Cent. Eur. J. Geosci. • 2(3) • 2010 • 362-384
DOI: 10.2478/v10085-010-0019-2

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Central European Journal of **Geosciences**

Volcanic architecture, eruption mechanism and landform evolution of a Plio/Pleistocene intracontinental basaltic polycyclic monogenetic volcano from the Bakony–Balaton Highland Volcanic Field, Hungary

Research Article

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Received 28 April 2010; accepted 17 June 2010

Abstract: Bondoró Volcanic Complex (shortly Bondoró) is one of the most complex eruption centre of Bakony-Balaton Highland Volcanic Field, which made up from basaltic pyroclastics sequences, a capping confined lava field (~4 km^2) and an additional scoria cone. Here we document and describe the main evolutional phases of the Bondoró on the basis of facies analysis, drill core descriptions and geomorphic studies and provide a general model for this complex monogenetic volcano. Based on the distinguished 13 individual volcanic facies, we infer that the eruption history of Bondoró contained several stages including initial phreatomagmatic eruptions, Strombolian-type scoria cones forming as well as effusive phases. The existing and newly obtained K-Ar radiometric data have confirmed that the entire formation of the Bondoró volcano finished at about 2.3 Ma ago, and the time of its onset cannot be older than 3.8 Ma. Still K-Ar ages on neighbouring formations (e.g. Kab-hegy, Agár-tető) do not exclude a long-lasting eruptive period with multiple eruptions and potential rejuvenation of volcanic activity in the same place indicating stable melt production beneath this location. The prolonged volcanic activity and the complex volcanic facies architecture of Bondoró suggest that this volcano is a polycyclic volcano, composed of at least two monogenetic volcanoes formed more or less in the same place, each erupted through distinct, but short lived eruption episodes. The total estimated eruption volume, the volcanic facies characteristics and geomorphology also suggests that Bondoró is rather a small-volume polycyclic basaltic volcano than a polygenetic one and can be interpreted as a nested monogenetic volcanic complex with multiple eruption episodes. It seems that Bondoró is rather a "rule" than an "exception" in regard of its polycyclic nature not only among the volcanoes of the Bakony-Balaton Highland Volcanic Field but also in the Neogene basaltic volcanoes of the Pannonian Basin.

Keywords: maar • scoria cone • monogenetic • polycyclic • polygenetic

1. Introduction

Monogenetic volcanoes are commonly referred to as those which erupt only once [1], but in general monogenetic volcanic edifices are built up by a discrete series of volcanic eruptions. Therefore monogenetic volcanoes are relatively small in volume; usually <0.1 km^3 [2]. However, an increasing number of recent papers have demonstrated that monogenetic volcanoes can evolve, producing as complex and diverse eruptions as their larger counterparts. This raises the question of how such volcanoes can be characterised, especially when they are old [3–5]. In the case of common monogenetic volcanoes (for instance maar, tuff ring or scoria cones) their eruption may be phreatomagmatic [6, 7], violent Strombolian [5, 8], Surtseyian [9], or Hawaiian-type [3, 10] in style. The behaviour of the eruption is largely controlled by internal factors such as the volatile content of the magma [11] or magma ascent speed [11, 12], as well as external factors such as the presence of surface water and/or ground water [13, 14], geographic elevation [15], and tectonic forcing [16]. This wide range of controlling conditions commonly governs the style of an eruption and leads to so called 'transitional eruptions' [11, 12]. 'Transitional' eruption styles commonly take place between Hawaiian- and Strombolian-style eruptions. However, the same processes can also be recognized between phreatomagmatic and magmatic explosive eruption styles [6, 17]. The volcano-facies architecture commonly records shifts in fragmentation styles of active and non-active monogenetic volcanic fields, such as Lamongan volcanic field in East Java [18], Waipiata Volcanic Field in New Zealand [19] and Meidob Volcanic Field in northwest Sudan [20].

On the other hand, long-lasting (decades to millions of years) and/or intermittent eruption of volcanoes associated with typical monogenetic volcanic fields is relatively rarely documented. Parícutin scoria cone (Michoacán Volcanic Field, Mexico) is perhaps one of the most recent examples of a relatively long-lasting eruption of a large scoria cone [21]. The total eruption history spanned just 9 years with additional decades of intense degassing after the explosive events ceased [5, 21, 22]. Although the total life of Parícutin is rather short (almost a decade), it is still longer than the time needed to solidify any basaltic magma column from the source to the surface. This suggests that there were repeated magma injections over a time period of years, which might indicate the existence of a magma plumbing system similar to large volume or polygenetic volcanoes. To contrast this magma plumbing system with nature and the common volcanic architecture typical for monogenetic volcanoes, it is better to use 'polycyclic' as a descriptor to distinguish this type of eruption style from very short lived single eruptions.

Here we define a monogenetic eruption as one where a small volume of magma is erupted in short period of time. In such monogenetic eruptions the magma is expected to

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reach the surface in a single eruptive episode (of weeks to years in duration) during which all features of the volcano are formed. However, even monogenetic volcanic structures may consist of several eruptive episodes and the resulting lava flows may inter-finger or pile on top of each other producing complex lava fields. In this terminology a monogenetic volcano represents the formation, ascent, and eruption of a single batch of magma, and takes place over a period of days to several years. Potential chemical variations of the eruptive product in a monogenetic context could be linked to varying degrees of mixing and fractionation of the magma batch involved in each eruption.

Volcanoes that erupt substantial volumes of material are generally polygenetic and are formed over thousands to millions of years by eruption of multiple magma batches, each having distinct chemical signatures. In the case where the erupted volume in each eruptive cycle is always small (typically in the 0.1–0.001 km^3 range), we can define a subset of polygenetic volcanoes: 'polycyclic monogenetic volcanoes'. In this definition, the polycyclic framework refers to a volcano, where magma batches may be separated by sufficient time for the volcanic plumbing system to have cooled after previous activity. During polycyclic activity, typical features such as unconformities within cones, scattered individual vents, and well defined lava flow morphologies are among the key features that can be preserved and recognized in the geological record. In the case, where compositionally distinct magmas are involved in a short lived monogenetic eruption, we can define it as polymagmatic rather than monomagmatic. It is likely, but not necessary, that a polycyclic eruption is also polymagmatic.

In addition, there are polygenetic maar volcanoes such as Albano maar (Colli Albani volcano, Italy) that represent another end-member style of volcanic activity involving volcanoes traditionally classified as monogenetic. Albano volcano is characterized by multiple but intermittent eruptions from several tens of thousands up to 5.8 ka BP [4, 23]. This time scale is certainly a few orders of magnitude larger than that over which Parícutin formed, and it would be necessary to express these differences in any classification. In addition, the size (e.g. diameter, volume, area covered by eruptive products) and complexity of the eruptive products of Albano maar make this volcano more closely resemble a large, polygenetic volcano. Another example of the long-lasting eruption history of a volcano considered to be monogenetic due to its volume and eruption history is the rhyolitic Cerro Pizarro volcano in Mexico where a significant time break (~50–80 ka) took place between eruptive cycles [24].

Nevertheless, volcanic facies architecture of volcanoes that would generally be considered as monogenetic, and yet are characterized by a shifting eruption style over relatively long time periods (several thousand up to millions of years) has only rarely been documented in detail. Thus, in this paper, we will provide new field-based evidence from logged surface exposures and drill core data to support the existence of long lived, but small-volume basaltic volcanism that would generally fall in the monogenetic category, using an example from the central part of the Bakony–Balaton Highland Volcanic Field (Figure 1). From the study of volcanic erosion remnants (the Bondoró Volcanic Complex), we demonstrate that in the course of the eruption history of the Bakony–Balaton Highland Volcanic Field, polycyclic monogenetic volcanoes were commonly formed.

The Bondoró Volcanic Complex (shortly Bondoró; Figure 1) has been considered to be a small-volume but long-lived volcano, where significant time differences between eruption cycles were assumed (based on existing K-Ar radiometric ages) [25]. However, detailed facies analysis, drill core interpretation and geomorphic investigations have not yet been carried out. To fill this knowledge gap, we present detailed descriptions of pyroclastic and solidified lava outcrops that are exposed at the southern and central part of the volcanic complex with the aim of understanding and recognizing the long-lasting and changing eruption styles responsible for forming a complex volcano through various eruption cycles. We use both volcanological and geomorphological observations to infer the main evolutional phases of Bondoró that support the idea of it being a polycyclic vent which formed an overall small-volume volcanic complex with multiple eruptions phases.

2. Geological background

The Bakony–Balaton Highland Volcanic Field is located in the western part of the Pannonian Basin and lies between the latitudes N 46° 39' 25" and N 47° 06' 02" and longitudes E 17° 13' 31" and E 17° 52' 37", covering an area of approximately 3500 km^2 (Figure 1). It is a classical continental monogenetic volcanic field with at least 50 moderate to deeply eroded remnants of maar/tuff rings and their diatremes, shallow sill and dyke complexes, shield volcanoes and Strombolian-type scoria cones from Miocene to Pliocene age [26–28] (or to the Pleistocene according to the new International Stratigraphic Chart [29, 30]). Generally, the volcanism is closely related to small, N–S alignments, that were hydrologically active in syn-volcanic time [31]. The basement of the Bakony–Balaton Highland Volcanic Field is mostly composed of Permian red sandstone and Mesozoic carbonates [32]. The thickness of the Middle to Upper Triassic,

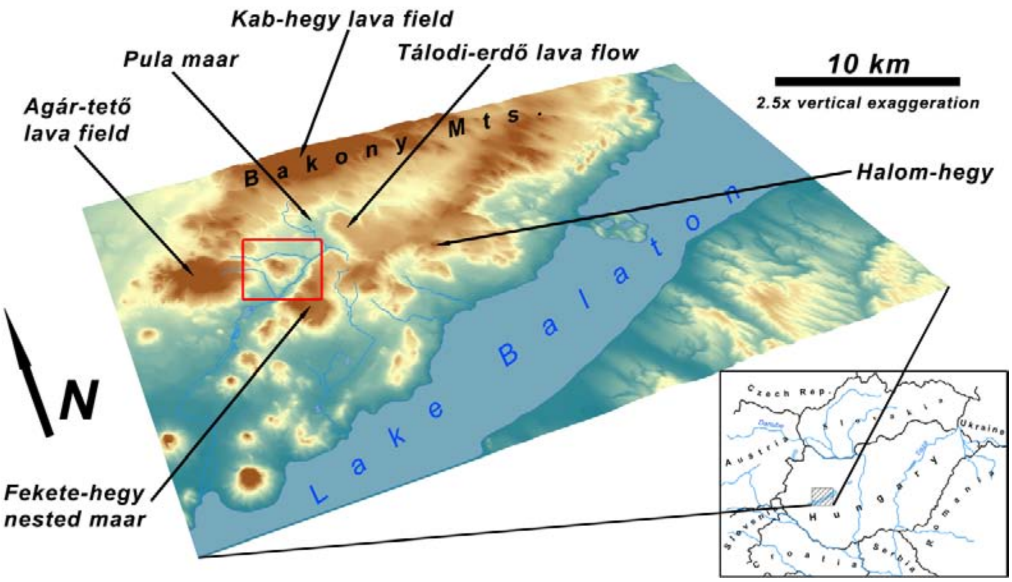

Figure 1. Location of the Bakony–Balaton Highland Volcanic Field in Central Europe and a Digital Elevation Model of the central part of the volcanic field showing the location of Bondoró (red framed area).

karstified carbonate sequence is 1500–3000 m. The thickness of sediments overlying the basement in the study area is estimated to have been 100–300 m at the time of the formation of Bondoró.

The pre-volcanic basin system at the boundary of the Balaton Highland and the Bakony Mountains, the so called Nagyvázsony Lagoon, is characterized by a wide range of siliciclastic (e.g. silt, sand) and other mostly loose, porous sediments including marl, silt and lacustrine limestone [32]. These deposits generally overlie the Permo-Triassic basement of the Bakony–Balaton Highland Volcanic Field [33]. This basin system was part of a large lake, Lake Pannon, which disappeared around 8 Ma [34, 35]. Shortly after the disappearance of a lacustrine environment, a drainage network evolved upon the loose deposits and this valley system may have hosted the majority of the volcanic vents [28, 36].

In general, the Mesozoic carbonates of the basement have played an important role in the eruption style of Bondoró. In addition, the loose, unconsolidated, siliciclastic sediments beneath the volcanic vent of the Bakony–Balaton Highland Volcanic Field also played an essential role as porous aquifers controlling the style of phreatomagmatism [28, 31, 36–39]. The geological setting and the hydrogeological characteristics of the rocks beneath Bondoró suggest that the mixed nature (hard versus soft substrate aquifers) of the country rocks had an influence on the overall eruption style of Bondoró.

3. K-Ar radiometric age measurements of Bondoró

K-Ar dating of the Bakony-Balaton Highland Volcanic Field started in the late 1970s [40, 41] and the first review paper appeared in 1986 [27]. These early works revealed that K-Ar data give either the real geological age, or a geologically unrealistic older age. It has been shown that older ages are caused by (1) incomplete degassing of previously accumulated 40Ar (radiogenic) from the lava, or (2) by the mantle xenoliths whose old age was not fully overprinted. In the case of (1), the real age usually can be obtained by applying isochron methods by dating more samples, which can be regarded as coeval on the basis of geological evidence. The measured isotopic data of these samples will approximate a straight line and the real age can be obtained from the slope of this line. On the other hand, in the case of (2) the data usually show an apparently random distribution. This indicates that the samples are unsuitable for dating and the obtained ages must be interpreted with caution. An advanced method of sample preparation was introduced by Fitch et al. [42], who applied the isochron method to fractions prepared by magnetic and heavy liquid separation from a single rock sample. Difficulties, and a new way of applying the isochron method have been described by Balogh et al. [43].

Samples of two units from Bondoró have been dated by K-Ar [27]. These were taken from the borehole Monostorapáti-1 (Mat-1) and represent one of the upper

(39.7–41.0 m; 2nd lava unit) and the lowest (120.8–122.4 m; lava "infill" in the Figure 6) lavas. In spite of large errors, the age of the upper lava unit (2.90±0.62 Ma) shows that Bondoró must belong to the youngest basalts of the Bakony–Balaton Highland Volcanic Field. On the other hand, ages on the lowest basalt layer scatter from 16.8 Ma to 3.86 Ma, showing that entrained xenoliths were not overprinted during eruption. No isochron age could be calculated for the samples of the lowest basalt. According to our experience in such a case, the real age is best approximated by the ages of the more magnetic fractions. Therefore the best estimate of the age of the lowest basalt is ⩽3.86±0.20 Ma.

Several years later a new dating was performed on a sample provided by A. Embey-Isztin [44]. On the basis of morphological-volcanological considerations he thought this rock was formed in the youngest volcanic eruption of Bondoró. New volcanological-morphological studies presented here suggest an age of 2.29±0.22 Ma [44].

As a consequence of this young age, the activity of Bondoró finally ended in the lower Pleistocene on the basis of the International Stratigraphic Chart by The International Commission on Stratigraphy [29, 30].

4. Volcanic stratigraphy

The simplified 3D architecture of Bondoró contains several parts, including the basal pyroclastic rocks that occur as continual layers on the slopes around the present volcanic edifice. The occurrence of pyroclastic rocks in the basal sequences of individual volcanoes in the Bakony–Balaton Highland Volcanic Field is common, and can be interpreted as a sign of magma/water interaction during the initial eruption phase [28]. Here, we systematically describe and interpret the supposed phreatomagmatic-dominated pyroclastic successions exposed at the southern side of Bondoró (Figure 2). These basal layers are mostly made up of pyroclastic rocks of facies T1, T2, LT1, 2, 3, 4 and 5 and are described in detail in the following sections.

In general, these initial phreatomagmatic eruptions generated pyroclastic materials that are commonly capped by effusive rock units such as lava flows and scoria cone remnants [28]. In the case of Bondoró, the pyroclastic units vary in thickness between 17 and 50 m [45]. The lavas of Bondoró sit directly on these basal pyroclastic rocks and form an extended lava plateau (facies LR2 and VB1a,b) with two small (<0.1 km^2) ephemeral lakes (Figure 2). A quite large cone-like mound (basal diameter: ~1200 m and height: ~60 m) sits upon this lava plateau (TB1 and LR1 lithofacies).

However, the present appearance of Bondoró neither resembles a fresh scoria cone nor a maar/tuff ring volcano due to its eroded nature. During the long period of erosion since its formation (~2–3 Ma on the basis of K-Ar datings) resistant units (mostly lavas) have largely protected the underlying pyroclastic units around the basal volcanic edifice. These have degraded faster than the volcanic rocks preserved in the volcanic edifice of Bondoró resulting in the formation of a volcanic butte that stands about 200–250 metres above the surrounding valley floor. In the steep cliff faces around the butte, the internal medial/proximal volcanic architecture of Bondoró is exposed; these sections form the main basis for the present study. The edifice has also been penetrated by 2 drill holes (cored during the 1970s, see Figure 2 for locations). The deepest borehole was the Monostorapáti–1 (Mat-1), which is about 121 m deep [46]. Furthermore, Mat-2 (~60 m deep) also penetrated the lava and pyroclastic successions of Bondoró (Figure 6), and reached the Neogene and Mesozoic country rocks [47]. Together with the logged sections, these boreholes provide an excellent opportunity to reconstruct the major evolutional stages of the whole volcanic edifice.

In spite of the obvious geomorphic inversion producing a volcanic butte, a small cone-shape mound can still be recognized at the top of the volcanic edifice in the central part of the preserved volcano. This mound is inferred to be a primary volcanic landform and is characterized by a poorly defined crater that is breached toward the east (breaching azimuth ~40–60° from north). The present cone-shaped remnant is characterized by maximum cone height ~80 m, crater depth ~60 m and maximum and minimum crater width of 800 and 500 m respectively on the basis of morphometrical measurements. It is also slightly elongated from N to S (Figure 2).

In general, the southern side of the present volcanic edifice is characterized by steeper slopes (~30–40°) than on the northern side (~10–15°). Thus, this condition is favourable for the formation of large outcrops (Figure 2). In addition, at these outcrops (Sec. 1, 2, 3 and 4) on the southern side, the contact zone is exposed between the basal pyroclastic rock units and capping coherent lava rocks. In order to establish the main stages of volcanic evolution at Bondoró as well as to find evidence(s) of significant time breaks, we measured the volcanic facies at these outcrops in detail and interpreted the existing drill core data. The aim is to reconstruct the potential eruption cycles that may be represented by certain facies changes. In addition, the central, cone-shaped, scoriaceous mound was also investigated.

The examined eruption sequences of Bondoró are represented by 2 facies associations (basal phreatomagmatic and capping magmatic) and 13 sedimentary facies on

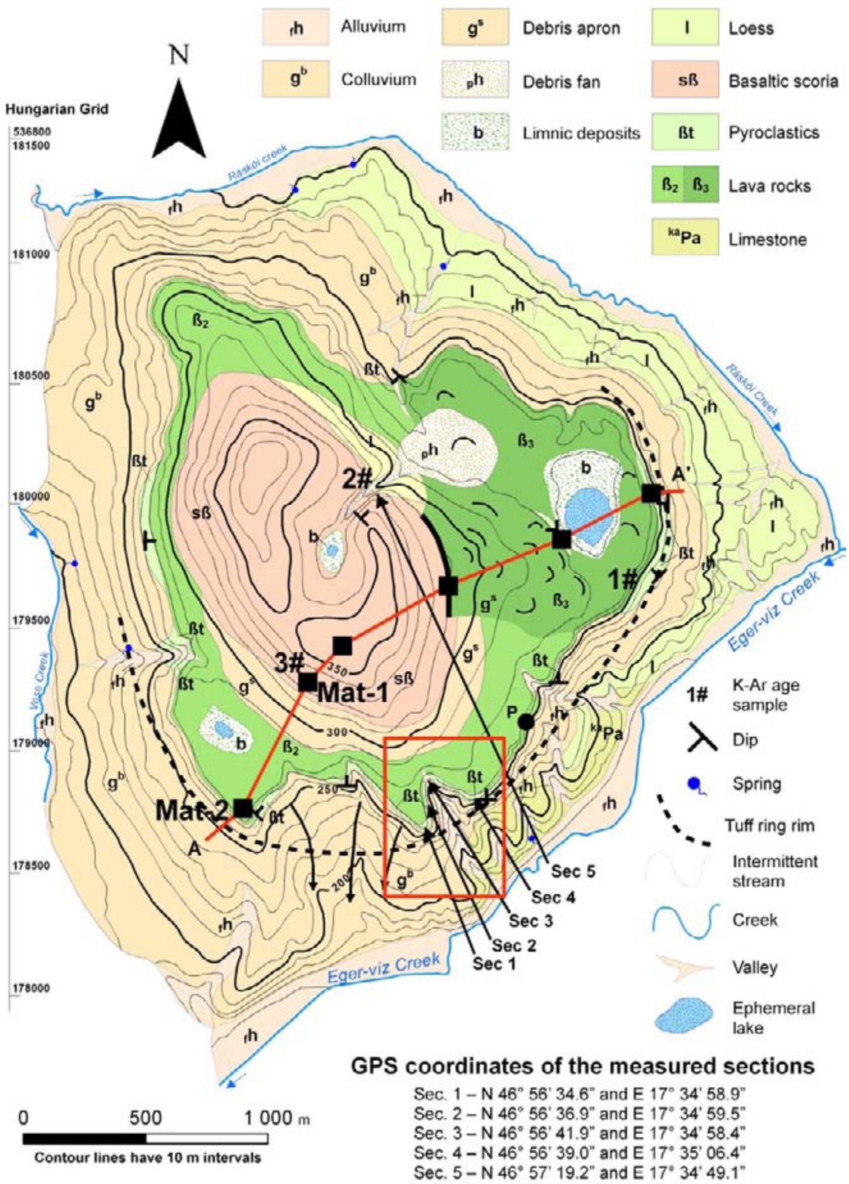

Figure 2. Geological sketch of Bondoró showing the location of the measured sections, the samples used for K-Ar dating and the two boreholes (Mat-1 and Mat-2). The red line marked A–A' shows the cross-section location in Figure 6.

the basis of bedding characteristics, bedding structures, grain-size and composition (Table 1). Terminology of pyroclastic rocks are after Fisher and Schmincke [48].

4.1. Basal pyroclastic facies associations

4.1.1. Very thinly bedded tuff (T1) and lapilli tuff (LT1)

Description: This facies occurs in Sec. 4 at the southern side of Bondoró (Figure 2). The outcrop is located at about 260–270 m a.s.l. as well as ~1100–1200 m from centre point of the present erosional butte (Figures 2 and 3).

This facies consists of very thinly bedded, well-stratified tuffs (T1) and lapilli tuffs (LT1) with the colour of grey to white (Figures 3 and 4A). Both T1 and LT1 are grain-supported with normal grading. However, significant textural discrepancy can be seen within Sec. 4 as coexistence of lapilli-rich (LT1) and lapilli-poor (T1) layers in the measured section (Figures 3 and 4A). The larger (few cm in diameter), angular to sub-angular accidental lithic

Table 1. Volcanic facies classification scheme based on grain size and bedding after Sohn and Chough [55].

Facies	Section	Tuff (T)	Lapilli tuff (LT)	Tuff breccia (TB)	Volcanic breccia (VB)	Lava rock (LR)	Interpretation	Position	Phase
Very thinly bedded	4	T1	LT1				phreatomagmatic base surge deposits in distal/medial position	~ 1100 m	I
Thinly laminated	4	T2					phreatomagmatic ash-fall deposits in distal/medial position	~ 1100 m	I
Massive	3		LT2				high concentration, phreatomagmatic base surge deposits in medial position	~ 900 m	I
Medium bedded	1,4		LT3				phreatomagmatic base surge deposits in distal/medial position	~ 1100 m	I
Medium bedded, clast and grain-supported	4		LT4a,b				phreatomagmatic, vent-opening/cleaning with base surge deposits with ballistically emplaced blocks in distal/medial position	~ 1100 m	I
Thinly to medium bedded	3,4		LT5				reworked pyroclastics in medial-distal position	~ 900 – 1100 m	II
Poorly sorted, reddish scoriaceous	5			TB1			magmatic Strombolian-type scaoriaceous deposits in proximal position	~ 200 – 300	IV
Poorly sorted, black	1,2,3,4				VB1,b		"wet" and "dry" auto-clastic breccias on lava flows foot	~ 900 – 1100 m	III
Undulating, coherent	5					LR1	cross-cut dyke in proximal position	~ 200 – 300 m	IV
Coherent	1,2,3,4,5					LR2	basaltic lava flow(s)	-	III

clasts from the underlying strata are abundant (mainly from Neogene and Mesozoic carbonates strata, ~30-40 vol.% by visual estimate). Maximum 5 vol.% of Permian red sandstone accidental lithic clasts can be found. Furthermore, there are a few rounded lithic gravels in this unit. The angular to sub-angular, dense, black juvenile fragments are common (~20 vol.% by visual estimate). These layers do not consist of any impact sags or accretionary lapilli.

Interpretation: The bedding characteristics, such as very thinly bedded or well stratified internal texture as well as abundance of accidental-lithics and basal location of this facies, point out the initial magma/water interaction [49]., This led to the formation of an oval-shaped tuff-ring with a possible shallow and wide crater. The eruption locus may have evolved in a carbonate-dominated environment (maybe at shallow depth) because the accidental lithic clasts are overwhelming in these basal layers.

The presence of thinly bedded lapilli and ash-dominated layers rich in glassy pyroclasts are inferred to be generated by phreatomagmatic eruptions that initiated base surges [17, 49, 50]. According to Chough and Sohn [51], this type of pyroclastic segregation may have been a result of a pyroclastic density current, which fluctuated in velocity and concentration. Similar pyroclastic facies ("Facies LT6: stratified lapilli tuff") described from Songaksan tuff ring (Jeju Island, South Korea) were systematically identified near the crater in proximal regions and ~600–700 m from the geometrical centre point of the crater [51], suggesting that the eruption centre of Bondoró also had to be close to the present location of Sec. 4 (Figure 2). But the overall grain-size is smaller than the Songaksan tuff ring, so the medial and distal position is reasonable.

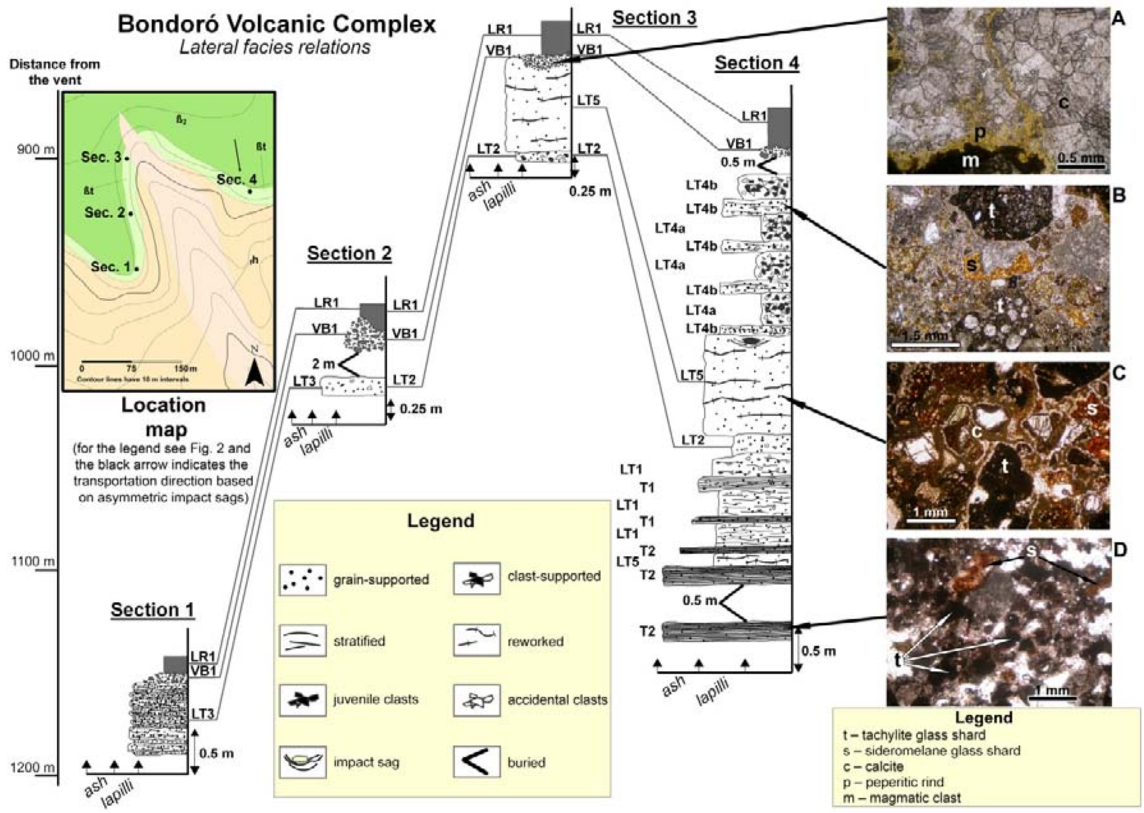

Figure 3. Simplified logs of the measured outcrops and their lateral relationship, together with thin section photos of representative lithologies.

4.1.2. Thinly laminated tuff (T2)

Description: This facies is located at the basal part of the pyroclastic units on the southern side of Bondoró, around 240-250 m a.s.l. (∼1100 m from the geometrical centre of the edifice) at Sec. 4 (Figure 2). Facies T2 is a continuous 20–30 cm thick layer within the successions of Bondoró, so the horizontal thickness variation is poor (Figures 3 and 4A).

T2 comprises monotonous, planar- and rarely cross-laminated, well-sorted, grain-supported as well as mantle-bedded thinly laminated tuff with 0.5–1 mm sized accidental lithic (∼10 vol.% by visual estimate) and juvenile clasts (∼5 vol.% by visual estimate) in addition to lherzolites. The colour of this facies is mostly grey to white. There is no evidence of any impact structures, accretionary lapilli, sedimentary deformations or larger bombs/blocks. In thin section, this facies contains large quantities of black tachylite and minor yellow-orange sideromelane glass shards (thin section photo D in Figure 3).

Interpretation: Based on the present distance from the centre point of the butte and bedding evidence, this facies is inferred to have been deposited at a medial position (∼1100 m from the supposed vent locality). The uniform bed thickness over the southern escarpment of Bondoró and well-sorted mantle-bedding texture of facies T2 indicate its ash-fall origin [14] or from an ash-fall after a slowly moving, low-concentration surge [51, 52]. Furthermore, the abundance of tachylite glass shards can be a sign that particles were most likely to travel through air [28]. The lack of impact sags or pyroclastic deformation suggests that this facies may have been dry during the course of the eruption. Furthermore, the well-sorted texture, fine grained volcanic glass rich beds and the thinly laminated ash layers resulted from the optimal fragmentation of uprising magmas under the ratio of magma/water between 0.1 and 1 [53]. The slightly cross-bedded appearance also indicates the fall-out origin from a turbulent surge.

4.1.3. Massive lapilli tuff (LT2)

Description: This facies is exposed in Sec. 3 (Figure 2). The distance of this outcrop is about 900–1000 m from the geometrical centre point of the erosional butte (Figure 2). This facies represents the closest exposed pyroclastic rock units to their source.

Figure 4. (A) Outcrop photo of the basal part of Sec. 4 (for the location see Figure 2). Note: Initial phreatomagmatic ash (T1) and lapilli-dominated sequences (LT1) of Bondoró in Sec. 4. Note the pencil is 15 cm in length. (B) Field photo of the upper part of Sec. 4; (C) Photo of Sec. 1 including the medium bedded lapilli tuff (LT3) and the capping VB1a; (D) Dune-bedded lapilli tuff (LT3). Note the hammer is 30 cm in length.

The LT2 facies includes monotonous, normal graded, poorly to moderately sorted, grain-supported lapilli tuffs (Figures 3 and 4B). The accidental lithics are abundant (red sandstone <5 vol.% and carbonates ~20–30 vol.% by visual estimate). Juvenile fragments are lapilli-sized, dark and angular, and their proportion is about ~30–40 vol.% by visual estimate. There are bombs/blocks with 10–15 cm diameter, but a lack of impact structures or any plasticity of the beds. The colour of these layers varies from grey to white.

Interpretation: Beds with massive internal texture commonly occur close to the vent [54], and are inferred to be deposited from a high-concentration, turbulent pyroclastic density current [48, 51, 54]. However, the present centre of the volcanic edifice is around 800–900 m away from Sec. 3 and 1000–1100 m away from Sec. 4. This large difference indicates that the eruption centre of the initial tuff-ring forming eruption had to be closer to the present location of Secs. 3 and 4 (Figure 2).

4.1.4. Medium bedded lapilli tuff (LT3)

Description: Sec. 1 and 4 is situated about 260–270 m a.s.l. at the southern escarpment of the erosional remnant of Bondoró (Figure 2). Both sections are relatively far from the geometrical centre of the volcanic remnant (between 1100–1200 m; Figure 2) and consist of medium bedded, centimetre-sized internally stratified, multiply normal graded lapilli tuffs mostly grey to white in colour with variable juvenile and angular, accidental lithic clasts. These clasts are mostly limestones (~20–30 vol.% by visual estimate) derived from the underlying carbonate strata (Figure 3) and are mostly lapilli-sized, rarely block-sized in a matrix of fine ash. Each bed is 15 to 30 cm thick and shows normal grading (Figure 4A). In addition, facies LT3 shows mostly parallel bedding and is rarely dune-bedded (Figure 4D). However, close to Sec. 1 (~100 m), this facies can be slightly dune bedded. The dunes are about 1.5 m in wavelength and around 30 cm in amplitude (Figure 4D). Larger clasts are common, but there are no evidences of impact sags and accretionary lapilli.

Interpretation: Based on the thickness of beds and the slightly dune-bedded appearance, facies LT3 is more likely to form in medial or distal positions as compared with LT1 facies. These pyroclastics were created by base surges [2, 55–57], which associated with initial phreatomagmatic explosions on the basis of bedding type (e.g. slightly dune bedded) and basal location within the succession of Bondoró. Evidence of large clasts without any deformation (e.g. impact sags) suggest that these blocks were transported laterally by a pyroclastic density current [55]. Furthermore, the lack of accretionary lapilli and deformation structures suggest that these base surges were dry [55].

4.1.5. Medium bedded, clast (LT4a) and grain-supported lapilli tuff (LT4b)

Description: This facies occurs only in Sec. 4, although, it is common along the southern flank of Bondoró, but missing from the neighbouring Sec. 3 (Figure 3); the distance between the two outcrops is only about 100–150 m (Figure 2).

LT4a and b mostly occur 1000–1100 m from the present geometrical centre of the volcanic edifice. The base of these layers is about ~260 m a.s.l. Only 3–4 individual beds have been identified in all outcrops, including Sec. 4 and other outcrops not described here.

The volcanic facies of LT4a and b commonly consist of basal, clast-supported and capping grain-supported lapilli tuffs (Figures 3 and 4B). In general, the basal beds (LT4a) are characterized by chaotically bedded, normal-graded and poorly-sorted appearance with larger basaltic (~50 vol.% by visual estimate and the largest is ~80 cm in diameter;) and accidental lithic blocks (red sandstone <5 vol.% and carbonates <10 vol.% by visual estimate). The juvenile fragments are: (1) dense, angular and (2) scoriaceous (rounded shaped with spherical vesicular). In thin section photo B (Figure 3), black angular and non-vesicular tachylite and yellow to brown, non-vesicular sideromelane glass shards can be recognized. The average size of the bomb and blocks are 10–15 cm in diameter, but a large spindle bomb (~80 cm diameter) is exposed between the LT5 and LT4a beds.

The volcanic facies LT4b is mostly lapilli-sized and plane- or sometimes dune-bedded with normal grading (Figures 3 and 4B). The juvenile and accidental lithic clasts are angular to sub-angular and the proportion is similar to the aforementioned facies LT4b.

In the case of LT4a and b, the proportion of basaltic fragments increases upward from around ~20–30 vol.% to ~60–70 vol.% by visual estimate. Both volcanic subfacies are brown, grey and white in colour.

Interpretation: The difference between the lower and upper beds is significant, which indicates the different origin. Those with normal grading, clast-support, chaotic bedding texture combined with abundant angular to sub-angular large blocks were transported ballistically. The interbedded finer, planar and slightly dune-bedded layers were generated by pyroclastic density current (for example basal surge) [14, 55, 58]. Impact sags are missing, so the eruptions may have been dry [55].

This chaotically bedded unit is inferred to represent deposits derived from vent opening and/or cleaning eruptions [2, 14]. The high proportion of glassy juvenile fragments in these beds suggests a phreatomagmatic origin (e.g. tachylite and sideromelane glass shards in the thin section photo B in Figure 3). Thus, this facies can be interpreted as deposits of dry, high-concentrated pyroclastic density currents such as phreatomagmatic base surges [55].

The interpretation of lithofacies of LT4a and b, which are missing from Sec. 3 is discussed in Section 4.2.2.

4.1.6. Thin to medium bedded lapilli tuff (LT5)

Description: This facies comprises layers in the middle part of Sec. 3 and 4 (Figures 2 and 3). These layers are almost continuous between Sec. 3 and 4, however, they are missing from Sec. 1 and 2 (probably covered by slope debris). These beds consist of white, brown and light orange coloured, moderate to well-sorted, thin to medium bedded, multiple reverse graded, massive to weakly stratified lapilli tuff (Figures 3, 4A, B). The lapilli-sized fragments (both accidental lithics and juvenile clasts) are cemented by white to light yellow, fine, microcrystals of $CaCO_3$ and also contain various amounts of tachylite and sideromelane glass shards (thin section photo C in the Figure 3). The particles are mostly rounded or sub-rounded (thin section photo C in the Figure 3). A large, 80 cm spindle-type bomb caused an asymmetric impact sag in the lithofacies LT5 with a N to S transportation direction (black arrow on the location map in Figure 3). Furthermore, the texture of these pyroclastics show an unaltered to strongly altered nature.

Interpretation: Based on the rounded to sub-rounded shape of both accidental and juvenile fragments (both sideromelane and tachylite), reverse graded, well-sorted, massive to weakly stratified texture and the slight to strong alternation indicates that this facies LT5 was deposited by secondary, reworking processes [17, 59]. In addition, there is no evidence (e.g. dune and/or cross-bedding) of high energy, turbulent pyroclastic density currents such as base surge or pyroclastic flow. Facies LT5 was most likely generated by debris flow and/or turbidity current, which are possibly related to (1) syn-eruptive earthquakes, rockslides and/or crater wall collapse [17, 49]; or (2) post-eruptive erosional processes.

4.2. Capping magmatic facies associations

4.2.1. Reddish, scoriaous tuff breccias (TB1) and associated lava rocks (LR1)

Description: The lithofacies TB1 occurs at the eastern slopes of the central part of the preserved, primary cone-shape mound, where Sec. 5 is exposed due to long-lasting erosion 200–300 m from the geometrical centre of the volcanic edifice (Figure 2). The elevation of the outcrop is about 320–330 m a.s.l. The geographical distribution of the facies TB1 is based on a circle as well as it depicts a cone-shaped mound in three-dimensions. This mound is open from the east and characterized by depth ~50–60 m and width ~300–400 m (Figure 2).

These deposits directly sit on the large (~4 km^2) coherent lava rocks. The facies TB1 consists of primarily reddish, partly sintered, oxidized, angular to sub-angular, moderate to highly vesicular lapilli (from ~20% up to ~80%), bomb and block clasts forming unsorted tuff breccias (Figure 5C). The particles are characterized by fractured, reddish scoriaceous clasts with rough relief. The individual particles of this tuff breccia are partially melted together. Large spindle type bombs are abundant in various sizes ranging from several cm up to 100 cm in diameter.

Furthermore, coherent lava rocks (LR1) are also exposed and these are intercalated by the previous, scoriaceous tuff breccias. These lava layers are wavy and undulating (Figure 5B). The colour is almost the same as the previous breccias, but slightly lighter as well as partly non-vesicular in appearance. The margin of the lava rocks is rough and the thickness is between 0.5–1.5 m. The direction/distribution of lava rocks in Sec. 4 does not follow the prevailing slope gradient conditions (Figure 5B).

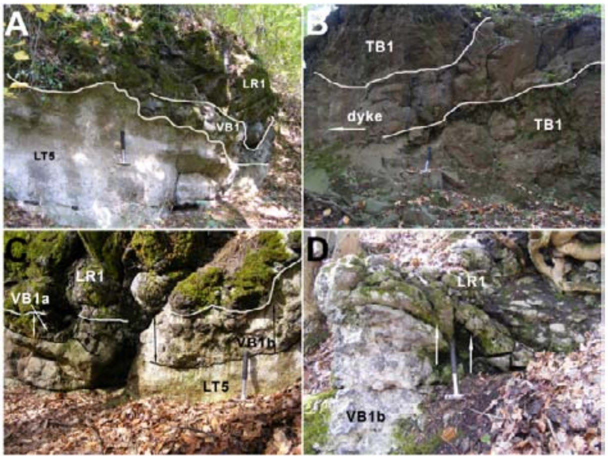

Figure 5. (A) The contact zone of phreatomagmatic deposits (LT2, LT5), capping magmatic lava flows (LR1), and autoclastic breccias (VB1a,b) in Sec. 3; (B) Variation in thickness of peperitic-autoclastic breccias within Sec. 3; (C) Outcrop photo of Sec. 5 in the breached side of the scoria cone remnant of Bondoró. Small-scale, cross-cut dyke is exposed between reddish, scoriaceous breccias (TB1). The white arrow indicates the possible direction of dyke injection; (D) Erosion remnant of a small tumuli structure at Sec. 2. The transition between peperitic units and the coherent lava rocks can be seen. Note the hammer is 30 cm in length.

Interpretation: The highly vesicular texture, colour and 3D distribution of scoriaceous deposits indicates that facies TB1 was created by Strombolian-type eruptions of upwelling magmas [2, 60–62], which led to the formation of a large scoria cone. The highly stacked, agglutinated appearance of tuff breccias indicate that the gradual cooling of hot particles during the (maybe short) trajectory and on the accumulation surface lead to some degree of agglutination of the particles [63, 64].

The reddish colour of tuff breccias may have derived from the heating effect of uprising lavas, indicating the proximity of the vent/crater zone. Furthermore, the proximity of the lava field and the crater (near vent cone-building pyroclastics) also indicates the baked and agglutination texture of individual clasts. Based on the characteristic agglutinate textures identified here, these clasts must have been hot and partially molten during transportation and retained heat long after their emplacement. They likely travelled along a short ballistic trajectory, which is an additional explanation for the close crater proximity.

The bedding characteristics of facies LR1, such as undulatation and varying thickness, indicates that in Sec. 5 this facies is a remnant of a small, cross-cut dyke. This dyke is exposed only at the breached side of the scoria cone, so the breaching may have resulted from 1) syn-eruptive slope failure triggered by dyke injection [65], or 2) lava effusion [10], or 3) erosional processes owing to the long-lasting erosion [66].

4.2.2. Poorly sorted, black volcanic breccias (VB1a and b)

Description: The facies VB1 occurs in all the measured sections on the southern slope of the remnants of Bondoró (Figure 2). These outcrops are situated between 260 and 270 m a.s.l. Between the 4 localities (Sec. 1, 2 3 and 4) along the southern rim of the erosion butte, this facies is almost continuous and partly visible.

There are two main types of appearance of this facies exposed in the measured sections (Figure 3). In general, both types of the facies VB1 are characterized by mostly grey to black coloured, poorly sorted, large (several cm up to tens of cm-sized), irregular, monomict, non to weakly vesicular (<20% and ~60–80%) volcanic breccias with jigsaw fit texture (Figure 5C, D). In addition, these facies are similar in colour and textural appearance to the covering lava units. Moreover, both types settle upon rough, undulating depositional surfaces (Figure 5A, C). Furthermore, there is no field evidence of paleosol horizons. The volcanic facies VB1 is intercalated with the basal pyroclastic rocks of LT3, LT4a,b and LT5 lithofacies, and capped by coherent lava rocks of the LR2 lithofacies (described in detail in the following section and Figure 3).

The major differences between the two types of volcanic breccia are the variation in their matrix, depositional position and thickness. The first type (VB1a) occurs only at Sec. 1, 3 and 4. This type of volcanic breccia is predominantly clast-supported and is concentrated only at the topographic height of the undulating depositional surface. Individual beds of this volcanic breccia are several tens of cm in thickness (~10 to 50 cm). A slight transition is apparent in Sec. 3, from clast-supported to grain-supported volcanic breccias (Figure 5C).

The second type (VB1b) is different in internal texture because it is hosted by a grain-supported sediment halo. This sediment matrix is characterized by white to grey colour, lapilli-sized particles which are cemented by large amounts of $CaCO_3$ (Figure 5C, D). The individual magmatic fragments have a rough surface and a thin chilled, peperitic rind (thin section photo A in Figure 3). This facies VB1b mostly occurs in Sec. 2 and 3 (Figure 5C, D). The beds of volcanic breccia VB1b are significantly thicker than VB1a (Figure 5C). The maximum thickness of VB1b beds (~1 m) is exposed in Sec. 2, where undulating deformed-structure is shown by capping lava rocks (Figure 5D).

Interpretation: In general, both clast types of VB1a and b can be interpreted as autoclasts on the basis of colour, textural similarity (with the capping lava unit) as well as their monomict and jigsaw fit style nature [67]. These autoclastic breccias are commonly located at the foot of lava flows and characterize most subaerial basaltic lava flows [67–70]. Volcanic facies VB1 settles between the basal, tuff-ring-forming phreatomagmatic and reworked sequences, as well as the subsequent lava units. However, the two types of facies VB1 could be formed under different conditions.

Based on chaotically bedded, matrix-poor texture and angular, monomict clasts, the first type of VB1a lithofacies can be interpreted as an ordinary autoclastic, lava flow foot breccia, which was created by the movement of semi-solid and/or solid lavas [68, 70–73].

Evolution of VB1b lithofacies is slightly more complex than the previous one, because significant differences can be seen in its matrix, which mostly consists of fine, grain-supported lapilli-sized reworked and primary volcaniclastic particles. Based on the presence of chilled margins on magmatic clasts, the host sediment (in this case the lithofacies LT5) must have been wet during formation of the lava foot breccia. The existence of mixing (mostly at topographic lows of the undulating depositional surface) in several parts of facies VB1 may indicate that facies LT5 was also un- or semi-consolidated. As a consequence of these conditions, magma/sediment interactions took place and led to the formation of peperitic domains in alternation with autoclastic lava foot breccias [74, 75]. It seems a moving lava flow (Figure 5C, D) partially 'bulldozed' into this slightly wet and loose, un- or semi-consolidated tephra rim, remobilizing its fine particles causing carbonate precipitation and fine grained sediment halo formation around larger, coherent lava clasts [75–78]. At Bondoró, however, both the water-saturation level and the stage of consolidation of the host sediments may have been limited because the peperitic domains concentrate only at topographic lows and the beds of facies VB1 are relatively thin (Figure 5C).

There is a significant facies change between the basal pyroclastic units and the subsequent lava flows exposed at all of the measured sections along the southern rim of the present degraded volcano. Based on significant undulation and existence of topographic lows on the depositional surface beneath VB1 facies, it can be interpreted as an unconformity (at about 260-270 m a.s.l.; Figure 5A). This depositional gap and the associated unconformity are possibly caused by an erosional stage during the evolution of Bondoró. Moreover, LT4a and b facies, which were most likely to be emplaced ballistically, are existing at Sec. 4 but missing from proximal Sec. 3 (lateral distance about 150 m). This field observation also indicates that an erosional stage took place, but the duration may have been short because there are no evidence of soil formation. Nevertheless, according to paleoclimatical data [79, 80], climatic conditions from wet/humid (~3.8–3 Ma ago) to dryer/semiarid (~2.9–2.3 Ma ago) took place during the formation of Bondoró. These conditions favoured soil formation, so the time gap between the two cycles may have been between decades to thousands of years long [81].

4.2.3. Coherent lava rocks (LR2)

Description: Coherent basaltic lava rocks cover the whole volcanic remnant of Bondoró between elevations of 270 and 310 m a.s.l., and are exposed in Secs. 1–4 (Figure 2). Upon this unit settles the reddish, scoriaceous tuff breccias of the TB1 lithofacies and directly beneath are the basal pyroclastics (LT3, LT4a, b and LT5) and autoclastic breccias (VB1a, b). Coherent lava rocks cover an area of almost 4 km^2. The general appearance of the LR2 lithofacies is grey to black in colour, coherent, non to moderately vesicular lava, usually platy jointed lava rocks with basal, volcanic breccias (Figure 5D). The vesicles are strongly elongated and flattened in shape. Vertical changes can be seen within Sec. 2, where the coherent lava rocks show continual transition into the volcanic facies of VB1 (Figure 5C, D). Nevertheless, we cannot see any lateral facies and morphological changes within Secs. 1–4, but these variations may be obscured since most of the present surfaces are covered by vegetation and/or slope debris.

Interpretation: Based on the vesicle orientation, coherent texture and surface orientation of coherent lava rocks, the volcanic facies of LR2 can be interpreted as an erosional remnant of a lava flow, located between the capping scoria cone deposits, and the foot breccias (<1 m) and basal pyroclastic successions [82]. This lava field completely covers the initial phreatomagmatic pyroclastic successions, preserving them from erosion. The geographical distribution and the stratigraphic position of lava rocks in the outcrops and Mat-1 and 2 boreholes (2^{nd} lava flow unit; $ß_2$ in the Figures 2 and 6) indicate that the lava flow field was emplaced prior to or during the scoria cone-forming eruptions. However, the exact source of these lava flows in Bondoró is unknown.

The original texture, shape and appearance of the present lava surface remnants (which are highly eroded, smooth and mostly non-vesicular) cannot be easily identified. As compared with a basaltic lava flow from Paraná Basin (Southern Brazil), where more or less intact lava toes have been preserved over 130 Ma [83], at Bondoró we have not found any morphometrical evidence of such lava toes or ropy surfaces, which clearly indicates their pahoehoe nature. Thus, the lava flows of Bondoró were most likely to be "aa"-type and purely pahoehoe type lavas were apparently rare and/or poorly preserved at the Bakony–Balaton Highland Volcanic Field [28].

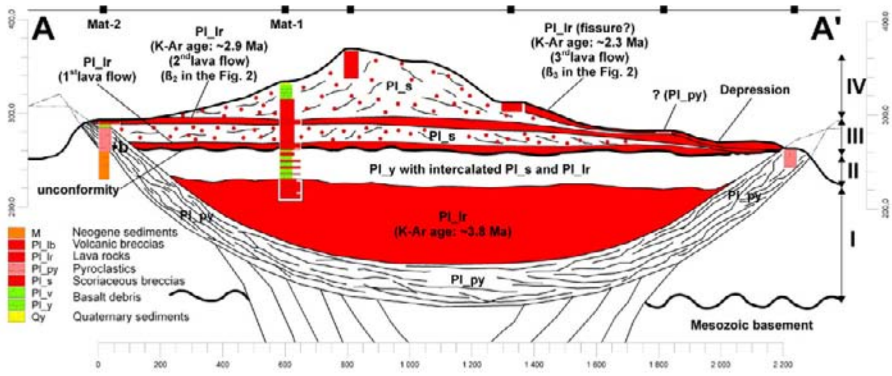

Figure 6. Interpretation of drill core data of Bondoró and the volcanic architecture (3x vertical exaggeration) of the present remnant including various type of volcanics of evolutional stages (I – basal tuff ring with a lava lake; II – reworked units; III – effusive units with intercalated scoriaceous tuff breccias; IV – capping scoriaceous tuff breccias) and wide range of eruptional deposits based on drill core descriptions by Á. Jámbor [46, 47].
Note: b – slightly backtilted pyroclastics.

4.3. Volcanic architecture: interpretation of drill core datasets

In this section we intend to correlate drill core data with surface exposures of volcanic rock units and interpret the volcanic architecture of Bondoró in the light of these correlations. According to drill core descriptions by Á. Jámbor [46, 47], the general volcanic stratigraphy of Bondoró is the following (Figure 6): basal pyroclastics (∼30 m thick) with thick infill (at least 20 m) lava units; chaotic calcareous (or bentonite?) cemented scoriaceous lapilli and breccias with intercalated lava units (∼30 m thick); 1st lava (∼6 m thick), scoriaceous lapilli and breccias (∼20 m thick); 2nd lava (∼5 m thick; $ß_2$ in the Figure 6), and the capping scoriaceous deposits (∼40 m thick). In addition, the 3rd lava units ($ß_3$) are exposed only at the surface in the south-eastern part of Bondoró (Figures 2 and 6).

4.3.1. Basal pyroclastics units

Descriptions: The location of these layers is limited to the basal part of Bondoró (level I in the Figure 6). The basal pyroclastic rocks are characterized by brownish, yellowish to grey tuffs and lapilli tuffs which are structureless in the upper levels and well stratified in the bottom of the drill cores. The beds are massive, poorly sorted in the upper levels (∼5–10 m depth) and gradually altered to well sorted and stratified and cross-bedded texture at the bottom (∼10–30 m depth). The juvenile clasts are cm-sized and vesicular in texture. Furthermore, in these beds accidental lithic fragments such as limestones and dolomites (only few %) are rare [47].

Interpretation: These pyroclastic rocks are similar to all of the phreatomagmatic pyroclastic rocks (e.g. LT1– and T1–2 lithofacies) on the surface and measured in the Sec. 1–4 along the southern escarpment of Bondoró (Figure 6). The phreatomagmatic origin is supported by the poorly to well-sorted texture, abundant vesicular and non vesicular juvenile clasts and the presence of accidental lithics in a generally cross-bedded pyroclastic succession.

4.3.2. Basalt debris with intercalated scoriaceous and coherent lava units

Description: These beds are situated between the "infill" lava rock and the 1st lava unit at about 70–100 m depth (level II in the Figure 6). These relatively thin layers (usually under 2–3 m) comprise mostly yellowish, brownish and poorly to non stratified lapilli (average grain size is 1 cm) and breccias (up to 15 cm in diameter). The scoriaceous lapilli are abundant, and their vesicles are commonly filled by calcite [46]. These deposits are hosted by a light yellow calcareous or bentonite matrix [46]. Between 72 and 74 m depth, this hosting matrix is thicker and mostly contains large (up to 15 cm), magmatic, angular blocks with a yellow, weathered rind. These layers are commonly intercalated by thin (only few m) scoriaceous and coherent lava rocks (Figure 6).

Interpretation: The colour, grain-size and hosting calcareous matrix make these deposits similar to the reworked LT5 lithofacies. The weathered rind and basalt debris with intercalated scoriaceous and coherent lava rocks are very thick; almost 30 m (Figure 6). This suggests that the deposition of these layers was complex and are inferred to be deposited during a relatively long period of time (from several decades up to hundreds of thousands years).

4.3.3. Coherent lava units

Description: According to Á. Jámbor [46, 47], these units are mostly rich in mantle xenoliths, coherent, black to gray, sometimes with platy jointing, non to weakly vesicular, lava rocks with microcrystal texture. They are located at several levels within the architecture of Bondoró (level III in the Figure 6). The very basal ("infill") coherent lava body is very thick ~20 m as compared to the upper, thin (~5 m) 1st and 2nd lava intercalations.

The two previously existing K-Ar radiometric measurements confine the age of the lava infill from ⩽3.8 Ma to 2.9 Ma (however, 3.8 Ma is better correlated to the real geological age on the basis of its position) and the 2nd lava unit (~2.9 Ma; Table 2 and Figure 6).

Interpretation: Based on the significant thickness variation, the lower (thickness of at least 20 m) lava body can be interpreted as a basal tuff ring infill lava lake. However, the additional two magma bodies are most likely to be thin lava flows (Figure 6). Based on the depositional elevation and its similarity to the present elevation of the lava field, 1st and 2nd lava flow intercalations may have reached the surface and capped the basal pyroclastics in the effusion stage of Bondoró (Figure 6).

4.3.4. Capping lapilli and breccia units

Description: The capping lapilli and breccias are located (level IV in the Figure 6) at various depths between 0 and 70 m [46]. However these layers are commonly interfingered by coherent lava units (mostly at the level III in the Figure 6). They are black to grey basaltic, moderate to highly vesicular, angular to sub-angular, moderately sorted scoriaceous lapilli and tuff breccias [46]. The average clast-size is between 1 and 20 cm. The vesicles are commonly in filled by acicular calcite.

Interpretation: On the basis of location and the vesicular-rich texture, these scoriaceous deposits are similar to the volcanic facies TB1. The deepest basaltic scoria occurrence is located at around 70 m in depth, so the total thickness of the scoria breccias with intercalated lava units is almost 80–100 m (Figure 6).

5. Geomorphic evolution

The present-day geomorphic features of Bondoró and its surroundings can be divided into three groups: (1) remnants of pre-volcanic paleo-surfaces, (2) syn-volcanic forms, or (3) features created post-eruption by intense denudation of the first two groups under variable climatic conditions. No differential vertical tectonic movements are known within the study area after the infilling of Lake Pannon, so we can infer that any elevation differences of the various paleo-surface remnants will reflect the topographic relief at the time of their formation.

5.1. Pre-volcanic features

As volcanism at Bondoró began, the main constituents of the topography were a level area lying on a few tens of metres of lacustrine lime mud and freshwater limestone (Nagyvázsony Limestone Fm.). Some etchplain remnants, mostly of Triassic carbonates, rose only slightly above this plain. The Nagyvázsony Limestone was deposited in the final stage of the infilling of the Late Miocene Lake Pannon [33]. In contrast to its modern eroded and patchy occurrence, it formed a continuous surface at the onset of volcanism, with a distribution area approximately the same as today. Although the resistant lithology exerted a strong control on denudation, resulting in a roughly planar surface, the location of the limestone sequence in the foreland of the Bakony Mountains resulted in moderate pedimentation creating low-relief topography. Remnants of the limestone plain and of the etchplain on Triassic rocks are still important elements of the regional topography.

At the onset of volcanism at Bondoró, the basaltic volcano of Kab-hegy to the east had already risen above the limestone plain, now lying at an elevation of 310–340 m a.s.l. Its lava flows covered the surrounding area (Tálodi-erdő), preserving the underlying paleosurface at about 300 m a.s.l. (Figure 1). To the west of Bondoró, the eruptions of Agár-tető onto this same surface started after the formation of Bondoró (approx. 3 Ma [26, 27]). Despite the younger age of the Agár-tető volcano, the limestone paleosurface lies somewhat higher, between 320–350 m as estimated from available data (Figure 1).

The maar complex of the Fekete-hegy [39] and the Pula maar [17] were formed roughly contemporaneously with Bondoró (with the initial activity around 3.8 Ma ago), but at a slightly lower elevation than the latter. According to Auer et al. [39], the topography at the location where these volcanoes erupted must have resembled a N–S striking valley that was carved into the Miocene sedimentary sequence rather than a higher-lying part of the pediment. Based on the inner structure and 3D-architecture of the volcanic edifice of Bondoró, it is inferred to have been formed on an elevated part of this paleosurface, represented by the present day level of about 290–300 m a.s.l.

5.2. Syn-volcanic forms

The tuff ring of the initial maar and its immediate underlying sediments have all been eroded (Figure 6). However, we can deduce the initial size and location of the maar crater from the structure and distribution of lava bodies, and from their appearance in the topography (Figure 2).

The morphology of the lava flows overlying the pyroclastic rocks of the maar indicates that the lavas did not break out

Table 2. Summary of the K-Ar ages of Bondoró and the surrounding volcanic remnants. Ages in bold represent the best fit with the geological and stratigraphical observations. Abbreviations: w.r. – whole rock; Mi,Dk – magnetic susceptibility and density; i, k in the order of increasing values.

No. code	Name and locality	Dated fraction	Measured age	Method	Ref.
2370 - Bon.680	Bondoró; 1	M2	**2.29±0.22**	K-Ar	42
7850	Bondoró; 2	M3	**2.52±0.28**	K-Ar	this work
		M2D1	3.01±0.46	K-Ar	this work
		M2D2	3.52±0.33	K-Ar	this work
		M1	5.21±0.66	K-Ar	this work
385 - Mat-1	Bondoró; 3 39.7-41.0 m	w.r.	**2.90±0.62**	K-Ar	27
386a - Mat-1	Bondoró; 3 120.8-122.4 m	w.r.	5.54±0.40	K-Ar	27
386b - Mat-1	Bondoró; 3 120.8-122.4 m	w.r.	5.42±0.26	K-Ar	27
		M1	16.80±0.75	K-Ar	27
		M2	**3.86±0.20**	K-Ar	27
863	Talodi-erdő	w.r., M1, M2	4.65±0.73	K-Ar; isochron age	27
406-409	Pula	w.r.	4.25±0.17	K-Ar; isochron age	27
FH-4	Fekete-hegy		3.81±0.02	Ar-Ar; plateau age	26
AG-1	Agár-tető		3.30±0.03	Ar-Ar; plateau age	26
1001	Agár-tető	w.r.	2.98±0.18	K-Ar	27
		M1	3.44±0.19	K-Ar	27
		M2	2.90±0.18	K-Ar	27

of the confines of the tuff ring (Figure 2). The lavas building up the plateau under the scoria cone produce a steep escarpment along the plateau edge and along the southwestern margin they have an extruded, piled-up structure (Figure 7) that appears as a low ridge in the topography. These refer to an intra-maar location at the time of lava effusion. On the eastern side of Bondoró, the map view of the youngest (2.3 Ma old) lava flow also indicates the existence of maar morphology (e.g. a confined semi-circular distribution of solidified lava) at that time ($ß_3$ lava units in Figure 2). From its discharge point at the base of the scoria cone, lava flowed radially from the centre of the volcano. The flow then turned perpendicularly to the NNE and ended shortly afterwards, indicating the presence of an obstruction (the maar edge). Joining these two inferred locations of the maar crater wall with the NW protrusion of the lava plateau, we get a slightly irregular crater circumference with a maximum diameter of approximately 2.5 km (Figure 2; [71]).

Considering the remarkable time span of volcanic inactivity after the maar formation, this raises important questions about the rate and method of denudation of the maar structure specifically its tephra rim. From the $\leqslant$3.8 Ma age of the lowest maar products and the 2.9 Ma age of the lava rocks constituting the plateau under the scoria cone (age data from the Mat-1 borehole; Figure 6), there was a denudation period of $\leqslant$1 Ma between the 2nd and 3rd eruption cycles. This period is represented by an approx. 30 m thick sequence of dominantly volcanoclastic sediments between the basal pyroclastic and capping magmatic bodies that were eroded from the inner slope of the tuff ring and from the maar edge (Figure 6). The upper boundary of this sedimentary sequence lies at an elevation of approx. 260 m in the borehole Mat-1, under the paleosurface the maar was formed in. Based on uncertainties of K-Ar radiometric ages (e.g. excess Ar in the samples) and on the low thickness of the volcanogenic sediments attributed to the erosional period, it is possible that the time span of volcanic inactivity was significantly shorter than 1 million years. The possibility of a shorter denudation period is also supported by the fact that at least the edge of the maar crater did not become entirely eroded as shown by the above mentioned morphology of the lava flows despite having formed in mostly unconsolidated sediments and/or the tuff ring. However, we must also take into account that the area had low relief at that time, which does not facilitate rapid denudation. Intensive down-cutting and removal of material started only with the regional denudation of the Transdanubian Range and its surroundings and the creation of a lower base level from the (Lower-Middle) Pleistocene [84].

The question of whether lava flows were able to leave the maar cannot yet be answered with complete certainty. An argument against this supposition is the fact that at nearby volcanoes (Kab-hegy, Agár-tető, Halom-hegy; Figure 1), the effusion lavas occurs as elongated flows rel-

Figure 7. Outcrop photo of extruded lava units along the southern escarpment of Bondoró. Note: ph – basal phreatomagmatic units; lr – capping effusive lava flows.

atively far away (<1 km) from the volcanoes. They have been preserved as continuous cover or as scattered debris, and the lava flows following paleo-valleys even caused inversion of the topography and are now represented by low ridges or hills with an elevation between 200 and 400 m a.s.l. [84, 85]. However, such features cannot be found in the vicinity of Bondoró.

5.3. Erosional forms created after the volcanism

Erosion of Bondoró was controlled by Quaternary denudation of the surroundings by the incision of the Eger-víz Creek valley between Bondoró and Fekete-hegy, which created a new local base level. This resulted in the selective denudation of the unconsolidated Upper Miocene rocks around Bondoró and the formation of the lava-capped Bondoró. The steep slopes with relief of about 100 m became subject to large landslides and collapses. Extension caused by mass movements has also produced a fissure cave in the basalt on the SE slope of Bondoró ("Pokol-lik", represented by "P" in Figure 2). The scarps of some landslides have been transformed into valley heads.

A small-scale, incipient landslide can be found on the SW side of Bondoró (black arrows in Figure 2), which has started to separate the south-western, roughly 500 by 300 m wide patch of the plateau from the main body of the volcanic edifice. From the small, rounded, stair-like topography of the scarp visible in the field and the borehole log Mat-2, the displacement has been no more than a few metres maximum (indicated by the black arrow in Figure 6). The movement slightly backtilted plateau blocks towards the volcano centre, resulting in the accumulation of a small ephemeral lake (Figure 2). The existence of other lakes on the eastern plateau can be explained without applying mass movements, but through the surrounding lava flows.

Landslides of considerable size and subsequent erosion have removed material from the volcanic edifice (e.g. on the southern and northern side of the hill). In spite of this, the majority of the volcano is still preserved, as shown by the lava features (described above) that mark the location of the original crater wall. The low ratio of basalt compared to Triassic dolomite in the alluvial material of the Eger-víz Creek also indicates that the volcanoes in the catchment area have not yet suffered significant denudation. The probable reason for this is that really intense erosion only started in the Middle Pleistocene, and the time since then was only sufficient for the surrounding unconsolidated Upper Miocene rocks to be eroded and removed.

The present shape of the capping scoria cone is characterised by ∼15° slope angle, which differs from an average, fresh scoria cone, which has initial slopes of around 30° [86]. In this context, the erosion remnant of the scoria cone of Bondoró is a moderately eroded primarily volcanic landform.

Generally, the magma intrusions are largely controlled by the physical properties of the cone material, such as degree of welding [65]. The dykes on the breached side of the scoria cone of Bondoró may indicate that this side of the cone was built up from loose, weakly welded deposits during the emplacement of the cross-cut dyke exposed in Sec. 5 (Figure 5B). This structural weakness of the scoria cone may have favoured post-eruptional processes, for instance gulling, and led to the formation of the large breaching on the eastern slopes of the capping scoria cone.

In summary, the breaching of the scoria cone can probably be attributed to erosional rather than magmatic processes. The Pleistocene base-level fall induced rapid erosion and downcutting that produced high local relief, and resulted in the strong headward erosion of gullies. The relatively large alluvial fan in front of the valley incising into the crater also indicates removal of material and breaching of the crater by erosion.

6. Complex evolutional history of Bondoró

K-Ar radiometric dating of specific volcanic units (including buried and surfacial lava flow units and the capping scoria cone) and field evidence (such as the discordance between initial phreatomagmatic and subsequent lava flows exposed at the southern side of present remnant) both indicate a complex, polycyclic evolution of Bondoró (Table 2 and Figure 6). From these data, we have divided the construction of Bondoró into a series of distinct phases: Phase (I) basal tuff ring pyroclastics "infilled" by lava rocks; Phase (II) reworked, basaltic debris beds; Phase (III) lava flow units and Phase (IV) capping scoria cone (Figure 6).

Phase (I): According to K-Ar radiometric measurements, the first magmas reached the surface ⩽3.8 Ma ago and formed a lava lake [27]. The K-Ar dated sample comes from these "infill" lava units that were penetrated by the Mat-1 drill core (Figure 6). The basal pyroclastics are situated directly beneath these lava flows. These were only penetrated by the Mat-2 drill core as well as being exposed along the southern side of the present erosional remnant (Figure 3). These pyroclastic rocks are characterized by cross-bedded, well-stratified, well to poorly sorted ash and lapilli dominated beds with high amounts of juvenile (both tachylite and sideromelane glass shards) and accidental lithic clasts. As a consequence of this, these very early eruptions of Bondoró were characterized by magma/water interaction, which triggered explosive eruptions that led to the fine fragmentation of the mafic magmas and the formation of at least one (potentially shallow) maar surrounded by a tephra ring [2, 50, 57]. These basal pyroclastics are probably related to this initial eruption cycle, which is characterized by alternations of base surges and fall originated deposits. This early eruption stage is inferred to have taken place on a higher-lying part of the paleosurface, at approximately 300 m a.s.l., and not in a surface depression or valley that could have provided an excellent source of groundwater to fuel phreatomagmatism [49, 50, 87–89]. In addition, the mainly Mesozoic and minor Neogene carbonate rocks were an excellent source of karstic and groundwater to fuel explosive phreatomagmatic fragmentation of the ascending magmas. Thus, this early eruption created a thick (at least 30 m at the southern escarpment of Bondoró) phreatomagmatic pyroclastic unit, which built up from various pyroclastic rocks ranging between tuffs and lapilli tuffs (Figure 6). The emplacement of the first lavas (⩽3.8 Ma) probably closely followed the phreatomagmatic explosions and filled the deepest part of the maar crater (Figure 6).

The pyroclastic units do not record any significant vertical characteristic in facies change within their succession, and there is only a slight change observed between the basal pyroclastics with minor juvenile content (e.g. T1, 2 and LT1, 2; 3) and the most juvenile fragment-rich (LT4a, b). This increased juvenile clast proportion could have resulted from shallow-level changes during the evolution (e.g. degassing pattern or total amount of available water in the vent system) [90]. Thus, the variations in bedding, component, colour, grading and other sedimentary structures and textures are interpreted to be the result of unsteady conditions during magma fragmentation, especially in the amount of external water available to fuel phreatomagmatism, and the way such water was supplied to the eruption sites.

Phase (II): According to the drill core description [46, 47], the basal tuff ring deposits and the infilling lava units are capped by a ∼30 m thick unit of basaltic debris that is probably reworked (Figure 6). These beds commonly consist of various amounts of scoriaceous lapilli and breccias as well as coherent, thin lava bodies with calcite and bentonite (?) matrix. These layers are inferred to represent a significant erosional period during the construction of Bondoró.

The upper part and the contact zone of these layers are exposed on the southern side of Bondoró (in Sec. 3 and

4). Along this escarpment, a small-scale unconformity can be found between the capping lavas and these reworked LT5 lithofacies (Figures 5A and 6). In addition, the ballistically emplaced LT4a and b show gradual thinning between Sec. 4 and 3 (Figure 3). The absence of these deposits from the proximally located Sec. 3 can be explained by erosional processes during the formation of a "monogenetic" volcano. Based on the lack of any paleosol horizons, this time break was most likely to be shorter than the $\leqslant$1 Ma suggested by existing K-Ar ages. This large time interval probably stems from uncertainties in the K-Ar ages due to excess Ar problems. Thus, this gap may have been shorter than required for the soils to form under favourable climatic conditions (a wet and temperate climate). This was probably several decades up to hundreds of thousand years. In either case, it is clear, that a significant time gap occurred between the early phase of the volcano growth at Bondoró and its later dominantly magmatic explosive and effusive phases.

Phase (III): The younger phase of volcanism at Bondoró is dated at around 2.9 Ma ago [27, 44]. Effusive lavas were emplaced onto the previously formed crater, which was partly eroded. These thin, 1st and 2nd lava flows may have party filled the previously mentioned reworked basaltic debris (Figure 6). These two lava flows are inter-fingered by scoriaceous breccias, formed by a Strombolian-type eruption, that can be deposited from a series of gas released at shallow depth under open vent settings [2].

Phase (IV): This renewed volcanic phase began as mainly a magmatic explosive eruption, such as Strombolian-type, and led to the formation of a capping scoria cone and the associated 3rd lava flow emplaced on the SE part of the partly intact crater ($ß_3$ in the Figure 2). These products may be the youngest volcanism dated by K-Ar at 2.3 Ma ago. A unit of pyroclastic material (a few meter thick) exposed in the eastern part of the plateau near the small depression (Figures 2 and 6), may have represented the new vent-opening cycle prior to the scoria cone formation [2], but the position and the origin of these pyroclastic deposits is uncertain due to poor exposure.

Erosional phase (V): The present morphology of the Bondoró scoria cone is relatively youthful with a well-distinguished crater and an average slope angle of 15°. Based on morphometrical parameter estimates, the scoria cone at the top of Bondoró is one of the largest cone remnants of the Bakony–Balaton Highland Volcanic Field with a volume of about 0.031 km^3 (Digital Elevation Model-based estimate). The narrow breaching of the scoria cone is formed during the erosional stage after the cessation of volcanism at Bondoró. Erosion within the last 2.3 Ma, in accordance with the regional denudation trends, removed the sediments surrounding the volcanic edifice, and thus the modern shape of the hill was formed by topographic inversion.

7. Concluding remarks

(1) At least four well-distinguished volcanic episodes can be identified at Bondoró on the basis of field-based observations combined with borehole data. Each recognized episode is inferred to be short lived (from hours to day), which is typical for monogenetic volcanoes such as tuff rings, maars or scoria cones. All of these eruptive episodes produced small-volume volcanic edifices, primarily dominated by pyroclastic successions. These observations are consistent with a monogenetic model for the formation of the volcanic edifices in each eruptive episode. However, field and drill core evidence as well as the K-Ar radiometric datings have revealed that significant time gaps took place between the episodes (between the Phase I and III resulting in the reworked deposits of the Phase II). The length of this gap is uncertain, however it may have been equivalent to the formation time of a ~30 m thick reworked volcaniclastic unit in the previously ($\leqslant$3.8 Ma ago) formed crater (Figure 6).

(2) The minimum estimate of the time interval between the two discrete volcanic episodes provide enough time to solidify a feeder dyke and cool the volcanic conduit. Subsequent eruptions must have been fed from a different magma batch and therefore the second evolutional phase would be considered as a new eruption at the same location. These observations not only indicate the rejuvenation of the volcanism, but the formation of a new individual volcano upon the former phreatomagmatic successions of the (I) phase episode. Consequently, Bondoró can be classified as a polycyclic monogenetic volcano, which formed a nested monogenetic volcanic complex.

(3) Bondoró appears as the erosional remnant of a rather simple monogenetic maar volcano with a lava lake and associated scoria cone similar to Acigol in Karapinar, Turkey [91] or La Brena in Durango, Mexico [92]. However, detailed facies analysis and geomorphological mapping has revealed that Bondoró evolved in a very different way, since at least two individual 'monogenetic' volcanic episodes formed its volcanic edifice. In the case of each volcanic episode, the term 'monogenetic' is correct, but from an overall evolutionary point of view, Bondoró is a small-volume, polycyclic monogenetic volcano of the Bakony–Balaton Highland Volcanic Field, that can be classified as a subset of polygenetic volcanoes.

(4) Compared with the neighbouring long-lived volcanoes (e.g. Agár-tető or Kab-hegy), the shape of these erosion remnants are different because these remnants have

extended lava fields (10–12 km^2) with a capping scoria cone [85]. The significant existence of these magmatically-dominated polycyclic volcanoes show that during the formation of these volcanoes (between 5.2 and 2.3 Ma), a constant magma support system would be present at the northern part of the Bakony–Balaton Highland Volcanic Field.

(5) The observed anomaly of 'monogenetic'-like polycyclic vents was formed by diverse explosive as well as effusive processes during the evolution of the entire Bakony–Balaton Highland Volcanic Field. This raises the question of how the K-Ar or Ar-Ar radiometric ages of coherent lava rocks represent the age of the whole volcanic remnant. Since samples for K-Ar and Ar-Ar dating are usually taken from the capping magmatic units, the measured age does not also represent the age of the basal pyroclastics. Thus, existing K-Ar and Ar-Ar datasets should be revised with the aim of identifying similar complex volcanoes in the Bakony–Balaton Highland Volcanic Field, or other continental "monogenetic" volcanic fields worldwide.

(6) Shifting of fragmentation style during a single eruptive episode is a common process among monogenetic volcanoes [9, 39, 93]. There are several controlling factors that can cause such a change in fragmentation: the elevation and/or position of the vent [94, 95]; hydrogeology of the subsurface strata [56, 87]; the total amount of magma output/supply [28, 90]; magma ascent rate and degassing pattern [11].

In the case of Bondoró, field-based evidence and K-Ar ages show a time gap and a change in fragmentation style from phreatomagmatic to effusive and magmatic explosive volcanic processes. This shift is different from the previously mentioned controlling factors because a significant erosional stage took place between the volcanic cycles. Thus, Bondoró represents a different change in fragmentation style that is not the same as a gradual shift from phreatomagmatic to magmatic fragmentation styles as observed in a single eruptive episode. In the case of Bondoró the recorded fragmentation styles represented by the initial and capping volcanic successions are changes that may have been influenced by long term variations in external conditions such as: (1) climate; (2) uplift of the vent (caused by the pyroclastic materials of the 1st volcanic event); (3) the isolation of previously deposited pyroclastic sequences from the local water-supply during the 2nd volcanic event. Finally, the observed processes at Bondoró make it an excellent example for demonstrating alternative ways of changing the eruption style after a significant time break in volcanism.

(7) On the basis of the aforementioned conclusions, the proposed evolutional scenario for Bondoró should be confirmed by detailed geochemical studies and additional K-Ar or Ar-Ar radiometric dating.

Acknowledgement

This paper was presented in the XIX Congress of the Carpathian Balkan Geological Association in Thessaloniki in 23-26 September 2010 and supported by Department of Geology and Mineral Deposits, Faculty of Earth Science and Engineering, University of Miskolc and "Szervezési és Vezetési Tudományos Társaság" as well as by the XIX Congress of CBGA to G. Kereszturi. A travel grant awarded by the Massey University Leave & Ancillary Appointments Committee granted fund (LAAC10/37) to K. Németh allowed these authors to present this work in the CBGA congress. The results presented here are part of research projects supported by the Foundation for Research, Science and Technology International Investment Opportunities Fund Project MAUX0808 "Facing the challenge of Auckland volcanism", and Massey University Research Fund (RM13227) to KN. This work was also partly funded by OTKA Hungarian Science Foundation (K62478) to G. Csillag and K. Sebe. Expenses of K/Ar dating were partially covered by an OTKA Hungarian Science Foundation grant (T060965) to K. Balogh.

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