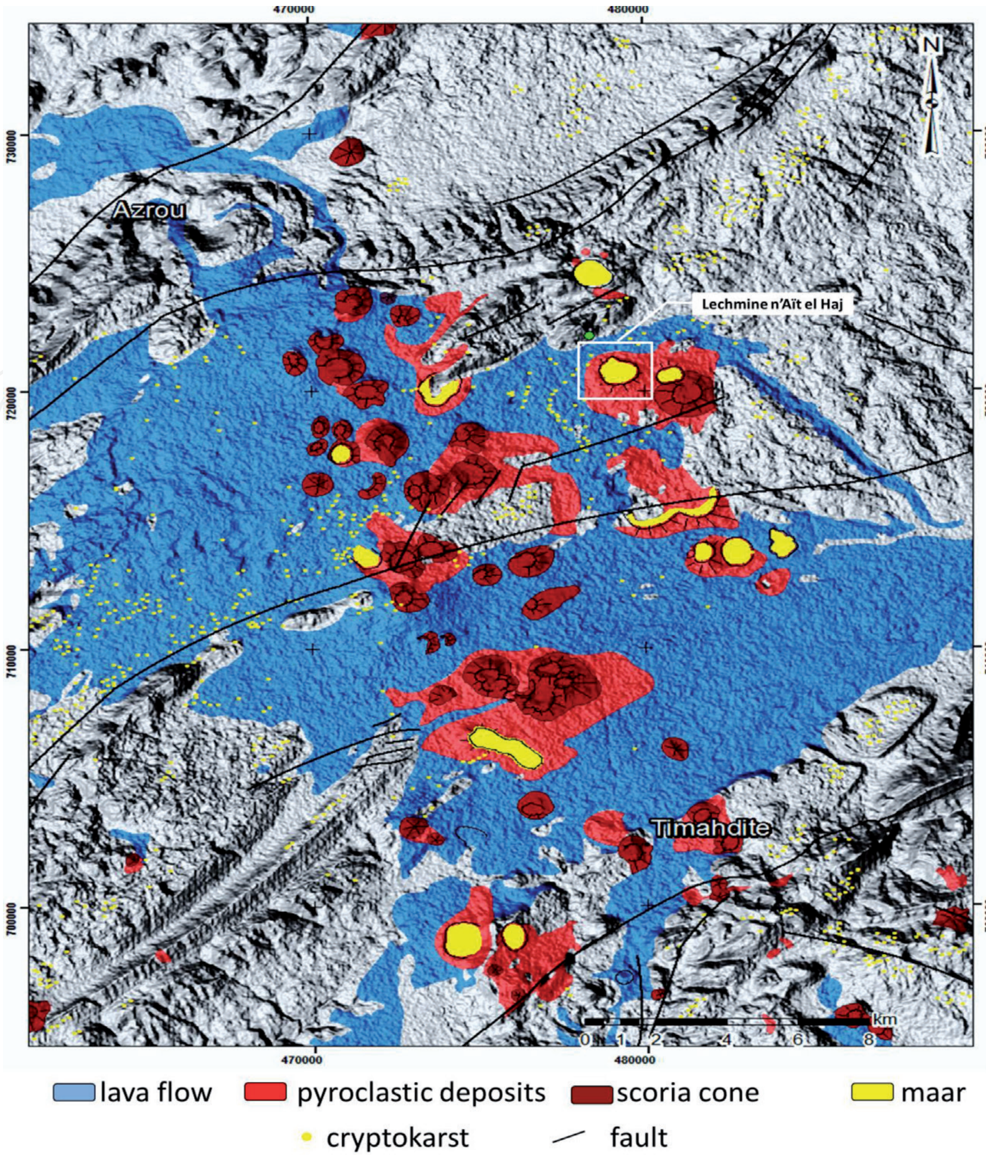

Figure 2.
Geographical location of the study area. Most of the volcanoes and lava flow units are settled between Azrou and Timahdite where the cryptokarstic cavities are dominating.

depression of the Guigou Valley and to the West by the Wadis of the Beht and Oum Rbia. Most of the volcanoes are strombolian (70%) disseminated in the entire volcanic area. on the other hand, maars are focused in the eastern part of the volcanic province [5] (**Figure 2**). The karstic-carbonate nature of the region combined with the fluctuations in rainfall contributes to the formation of the water table in the epikarstic level [34, 35]. The variation of the karstic water at this level has an impact on the volcanic dynamic and the changing of the eruptive style. In The MAVP, 8% of volcanic vents have witnessed a shifting between wet and dry dynamics during the same monogenic eruption [5].

4. Case of study: the Lechmine n'Aït el Haj maar

4.1 Lithology and deposition process

The Lechmine n'Aït El Haj maar is located in the volcanic plateau near Azrou, in the eastern part of the province (**Figure 2**). The maar deposits are mainly formed of pyroclastic breccia consisting of accidental lithics extracted from the substrate associated with juvenile fragments, and volcanic ash. Several lithological sections were established around the rim of the LNH crater, using a graphical semiology that shows the cadence of the eruptive sequences and their variability according to the nature of the activity phase (**Figure 3**). Two criteria allowed understanding the environmental condition at the time of the eruption: The outcrop of the Liasic limestone, and the lacustrine deposits in the northern flank of the maar.

The LNH maar is set on the limestone of the Middle Lias. It occupies less surface comparing to the dolomite of the Lower Lias in the Causse of Middle Atlas. The distribution of limestone follows often the structural undulations in the region [6]. With their white color, their stratification is clearly visible. Typical karstic forms (lapiez) are distinguished at the surface.

On the northern flank, between the limestone and the first phreatomagmatic unit appears a 1,5 m thick level of reddish deposits (**Figure 4a**). This facies appears also in small outcrops cleared by streams (**Figure 4b**). It is formed by a mixture of fine tuffs and clay interspersed with centimetric levels of breccia with juvenile and limestone fragments (4 mm to 4 cm) (**Figure 4d**). This aspect indicates an

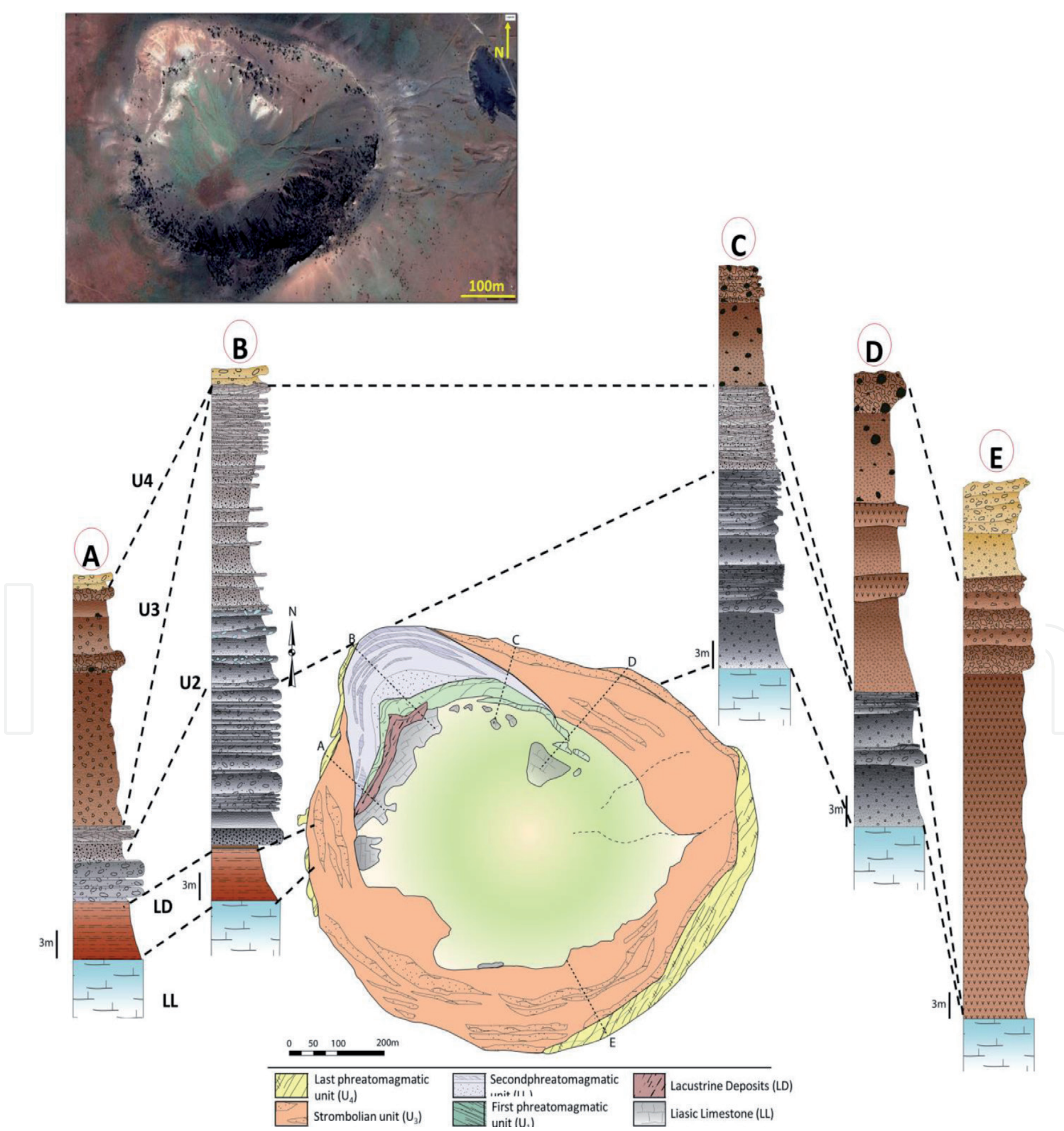

Figure 3.
Volcanic map of the maar of Lechmine n'Aït el Haj in the Causse of the Middle Atlas with logs describing the evolution of the eruptive dynamics of the maar.

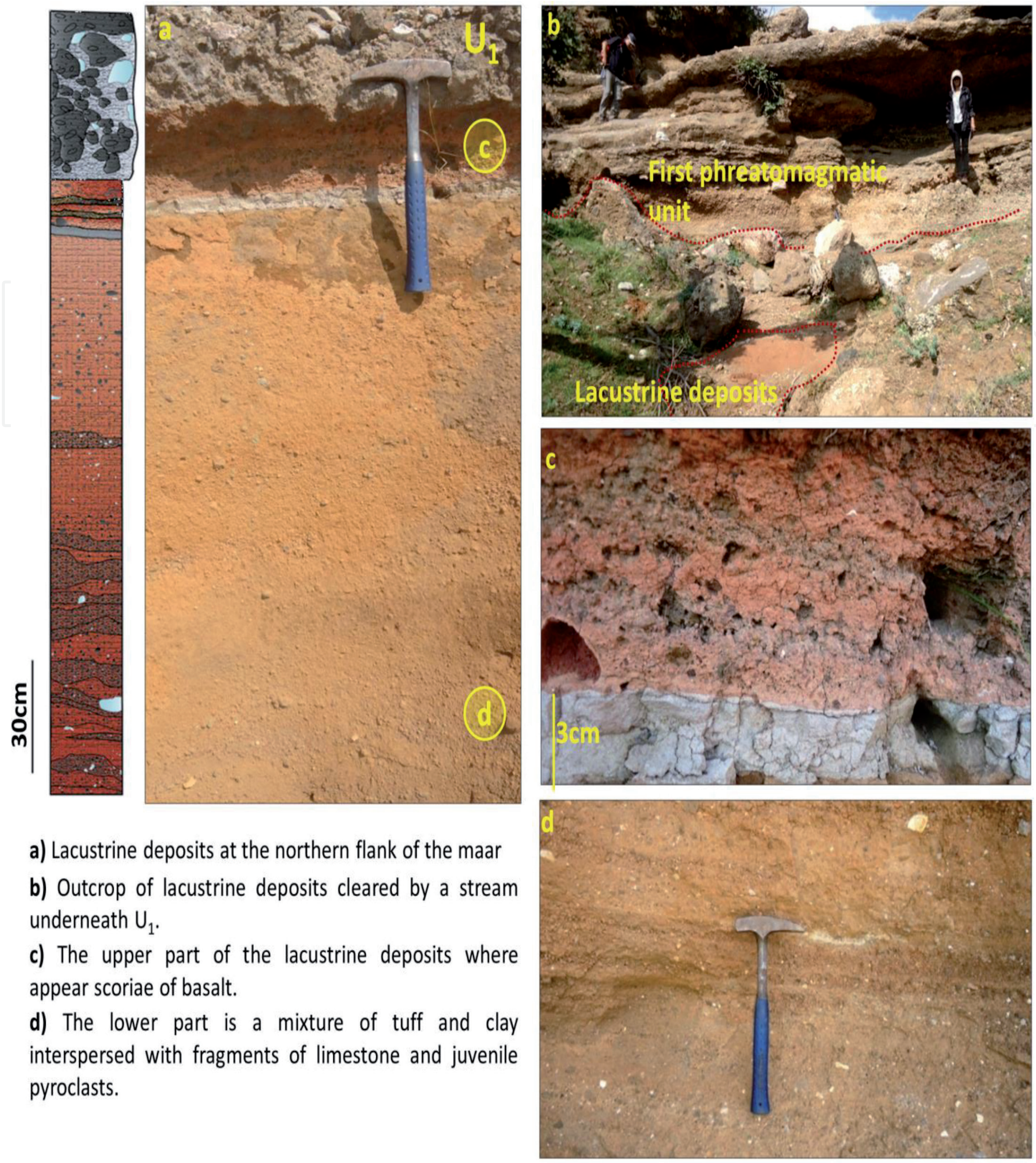

Figure 4.
The lacustrine deposits at the base of the first phreatomagmatic unit (U1) of the maar of Lechmine n'Aït el Haj.

explosive dynamism that occurred while the sediment was still rich in water. Towards the summit appears fine gray ash overlain by gray and reddish vacuolar and scoriaceous beds revealing the eruptions that preceded the hydromagmatic explosion (**Figure 4c**). A palynological analysis was carried out on these lacustrine deposits at the GEOBIO laboratory of the Scientific Institute of Rabat. It showed that these deposits are extremely poor in palynomorphs. The gray deposits are rich in bisaccate called "Pinus pollens" that have existed from the Paleozoic to the present day [36, 37].

The tephrostratigraphic sequence of deposits shows color and dip variation corresponding to four eruptive phases (U1–4). The first two units are describing a phreatomagmatic activity with heterogeneous lithology; U1 is highlighted by alternating beds of variable thickness rich in limestone blocks, while U2 shows relatively thin regular bedding compared to the first deposit, with a white basal level formed almost of blocks and fragments of accidental lithics overlain by another level of red scoriaceous to finely pulverized fragments. The third unit (U3) results from strombolian activity. Its eruptive products are composed of massive breccia tuffs rich in volcanic bombs and mantle-derived xenoliths. The activity of the maar end with a final phreatomagmatic activity highlighted by the deposition of pyroclastic breccia located in the north and south of the crater [13].

4.1.1 The phreatomagmatic phase

The first phreatomagmatic deposits show a heterogeneous lithology characterized by the association of juveniles formed by basalts and accidental lithics from the substratum of limestone. The pyroclastic projections fall around the maar in crossed strata centered on an axis that describes a semi-annular geometry. Depending on the abundance, size, and sequential organization of the constituent elements, the phreatomagmatic unit is subdivided into two units U1 and U2 [13].

Unit 1: it corresponds to the initial explosive phase, declined in two sequences of deposits with a weak external dip of 15° to 20° (**Figure 5a**). These two sequences indicate a variation in fragmentation intensity during the activity of the maar. The first phase (U1a) of vent opening is highlighted by an alternation of beds of variable thickness between 50 cm and 1.5 m, composed of breccia and fine tuffs, rich in accidental lithics (1 to 10 cm in diameter) (**Figure 5b**). In the second stage (U1b) describes thin regular bedding compared to the first deposit with a clear decrease in the accidental lithic and an increase of juveniles (**Figure 5c**). The beds at the base correspond to lapilli-tufts with calcareous interstitial ramifications, resulting from the circulation of water.

Unit 2: It shows a succession of heterogeneous cross-bedded layers of lapilli tuffs (**Figure 6a**). It is distinguished by a white color at the bottom (U2a) because of the abundance of blocks and fragments of accidental lithics (**Figure 6d**). This level indicates the resumption of hydromagmatic activity since enclaves of breccias from the first explosion are packed into the deposit (**Figure 6b**). it is overlain by (U2b), a thick column (40 to 50 m) of parallel, locally crossbedded, strata, formed essentially of scoriaceous to finely red pulverized material interspersed with fine beds of accidental lithics (**Figure 6c**). In this unit a range of sedimentation features characterizing maar projections are observed, notably mud crack at the summit of the phreatomagmatic deposit (**Figure 6e**).

4.1.2 The strombolian phase

The maar is surrounded on the northern and southern sides by strombolian deposits (U3) (**Figure 7a**) which announces the transition to an activity where water participation has substantially decreased. The first deposits on the eastern and southern flanks are essentially rust-colored, centimetric scoria, well-classified, more or less vesicular (U3a) (**Figure 7b**). They correspond to pyroclastic fallout from a plume. The color variations indicate a beginning of alteration suggesting that the pyroclastics were wet at the time of their deposition. The beds become heteromeric with centimetric scoria with dense and angular bombs. Towards the top, the fallout has a relatively chaotic character (U3b). The hot fallout can weld together locally and form conical accumulations of scoria (spatter cones), piled up lava, and blocks or bombs of lava (**Figure 7c**). The summit of this unit is composed of a mixture of scoria and bombs (U3c). The whole is globally homogeneous with a reddish color due to hot oxidation. It is an eruption in a regular regime but with some slightly more powerful explosions; levels richer in bombs (**Figure 7d**). On the western flank, the U3c unit is poorly deposited. The lava flow that cap U3b is formed by agglutination

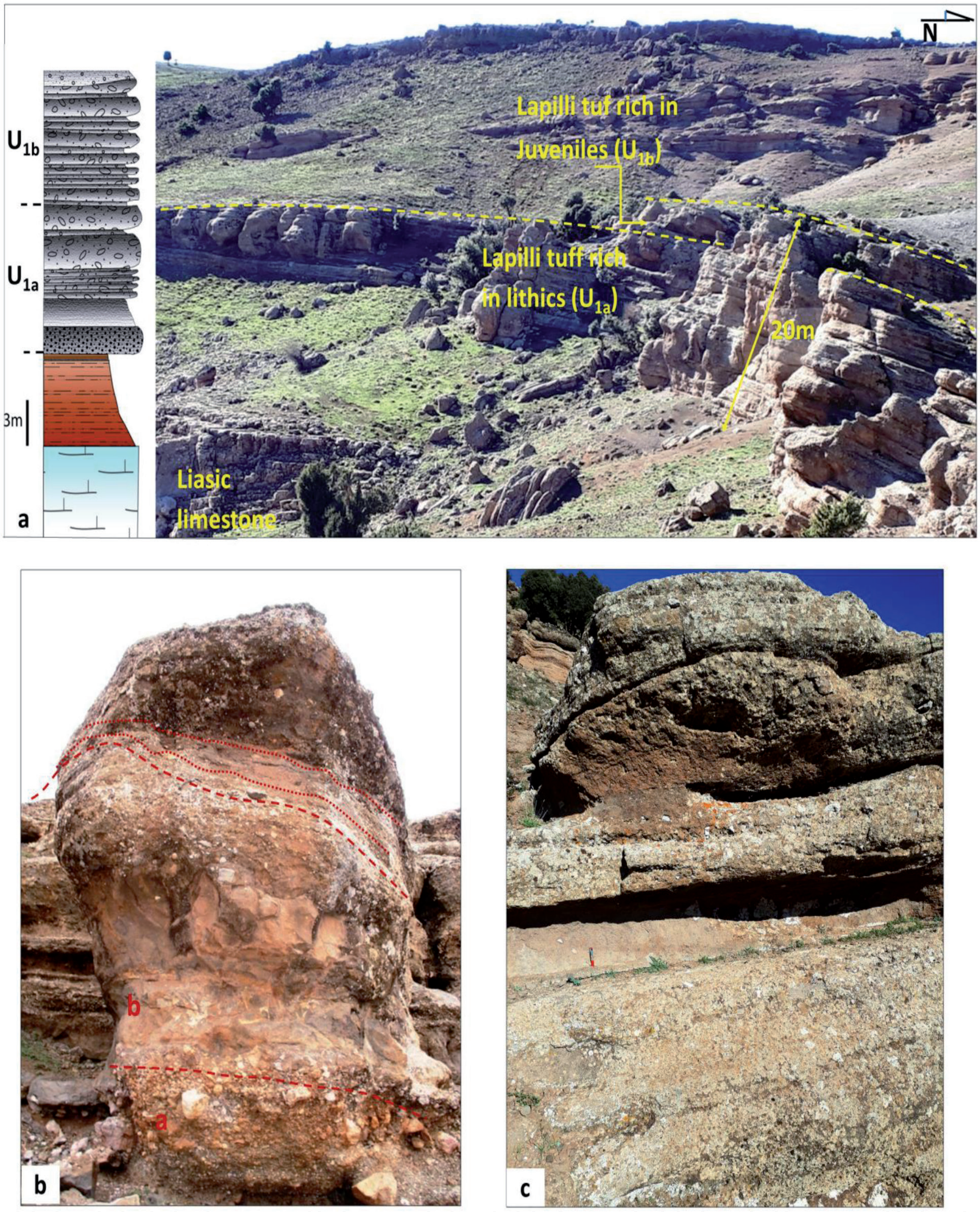

Figure 5.
The northern flank of the Lechmine n'Aït el Haj crater; (a) the contact between the limestone base and the first phreatomagmatic phase (U1); (b) the first sequence (U1a) showing an opening facies with unsorted accidental lithics (level a) and beds rich in scoriaceous basalt (level b); (c) the second sequence (U1b) with regular and less thick bedding, where the proportion of accidental lithics decrease.

of packages of low-viscosity lava flowing towards the center of the crater (**Figure 8**), through a path oriented ENE-WSW probably linked to a sectorial collapse.

4.1.3 Terminal phreatomagmatic deposits

The activity of LNH ended with a phreatomagmatic phase, highlighted by the deposition of pyroclastic lapilli tuff layers thicker on the northern flank of the maar (10 to 15 m) than on the southern flank (2 m to 5 m). This unit (U4) is formed essentially of scoria and rare lava blocks mixed with accidental lithics. The whole forms a rhythmic sequence that is particularly well represented on the southern flank (**Figure 9**).

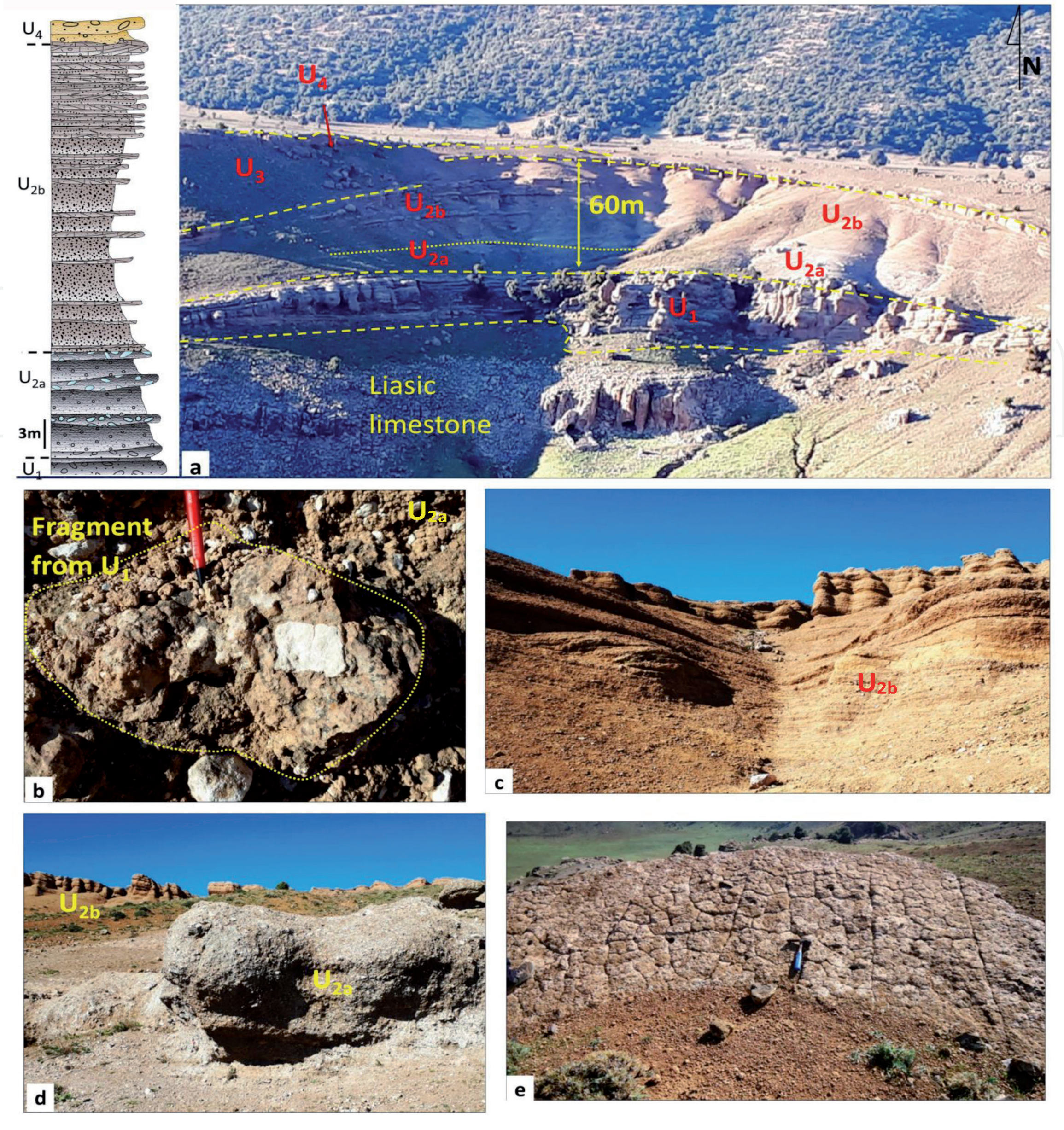

Figure 6.
Volcanic lithofacies accompanying the two sequences U2a and U2b of the second phreatomagmatic phase (U2); (a) the succession of the first and the second sequence of U2 (U1a and U2b) with varying thicknesses and compositions; (b) enclave of the first phreatomagmatic phase (U1) packed in the fallout of the second phreatomagmatic phase (U2a); (c) the second sequence (U2b) with reddish color richer in juvenile pyroclasts; (d) variation of composition and color between U2a and U2b. (e) Mud cracks structure at the summit of U2b.

4.2 Volcanic dynamics and structural context of the formation of Lechmine n'Aït el Haj

The LNH maar is set on the path of the Lbouatène tectonic corridor (ALB) (**Figure 2**), between the Fault of Tizi n'Traten (TTF) and North Middle Atlas Fault (NMAF). This area is particularly distinguished with cryptokarst cavities. These are aligned according to the orientations of the major faults in the Causse of the Middle Atlas (**Figures 2, 10**). It has been shown [8] that the formation of the cryptokarsts in the Quaternary basaltic flow is controlled by the fracturing. Around the maar, the cryptokarstic cavities are arranged in two alignments N60 and N160 conforming to those recognized in the Causse of Middle Atlas [8, 38] highlighting the karstic context of the formation of the maar. In order to analyze the instability at the scale of LNH, fracturing measurements were made in both phreatomagmatic and strombolian deposits (**Figure 11**).

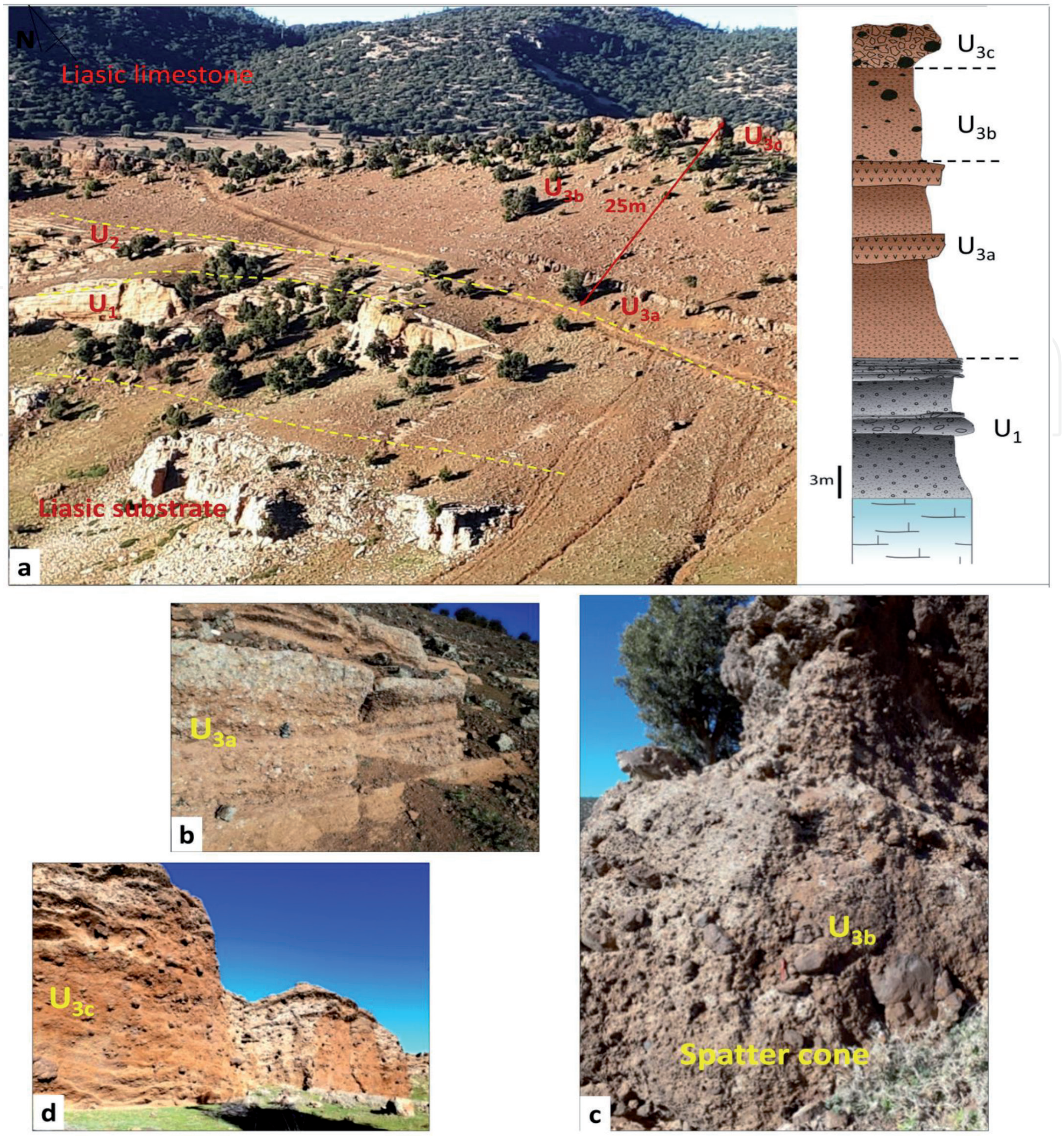

Figure 7.
Strombolian pyroclastic fallout on the eastern flank of LNH; (a) succession of phreatomagmatic deposits overlain by the strombolian unit (U4); (b) air fallout from the first plume of the strombolian phase; (c) formation of spatter cone near the emission zone; (d) fallout of scoria with bombs far from the volcanic eruptive center.

In the phreatomagmatic deposits (U1, U2) general subsidence is marked by conjugate fault-systems (**Figure 12d**) found also in the limestone basement (**Figure 11**). In the uppermost part of U2 (**Figure 12e**), there is a shift from an extension by normal fault perpendicular to the NE–SW structural direction, to a strike-slip system by permutation of the stress axes σ_1 - σ_2 (**Figure 13**).

The distribution of strombolian deposits have an elliptical shape in map view with a 900 m long axis (550 m short axis) oriented N60E which corresponds to the regional structural direction. The NE and SW extremities of the major axis are distinguished by markers that reflect a general northward collapse movement. This distension controls the injection of basalt and its massive westward flow;

- On the western flank, a shear has been observed at the southern limit, cutting the blocks of the massive basalt flow with a right lateral movement of 30° dip towards the foci as shown by the striation on the fault plane (**Figure 12a**). On this flank, basalt flows are piled up or corded. These flows form lobes that slide towards the center of the crater or that follow the gaps between the blocks of lave of the initial massive flow. The overlying scoriaceous layers attesting the strombolian explosion are affected by conjugate faults systems (**Figure 12c**) which could be an indicator of an extension oscillating swinging between WNW-ESE and NNW–SSE.

- On the eastern flank, the faults are sometimes decametric where the scarp is outlined by the bleached zone of alteration (**Figure 12b**). Subparallel cracks are associated with conjugate fault system related to this sectoral collapse NW-SE (**Figure 12d, e, f**).

4.3 Characterization of the structure of the LNH maar by applied geophysics

The treatment of the magnetic anomalies of the Middle Atlas allowed highlighting the existence of anomalies of short and long wavelengths. These last are linked to magnetized sources, notably the plio-quaternary basalts. Other anomalies

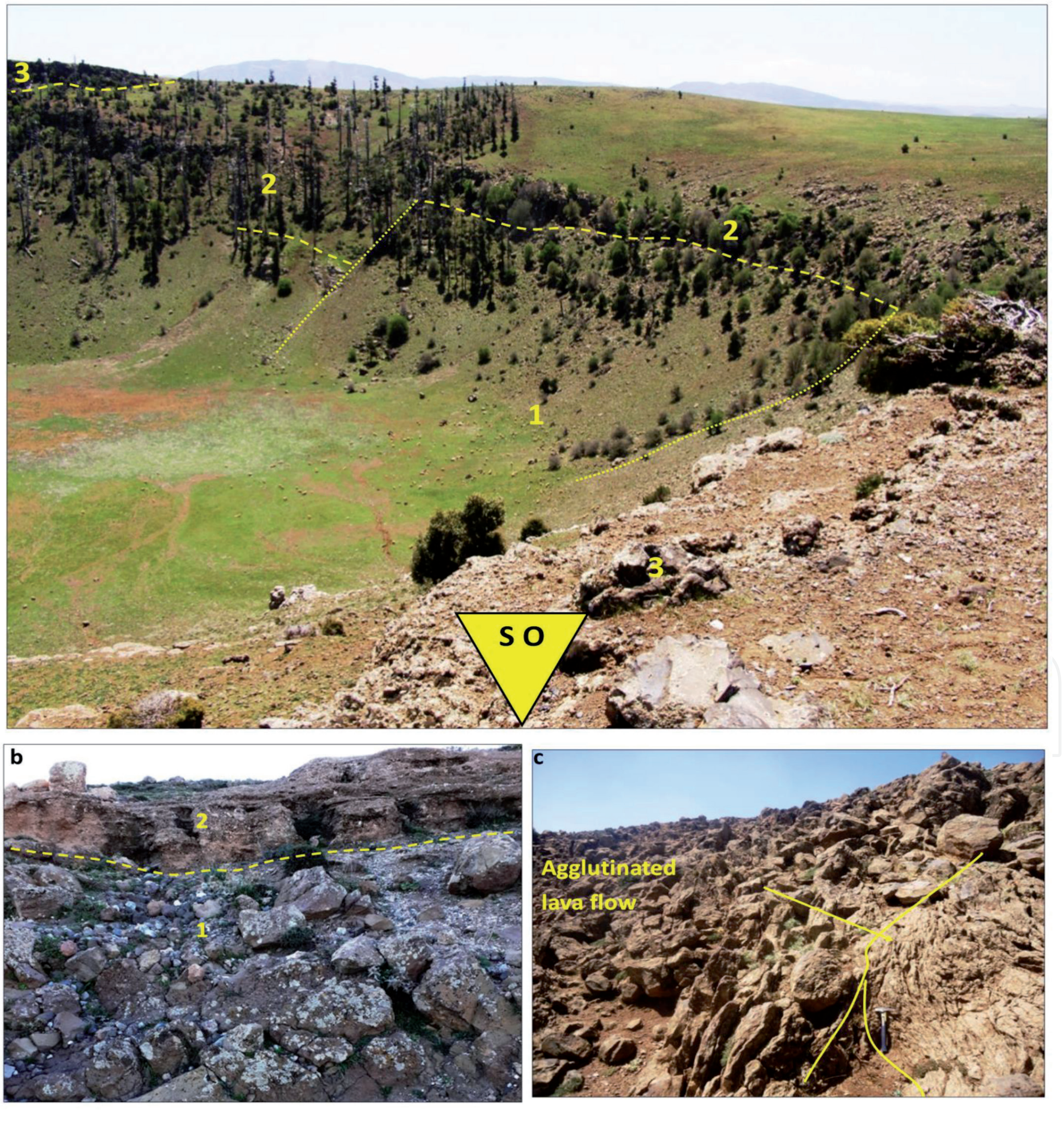

Figure 8.
Modality of expression of the eruptive activity in the maar of Lechmine n'aït el Haj in the Causse of Middle Atlas; (a) flow of basalt emitted during a collapse of the western sector of the crater (1) overlain by strombolian (2) and then phreatomagmatic fallout (3); (b) basalt prisms (1) overlain by Strombolian fallout of U3b (2); (c) corded lava flow resulting from the agglutination of lava.

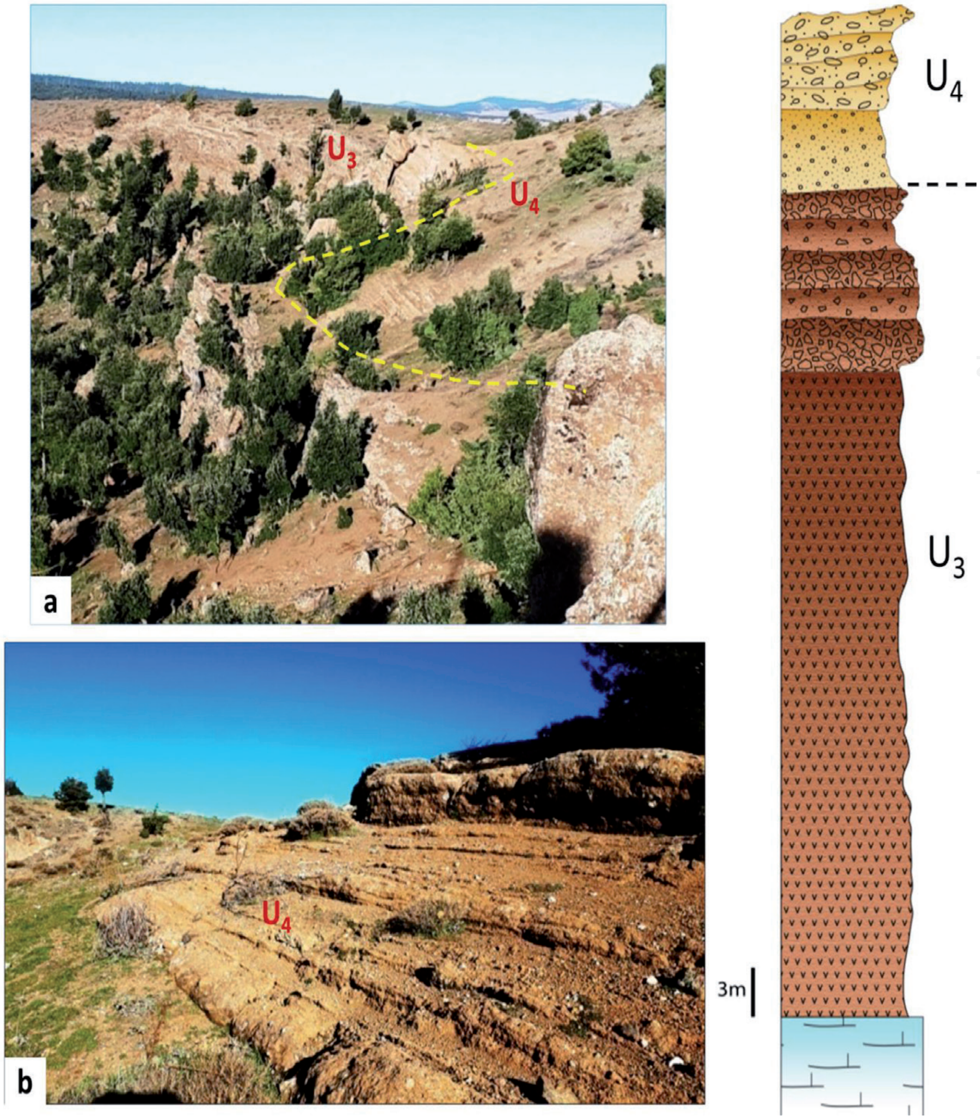

Figure 9.
Volcanic lithofacies of the last phreatomagmatic unit (U4); (a) in the northern flank; (b) in the southern flank.

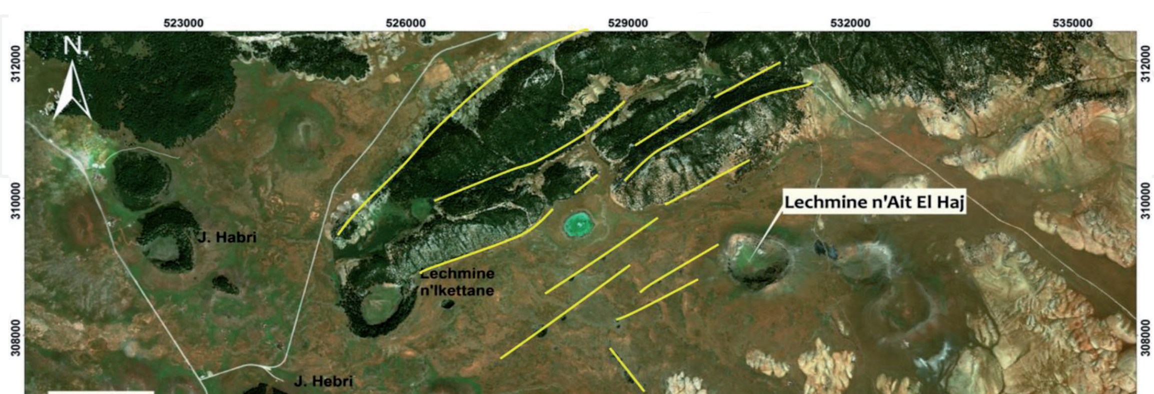

Figure 10.
The outcrop of the Maar of Lechmine n'Aït el Haj in the middle of basaltic lava flows where cryptokarstic cavities are aligned according to the major directions of the Middle Atlas.

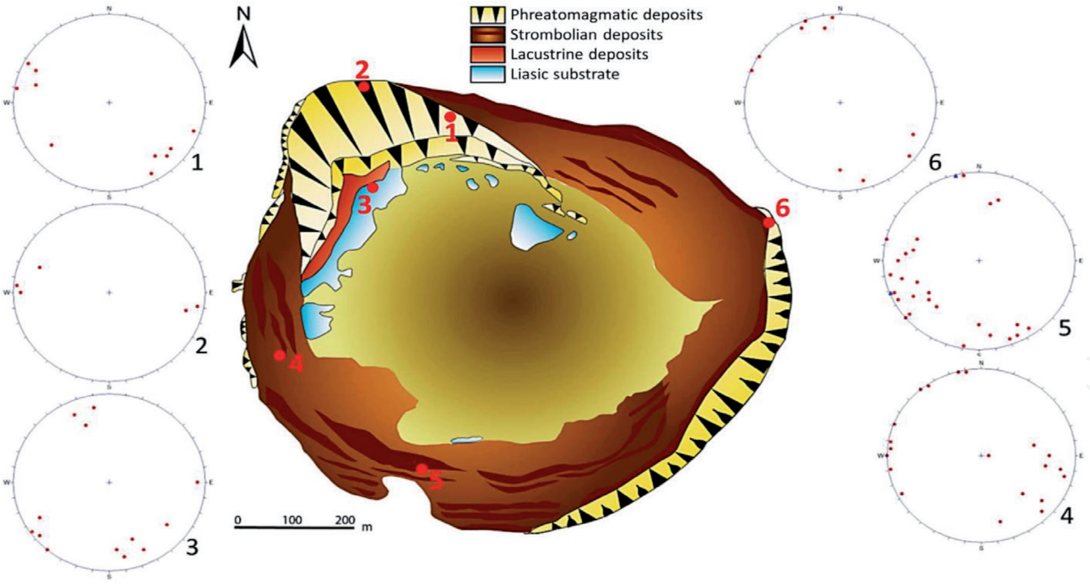

Figure 11.
Distribution of fracturing in the Maar of Lechmine n'Aït el Haj (southern hemisphere) [38].

Figure 12.
Fracturing systems in the Lechmine n'Aït el Haj maar; (a) striated fault in the basalt casting west of the maar; fracture types affecting the strombolian (b,c) and phreatomagmatic (d,e) formations of the maar; (f) geometric feature indicating a permutation of the stress parameters controlling fracturing.

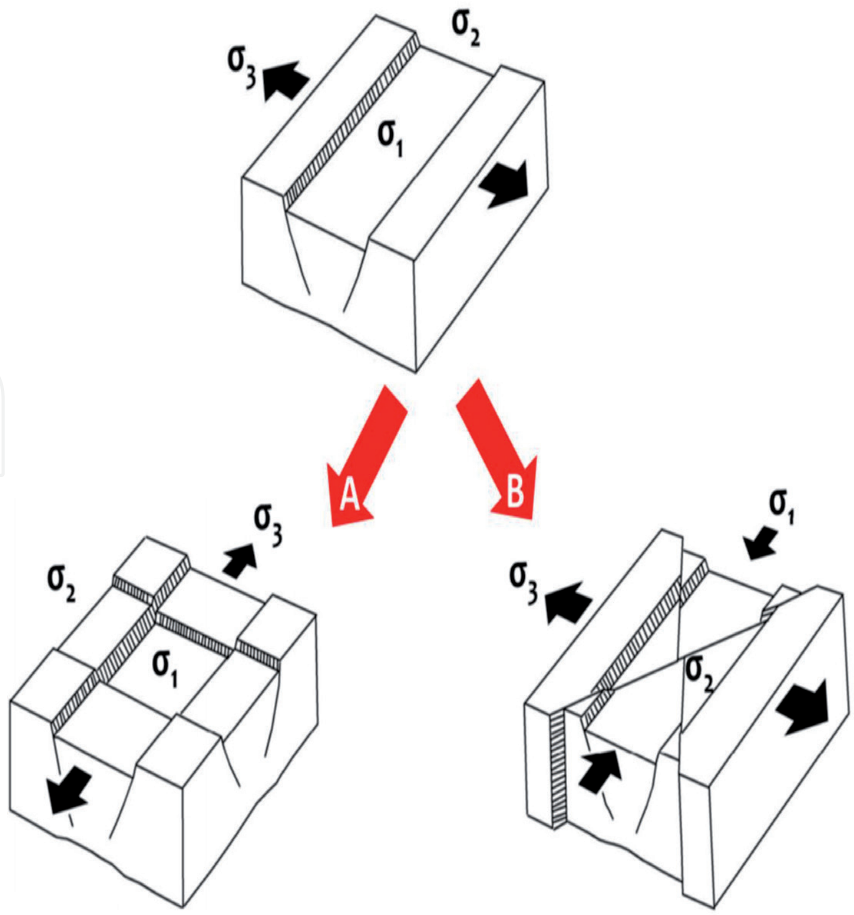

Figure 13.
Stress permutation during the volcanic activity of LNH maar.

coincide with the major accidents, such as those delimiting the Middle Atlas [39]. On the other hand, for the entire volcanic field of the Middle Causse atlas, very few studies focus on physical volcanology [40]. For example, a recent study [38] provides new information, based on geophysical prospecting combining magnetic and gravimetric methods, to the analysis of volcaniclastic deposits of LNH maar.

Gravity and magnetic data were obtained from a geophysical campaign in the LNH maar. The treatment and modelization of the collected data allowed understanding the geological features of the volcanic center and its geophysical properties [38]. Each model is limited by available geological information, including petrophysical properties, surficial geology and interpretation of geophysical data (regional and local magnetic survey data).

The 2D model was built by the GM-SYS software incorporating the geological and petrophysical properties of the study area [39] or those of comparable materials [41], and a design of the structures expected in these types of volcanoes. Approximate diatreme depths were constrained based on accessory lithic fragments observed in pyroclastic deposits. However, they represent minimum values, as phreatomagmatic explosions at deeper levels are often too small to transport material to the surface [42–44]. The gravity anomaly is modelized considering the topography. The gravity value is calculated at the surface and compared to the observed data. The reduced magnetic field to the pole (RTP) is calculated at an altitude of 2 m which corresponds to the height of the sensor. Since the magnetic susceptibility values considered represent minimum values, the susceptibility of the model has been increased to the maximum range expected for basaltic rocks [45, 46].

In the LNH model, the low gravity observed through the volcanic crater corresponds to shallow diatremes (~500 m), of lower density than their environment.

Local positive gravity anomalies, associated with magnetic anomalies of similar wavelength, are observed in the volcanic edifice (**Figure 14**). These anomalies express the presence of intrusive dykes or vents that have a higher density and magnetic susceptibility than those of the diatremes and surrounding host rocks [38]. The low magnetic signal around the diatreme fits with the pyroclastic nature of the volcanic deposits. Model adjustments suggest the involvement of a karst component to minimize the gaps between the calculated and observed anomalies. These adjustments take into consideration the density and magnetic susceptibility values of the volcanic materials.

Wide and shallow diatremes indicate abundant water supply and/or poorly lithified sediments. Deeper diatremes suggest a downward propagation of water-magma interaction due to the drying of water in the deep levels [44, 47, 48]. This suggests that explosive magma-water interactions in LNH initially occurred with shallow, poorly lithified, and water-saturated sediments, before propagating downward.

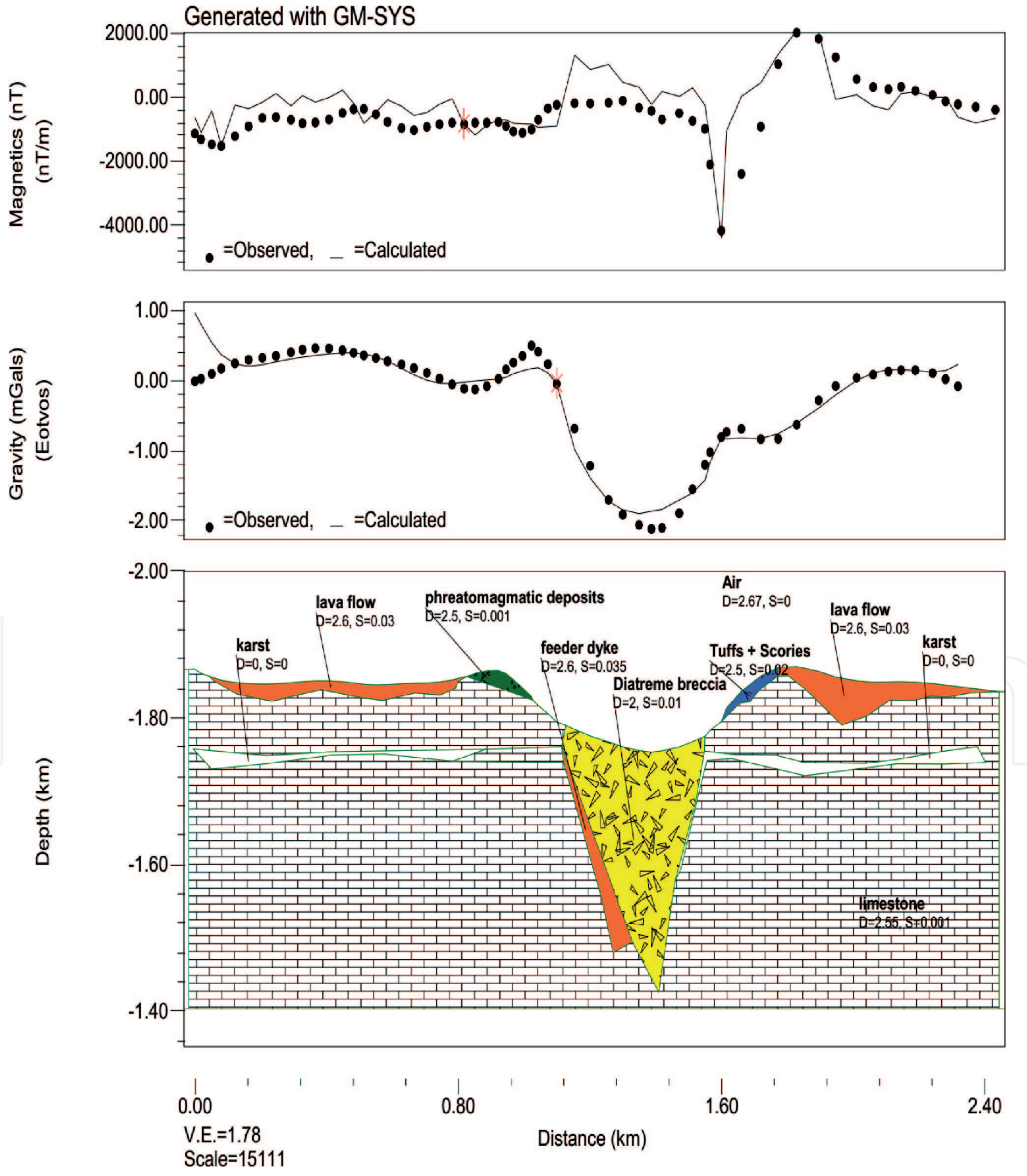

Figure 14.
Simulated model of the maar Lechmine n'Aït el Haj from observed and measured values of gravity and pole-reduced magnetic response [38].

5. Discussion and interpretation

The installation of the crater of Lechmine n'Aït el Haj is the result of explosive phenomena associated with concentric collapses at the crater. These explosions imply the meeting of basaltic magma with water, here probably underground and/or superficial water. The crater is probably open on the path of lake or streams that feed the depressions that emerge near the limestone chain in the north of the limestone plateau. The involvement of groundwater of karstic origin in the phreatomagmatic activity is justified by the position of the maar on the path of faults of cryptokarstic origin (**Figure 3**). The second phreatomagmatic phase highlighted at LNH is probably due to an input of underground water that interacts with the magma and causes the deposition of the last pyroclastic breccia (**Figure 15**).

Tectonic analysis of the fractures in the quaternary pyroclastic deposits in the LNH crater allows reconstructing the stress systems. That helped to highlight vertical markers coupled with horizontal shifts. These localized distensions are confirmed by the geometry of the fractures, the presence of tectonic markers, the mixed eruption style of the maar (strombolian-phreatomagmatic), and the mechanisms of syn-eruptive tectonics.

The eruptive activity of LNH is controlled by an NW-SE to WNW-ESE subsidence, with a changing depending on the eruptive style evolution. Thus, the activity of the LNH maar, whose first phreatomagmatic then shifted to strombolian; there is a transition from an extending system to a strike-slip system. This permutation of the stress regime $\sigma_2 - \sigma_3$ can be linked to a short-term instability (at the scale of an eruption) that can be enhanced by several factors, notably: 1. the accumulation of volcanic products that vary the position of the center of gravity and deform the edifice [49], 2/a sudden change in the composition of the magmas, notably the increase in the SiO2 content [50] or in water [51], and thus of the eruptive behavior.

During the explosions, collapse phenomena along curved fractures contribute to the widening of the crater [51]. The direction of collapse, particularly sectoral, is generally normal to the direction of active faults (normal or inverse), to alignments of parasitic cones and preferential directions of intrusion [52]. In a strike-slip context similar to that of LNH emplacement, collapse tends to have a parallel direction to the fault direction [53]. However, these relationships between tectonics and the direction of collapse are not always obvious [53]. The direction of the substrate slope, reflecting local tectonics, erosion, or volcanic activity, is generally parallel to the direction of sectoral collapse [54, 55].

The shallow diatremes suggest an eruption where the water-magma interaction remained at shallow levels. It is also an indication of a water-saturated or weakly lithified to unconsolidated host rock [47], which is consistent with the LNH volcanic structure. The multiple vents observed in this eruptive center constitute another indication of an eruption hosted in a substrate weakened by karstic corrosion or poorly consolidated sedimentation [56]. The substrate is unable to support the sloping walls of the diatreme and eventually collapses and obstructs the vent, provoking its migration and explosion in another place [56]. This explains the structure of the LNH maar, distinguished by the non-centered position of the first phreatomagmatic explosion, comparing to the center of the Strombolian explosion. The transition between magmatic and phreatomagmatic eruptive styles is explained by the variation in the groundwater supply and/or variable magma flow [57]. The preservation of the dykes in contact with the diatreme means that they took place during the later phases of the eruption, otherwise they would have been destroyed by the progressive mixing of the diatreme when deeper explosions transported material upwards [42]. This suggests that in the final stages of the eruption, the explosive fragmentation is reduced to become predominantly magmatic.

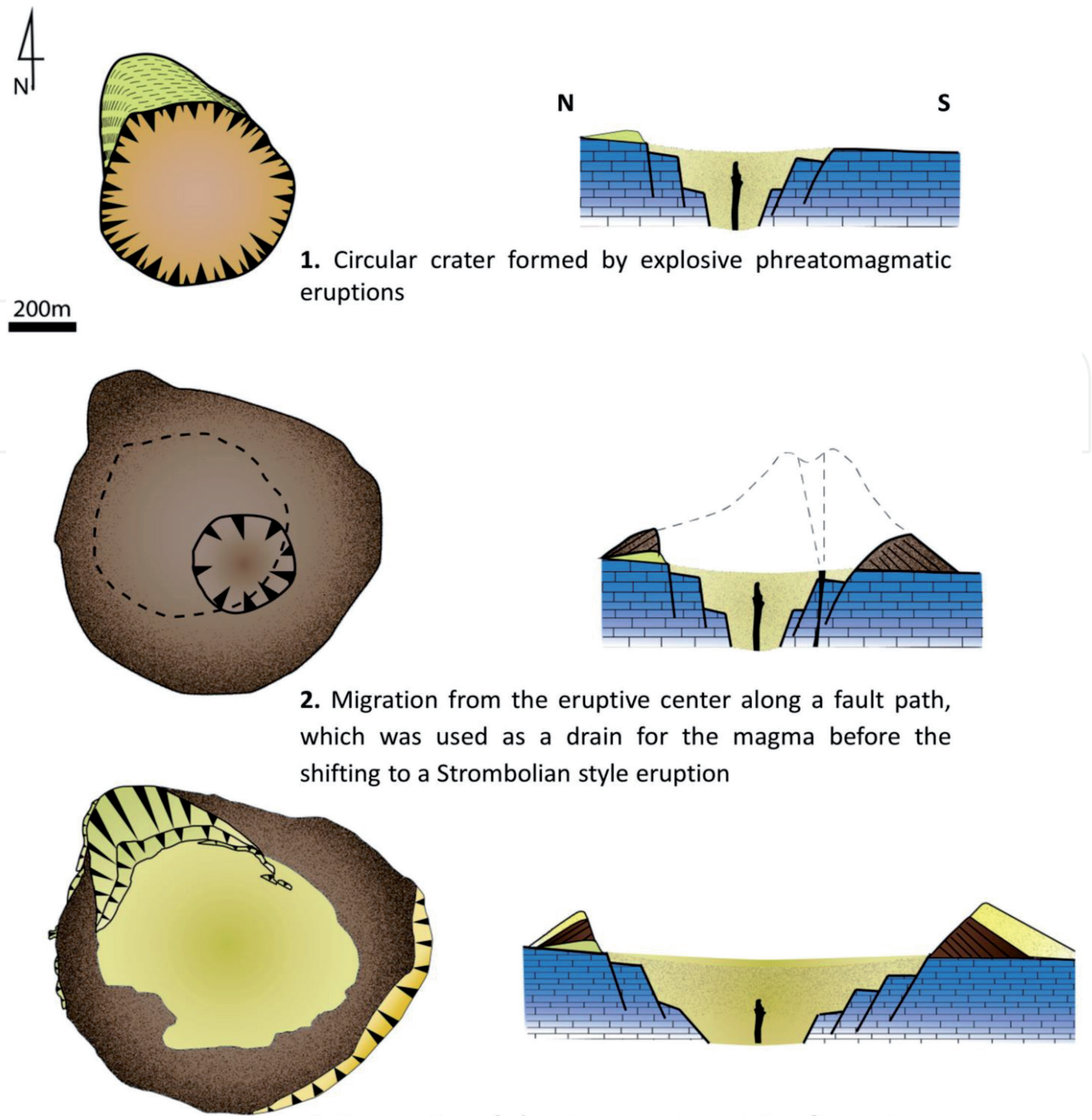

Figure 15.
Reconstruction of the volcanic evolution of the maar of Lechmine n'Aït el Haj in the Causse of Middle Atlas. (in yellow: Phreatomagmatic activity; in brown: Strombolian activity.

6. Conclusion

The application of the methods of tephrostratigraphy and geophysic to the pyroclastic deposits of the volcano Lechmine n'Aït el Haj in the Causse of the Middle Atlas allowed understanding and interpretation of the volcanic dynamics of this mixed edifice set up during the quaternary.

The LNH maar is a large-diameter explosion crater, settled in the Liasic limestone substrate and the overhanging Plio-Quaternary basaltic flows that cover the plateau. The fragments of lithics from the substrate constitute an important part of the projected products (pyroclastics), associated with the juvenile magma. The data provided by the pyroclastic deposits allow us to estimate the importance, frequency, and chronology of the eruptions of the LNH volcano. It is structured by two phases of eruptive activity, phreatomagmatic and strombolian. The pyroclastic projections of the first phreatomagmatic phase offer numerous variants with a clear dominance of Liasic limestone fragments which constitutes 60 to 70% of the deposits. Their very clear stratification is due to the rhythmicity of the explosions. The juvenile fragments only present 30 to 40% of projections in the form of scoria, bombs, and blocks.

Two important eruptive sequences marked the first phreatomagmatic phase composed of stratified deposits with an abundant lithic fraction of limestone from the Liasic basement and juvenile pyroclasts. The accidental lithics decrease during the emissive process. This phreatomagmatic activity is initiated by lake water attested by lacustrine deposits.

A second explosive phase of the strombolian eruption style follows the first phreatomagmatic phase. It begins with the effusion of a thick basalt flow due to a collapse inclined slightly to the west, and then it is a pyroclastic plume that will be launched with the fallout of different sizes and shapes depending on the proximity of the eruptive center.

The last pyroclastic breccia surrounds the crater of LNH. It occurs in discontinuous pyroclastic deposits with well-sorted bedding where the fraction of lithics is less abundant than that of the early phreatomagmatic stages.

The tectonic analysis allowed the reconstruction of the stress systems and the highlighting of the mechanisms of syn-eruptive tectonics which had an important impact on the transition of the eruptive style (phreatomagmatic-strombolian).

LNH is only one example of the 105 monogenic volcanoes of the Causse of the Middle Atlas, this study represents a first step towards the discovery of this province at the scale of volcanoes, in order to build a model of volcanic dynamics in this region, starting from the approaches mentioned above. Scientific knowledge can be exploited in addition to the natural potentialities of the region to build a model of development that fits with the particularities of this territory. Finally, the richness of the Causse of the Middle Atlas in recent monogenic volcanoes with well-preserved forms in a karstic geological context, as well as the great variety of morphology, both in terms of flows and volcanic devices, make this territory a privileged area to establish a natural geopark accessible to all and easily mediatized.

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References

[1] Kereszturi G, Csillag G, Németh K, Sebe K, Balogh K, Jáger V. Volcanic architecture, eruption mechanism and landform evolution of a Plio/Pleistocene intracontinental basaltic polycyclic monogenetic volcano from the Bakony-Balaton Highland Volcanic Field, Hungary. Cent Eur J Geosci. 2010;2(3):362-384.

[2] Németh K, Cronin S, Haller M, Brenna M, Csillag G. Modern analogues for Miocene to Pleistocene alkali basaltic phreatomagmatic fields in the Pannonian Basin:"soft-substrate" to "combined" aquifer controlled phreatomagmatism in intraplate volcanic fields Research Article. Open Geosci. 2010;2(3):339-361.

[3] Keating GN, Valentine GA, Krier DJ, Perry FV. Shallow plumbing systems for small-volume basaltic volcanoes. Bull Volcanol. 2008;70(5):563-582.

[4] Kereszturi G, Németh K. Monogenetic basaltic volcanoes: genetic classification, growth, geomorphology and degradation. In: Updates in Volcanology-New Advances in Understanding Volcanic Systems. InTech; 2012.

[5] Amine A, El Hassani I-EEA, Remmal T, El Kamel F, De Vries BVW, Boivin P. Geomorphological classification and landforms inventory of the Middle-Atlas volcanic Province (Morocco): Scientific value and educational potential. Quaest Geogr. 2019;38(1):107-129.

[6] Martin J. Le Moyen Atlas central étude géomorphologique. Vol. 258. Editions du Service géologique du Maroc; 1981.

[7] Harmand C, Cantagrel JM. Le volcanisme alcalin tertiaire et quaternaire du moyen atlas (Maroc): chronologie K/Ar et cadre géodynamique. J Afr Earth Sci 1983. 1984 Jan 1;2(1):51-5.

[8] Menjour F, Remmal T, Hakdaoui M, El Kamel F, Lakroud K, Amraoui F, et al. Role of Fracturing in the Organization of the Karst Features of Azrou Plateau (Middle Atlas, Morroco) Studied by Remote Sensing Imagery. J Indian Soc Remote Sens. 2017 Dec;45(6):1015-30.

[9] El Azzouzi M, Maury RC, Bellon H, Youbi N, Cotten J, Kharbouch F. Petrology and K-Ar chronology of the Neogene-Quaternary Middle Atlas basaltic province, Morocco. Bull Société Géologique Fr. 2010;181(3):243-257.

[10] Bosch D, Maury RC, Bollinger C, Bellon H, Verdoux P. Lithospheric origin for Neogene–Quaternary Middle Atlas lavas (Morocco): Clues from trace elements and Sr–Nd–Pb–Hf isotopes. Lithos. 2014;205:247-265.

[11] Mhiyaoui H, Manar A, Remmal T, Boujamaoui M, El Kamel F, Amar M, et al. Structures profondes du volcanisme quaternaire du Moyen Atlas central (Maroc): Apports de la cartographie aéromagnétique. Bull L'Institut Sci Rabat Sect Sci Terre. 2016;(38):111-25.

[12] Ayarza P, Carbonell R, Teixell A, Palomeras I, Martí D, Kchikach A, et al. Crustal thickness and velocity structure across the Moroccan Atlas from long offset wide-angle reflection seismic data: The SIMA experiment. Geochem Geophys Geosystems. 2014 May;15(5):1698-717.

[13] Mountaj S, Remmal T, El Amrani I-EEH, Makhoukhi S, Lakroud K, de Vries BVW. Phreatomagmatic plioquaternary volcanism in the Middle Atlas: Analysis of the eruptive sequence of the Lechmine n'Aït El Haj maar. Arab J Geosci. 2020;13(13):1-16.

[14] Németh K. Monogenetic volcanic fields: Origin, sedimentary record, and relationship with polygenetic volcanism. In: Geological Society of America Special Papers [Internet]. Geological Society of America; 2010 [cited 2018 Aug 3]. p. 43-66. Available from:https://pubs.geoscienceworld.org/books/book/624/ chapter/3805526/

[15] Smith IEM, Blake S, Wilson CJN, Houghton BF. Deep-seated fractionation during the rise of a small-volume basalt magma batch: Crater Hill, Auckland, New Zealand. Contrib Mineral Petrol. 2008;155(4):511-527.

[16] Connor CB, Stamatakos JA, Ferrill DA, Hill BE, Ofoegbu GI, Conway FM, et al. Geologic factors controlling patterns of small-volume basaltic volcanism: Application to a volcanic hazards assessment at Yucca Mountain, Nevada. J Geophys Res Solid Earth. 2000;105(B1):417-432.

[17] Canon-Tapia E, Szakács A. What is a Volcano? Geological Society of America; 2010. 152 p.

[18] Márquez A, Verma SP, Anguita F, Oyarzun R, Brandle JL. Tectonics and volcanism of Sierra Chichinautzin: extension at the front of the Central Trans-Mexican Volcanic belt. J Volcanol Geotherm Res. 1999;93(1-2):125-150.

[19] Baloga SM, Glaze LS, Bruno BC. Nearest-neighbor analysis of small features on Mars: Applications to tumuli and rootless cones. J Geophys Res Planets. 2007;112(E3).

[20] Nemeth K, White JD, Reay A, Martin U. Compositional variation during monogenetic volcano growth and its implications for magma supply to continental volcanic fields. J Geol Soc. 2003;160(4):523-530.

[21] Kereszturi G, Németh K, Csillag G, Balogh K, Kovács J. The role of external environmental factors in changing eruption styles of monogenetic volcanoes in a Mio/Pleistocene continental volcanic field in western Hungary. J Volcanol Geotherm Res. 2011;201(1-4):227-240.

[22] Valentine GA, Perry FV. Tectonically controlled, time-predictable basaltic volcanism from a lithospheric mantle source (central Basin and Range Province, USA). Earth Planet Sci Lett. 2007;261(1-2):201-216.

[23] Gutmann JT. Strombolian and effusive activity as precursors to phreatomagmatism: eruptive sequence at maars of the Pinacate volcanic field, Sonora, Mexico. J Volcanol Geotherm Res. 2002;113(1-2):345-356.

[24] Walker GPL, Sigurdsson, H, Houghton B, Rymer H, Stix J, McNutt S. Basaltic volcanoes and volcanic systems. In: Encyclopedia of Volcanoes. Academic Press; 2000. p. 283-9.

[25] Brenna M, Cronin SJ, Nemeth K, Smith IE, Sohn YK. The influence of magma plumbing complexity on monogenetic eruptions, Jeju Island, Korea. Terra Nova. 2011;23(2):70-75.

[26] Kelemen PB, Hirth G, Shimizu N, Spiegelman M, Dick HJ. A review of melt migration processes in the adiabatically upwelling mantle beneath oceanic spreading ridges. Philos Trans R Soc Lond Math Phys Eng Sci. 1997;355(1723):283-318.

[27] Sleep NH. Tapping of melt by veins and dikes. J Geophys Res Solid Earth. 1988;93(B9):10255-10272.

[28] Valentine GA, Krogh KE. Emplacement of shallow dikes and sills beneath a small basaltic volcanic center–The role of pre-existing structure (Paiute Ridge, southern Nevada, USA). Earth Planet Sci Lett. 2006;246(3-4):217-230.

[29] Connor CB. Cinder cone clustering in the TransMexican Volcanic Belt: implications for structural and petrologic models. J Geophys Res Solid Earth. 1990;95(B12):19395-19405.

[30] Guilbaud M-N, Siebe C, Layer P, Salinas S, Castro-Govea R, Garduño-Monroy VH, et al. Geology, geochronology, and tectonic setting of the Jorullo Volcano region, Michoacán, México. J Volcanol Geotherm Res. 2011;201(1-4):97-112.

[31] Huon S, Piqué A, Clauer N. Etude de l'orogenèse hercynienne au Maroc par la datation K-Ar de l'évolution métamorphique de schistes ardoisiers. Study of the Hercynian orogeny in Morocco by the K-Ar isotopic datation of metamorphic evolution in slates. Sci Géologiques Bull Mém. 1987;40(3):273-84.

[32] de Lamotte DF, Zizi M, Missenard Y, Hafid M, El Azzouzi M, Maury RC, et al. The atlas system. In: Continental evolution: the geology of Morocco. Springer; 2008. p. 133-202.

[33] Zizi M. Triassic-Jurassic extensional systems and their neogene reactivation in northern Morocco. BRides Prérifaines Guercif Basin Notes Mém Serv Géol Maroc. 2002;416.

[34] Charriere A. Évolution néogène de bassins continentaux et marins dans le Moyen Atlas central (Maroc). Bull Société Géologique Fr. 1984;7(6):1127-1136.

[35] Williams PW. The role of the epikarst in karst and cave hydrogeology: a review. Int J Speleol. 2008;37(1):1.

[36] Boulouard C. Contribution à l'étude des" saccates": essai de classification et application stratigraphique [PhD Thesis]. Université de Paris; 1963.

[37] Chateauneuf Jj, Reyre Y. Eléments de palynologie. Applications géologiques. Cours de 3eme cycle en science de la terre. 1974.

[38] Mhiyaoui H. Approche géophysique du volcanisme quaternaire du Moyen Atlas : Caractérisation magnétique et gravimétrique. Thèse, Université Hassan II, Faculté des Sciences Aïn Chock de Casablanca, 2019, 139p.

[39] El Azzab D, El Wartiti M. Mise en place de la chaîne volcanique du moyen Atlas (Maroc): Traitement des données aéromagnétiques. The Middle Atlas volcanic orogen setting (Morocco): aeromagnetic data analysis. Pangea. 1998;29:45-51.

[40] Mountaj S. Dynamique éruptive du volcan mixte Lachemine n'Aït el Haj (Moyen Atlas-Maroc): Caractérisation pétro-structurale, chimico-minéralogique et valorisation du géosite volcanique. Thèse. Université Hassan II Faculté des Sciences Aïn Chock-Casablanca;p.174. 2020.

[41] Blaikie TN, Ailleres L, Betts PG, Cas RAF. Interpreting subsurface volcanic structures using geologically constrained 3-D gravity inversions: examples of maar-diatremes, Newer Volcanics Province, southeastern Australia. J Geophys Res Solid Earth. 2014;119(4):3857-3878.

[42] Valentine GA, White JD. Revised conceptual model for maar-diatremes: Subsurface processes, energetics, and eruptive products. Geology. 2012;40(12):1111-1114.

[43] Lefebvre NS, White JDL, Kjarsgaard BA. Unbedded diatreme deposits reveal maar-diatreme-forming eruptive processes: Standing Rocks West, Hopi Buttes, Navajo Nation, USA. Bull Volcanol. 2013;75(8):739.

[44] Ross P-S, White JDL, Valentine GA, Taddeucci J, Sonder I, Andrews RG. Experimental birth of a maar–diatreme volcano. J Volcanol Geotherm Res. 2013 Jun;260:1-12.

[45] Clark DA. Comments on magnetic petrophysics. Explor Geophys. 1983;14(2):49-62.

[46] Clark DA. Magnetic petrophysics and magnetic petrology: aids to geological interpretation of magnetic surveys. AGSO J Aust Geol Geophys. 1997;17:83-104.

[47] Auer A, Martin U, Németh K. The Fekete-hegy (Balaton Highland Hungary) "soft-substrate" and "hard-substrate" maar volcanoes in an aligned volcanic complex–Implications for vent geometry, subsurface stratigraphy and the palaeoenvironmental setting. J Volcanol Geotherm Res. 2007;159(1-3):225-245.

[48] Lorenz V. Maar-diatreme volcanoes, their formation, and their setting in hard-rock or soft-rock environments. Geolines. 2003;15:72-83.

[49] Tibaldi A. Multiple sector collapses at Stromboli volcano, Italy: how they work. Bull Volcanol. 2001;63(2-3):112-125.

[50] Belousov A, Belousova M, Voight B. Multiple edifice failures, debris avalanches and associated eruptions in the Holocene history of Shiveluch volcano, Kamchatka, Russia. Bull Volcanol. 1999;(61):324-42.

[51] Moore JG, Nakamura K, Alcaraz A. The 1965 eruption of Taal volcano. Science. 1966;151(3713):955-960.

[52] Capra L, Macias JL, Scott KM, Abrams M, Garduño-Monroy, V.M. Debris avalanches and debris flows transformed from collapses in the Trans-Mexican Volcanic Belt, Mexico - behavior, and implications for hazard assessment. J Volcanol Geotherm Res. 2002;(113):81-110.

[53] Ponomareva VV, Melekestsev IV, Dirksen OV. Sector collapses and large landslides on Late Pleistocene–Holocene volcanoes in Kamchatka, Russia. J Volcanol Geotherm Res. 2006;158(1-2):117-138.

[54] Belousov A, Walter TR, Troll VR. Large-scale failures on domes and stratocones situated on caldera ring faults: sand-box modeling of natural examples from Kamchatka, Russia. Bull Volcanol. 2005;5(67):457-68.

[55] Carrasco-Núñez G, Díaz-Castellón R, Siebert L, Hubbard B, Sheridan MF, Rodríguez SR. Multiple edifice-collapse events in the Eastern Mexican Volcanic Belt: The role of sloping substrate and implications for hazard assessmen. J Volcanol Geophys Res. 2006;(158):151-76.

[56] Ort MH, Carrasco-Núñez G. Lateral vent migration during phreatomagmatic and magmatic eruptions at Tecuitlapa Maar, east-central Mexico. J Volcanol Geotherm Res. 2009;181(1-2):67-77.

[57] Houghton BF, Wilson CJN, Smith IEM. Shallow-seated controls on styles of explosive basaltic volcanism: a case study from New Zealand. J Volcanol Geotherm Res. 1999 Jul 1;91(1):97-120.