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COLLECTION: MONOGENETIC VOLCANISM

# High-resolution $^{40}Ar/^{39}Ar$ study of Mount Avital, northern Golan: reconstructing the interaction between volcanism and a drainage system and their impact on eruptive styles

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**Abstract** We present a high-resolution $^{40}Ar/^{39}Ar$ data set of a volcanic complex at Mt. Avital, northern Golan, which experienced a transition from strombolian to phreatomagmatic activity. Previous studies attributed this transition to a change in the drainage basin of a nearby stream due to the damming by a lava flow, which resulted in flooding of the eruption site. In this study we determined the age of different volcanic phases and events in the history of Mt. Avital, as well as that of the damming flow, and examined the cause of the transition in light of the new $^{40}Ar/^{39}Ar$ ages. The $^{40}Ar/^{39}Ar$ results show that the history of Mt. Avital includes two main phases of volcanic activity, an early phase at ca. 800–600 ka and a late phase at 120–95 ka. Most of the activity of the late phase was continuous (within the $^{40}Ar/^{39}Ar$ error), including the transition to phreatomagmatic explosions, which occurred sometime between 115–107 ka, probably between 115–113 ka. The age of the damming flow is 115.6±3.1 ka, which suggests that the volcanic activity immediately reacted to the change in the drainage basin dynamics. The activity culminated with lava flow eruptions, the latest at 100±4 ka, either due to the establishment of the tuff ring levees, which prevented access of water to the eruption site, or due to the migration of activity to the northern part and then to the southern part of the complex.

**Keywords** Phreatomagmatism · Dry-wet transition · $^{40}Ar/^{39}Ar$ · Drainage system

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## Introduction

Most geologic processes shape the landscape very slowly. Volcanism, on the other hand, may cause significant changes to the regional landscapes within a very short time (e.g., Schmincke 2004). Cases where a change in the landscape causes a change in the type or pattern of volcanic activity are less common and hardly documented. In this paper we discuss the chronology of a chain of events, where volcanic activity caused a landscape change, which in turn affected the style of activity in another volcanic system.

Shifts from strombolian to phreatomagmatic activity are usually attributed to intrinsic changes in the volcanic system (reduced magma pressure or crater subsidence), which allow the introduction of groundwater or surface water into the system and an efficient interaction with the magma (e.g., Christiansen 1979; Decker and Christiansen 1984; Mastin 1997; Gutmann 2002; Di Traglia et al. 2009). An alternative driving force is presented by Brand and White (2007) and Weinstein (2007), who described two volcanic systems, the first at the Snake River Plain (Idaho, United States) and the other at Mt. Avital (northern Golan), where damming of a stream or river due to volcanic activity facilitated a dry–wet shift in volcanic activity. In the latter case, the chronology of events was not well constrained, which is critical to the understanding of the transition in eruptive styles.

This paper presents a set of high-resolution $^{40}Ar/^{39}Ar$ age determinations from Mt. Avital, which is used to elucidate the sequence of events and to better understand the trigger for the dry–wet transition in this volcanic complex.

## Mount Avital volcanic complex

The northern Golan is covered by Pleistocene volcanic rocks, which are part of the large volcanic field Harrat ash Shaam (inset in Fig. 1). The landscape is dominated by numerous scoria cones and lava flows (mainly basanites, Weinstein et al. 2006) of Pleistocene age (Mor 1993). Phreatomagmatic structures are rare, including only the maar of Birket Ram (Shaanan et al. 2011) and the tuff ring

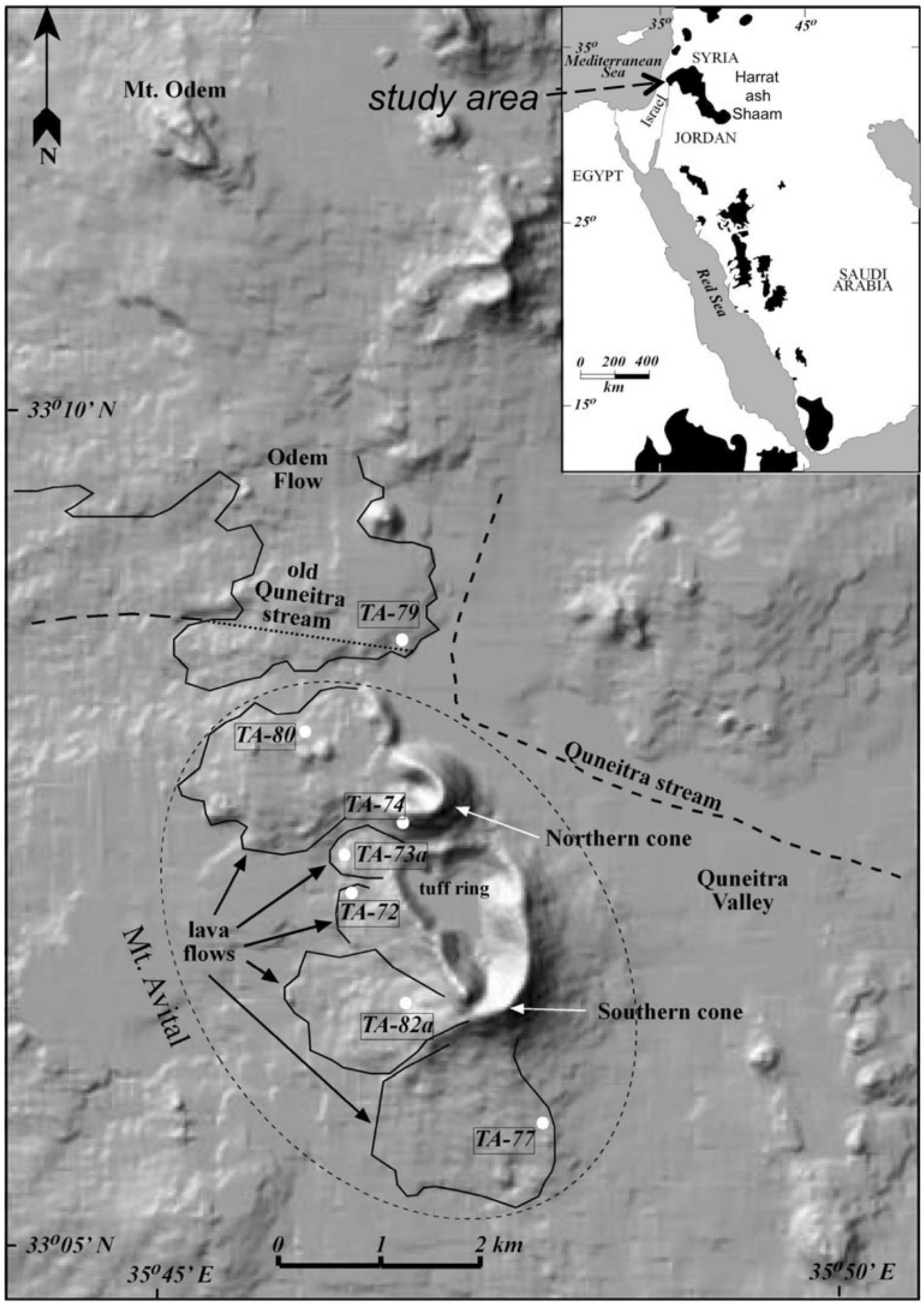


**Fig. 1** Digital terrain model of the Mt. Avital area with sample locations; *inset* is a regional location map

in the volcanic complex of Mt. Avital (Weinstein 2007). The latter shows a temporal shift from strombolian to phreatomagmatic activity, which implies a transient interaction of magma and shallow water.

The volcanic succession at Mt. Avital (Figs. 1 and 2) includes lava flows, scoria cones, and phreatomagmatic deposits (Weinstein 2007). The stratigraphy and structure of the Mt. Avital volcanic complex were summarized by Weinstein and Weinberger (2006) on a 1:5,000 scale geological map. Here we superimpose this map on a satellite image draped on a digital elevation model (Fig. 2b). The volcanic succession includes a basanitic basal unit, which consists of the lavas of 'En Zivan Basalt' (Qβe, Fig. 2a), overlain by two scoria cones (the Southern and the Central cones) mapped as the 'Avital Coarse Scoria' (Qσa). The Central cone was mostly destroyed during later events. The cones are covered by lava flows ('Lower Avital Basalt'—Qβa). These, in turn, are covered by phreatomagmatic deposits that built a partial tuff ring at the center of the complex (Avital Tuff—Qτa). Field relations indicate that the phreatomagmatic activity was coeval with the construction of another scoria cone at the northern part of the complex ('Bental Coarse Scoria'—Qσβ). The Avital tuff is also intercalated with a fine scoria unit (Qσfa and Qτσfa, Fig. 2), which erupted between the Northern cone and the phreatomagmatic eruption sites (Weinstein and Weinberger 2006). The volcanic activity culminated with the effusion of basalts, known as the 'Upper Avital Basalt' (Qβb), which breach the Northern and the Southern cones.

Unlike Birket Ram, where the groundwater level is very shallow (Shaanan et al. 2011), the groundwater table in the Mt. Avital area is 250–300 m beneath the surface (Dafny et al. 2003). Hence, it is unlikely that the interaction of groundwater with magma is the cause for phreatomagmatism at Mt. Avital. Weinstein (2007) suggested that the water source was a Late Pleistocene lake in the nearby Quneitra Valley (Fig. 1). Mor (1973) suggested that the 'Quneitra Lake' was created as a result of the damming of the local westward-flowing Quneitra stream (Fig. 1) by a lava flow (the Odem Flow) that arrived from the north (Fig. 1). The flow was dated by the K-Ar method at 320±140 ka (Mor 1993), which implies that the lake or at least poor drainage conditions existed in the Quneitra Valley since that time.

There are no age constraints for the Avital Tuff or any other volcanic rocks in the Mt. Avital complex. However, a Late Pleistocene Paleolithic site from the Quneitra Valley was dated by the ESR method to 53.9±5.9 ka (Ziaei et al. 1990). The artifacts of this site and a large amount of animal bones that were evidently hunted and consumed on the Quneitra Lake shore were found directly on top of the Avital phreatomagmatic deposits with no palaeosol or alluvial deposits separating the two. This suggests that the phreatomagmatic deposits (and the eruption) were not significantly older than the human artifacts (Weinstein 2007). This further implies that if the age of the Odem Flow (320 ka) is correct, then the dry–wet transition in the eruptive style at Mt. Avital was not an immediate consequence of the damming of the stream, and one should look for a different or additional trigger.

We present here a set of $^{40}Ar/^{39}Ar$ ages of samples, which represent different phases in the volcanic history of Mt. Avital as well as that of the damming flow. We show that all the events, including the damming and the consequent stream diversion, were concurrent, significantly younger than 320 ka, and closer to the age of the Paleolithic site, and that they probably occurred as one chain of events.

## Methods

Rock samples, 1–4 kg in size, were taken from several key sites in the Mt. Avital complex. After careful examination of thin sections under the microscope, holocrystalline samples (Fig. 3) were chosen for dating by the $^{40}Ar/^{39}Ar$ incremental heating technique. Dense, clean groundmass was separated, irradiated at the USGS TRIGA reactor facility, and analyzed in the USGS-Menlo Park geochronology laboratory following the techniques described in Calvert and Lanphere (2006). The neutron flux was monitored using the 27.87 Ma TCR-2 sanidine. Complete analytical techniques and data tables are included in the data appendix.

## Samples and field relations

Rock samples were collected as to cover all suspected events in the Mt. Avital volcanic complex. Seven were found to be holocrystalline and suitable for $^{40}Ar/^{39}Ar$ age determinations. In the following section we describe the dated samples and their relevance to the volcanological history of Mt. Avital. Figures 1 and 2 show the location of the samples and their field relations.

TA-77 was chosen as to represent the early volcanic phase (the 'basal unit' of Weinstein and Weinberger 2006; 'En Zivan Basalt'—Qβe on Fig. 2). It was taken from the front of a basaltic flow south of the Southern cone. The cone covers the dated flow. This is supported by the chemical composition of the dated flow, which is chemically and petrographically distinct (e.g., MgO and Ni concentrations, as well as the content of olivine phenocrysts) from other lava flows and scoria units in Mt. Avital (Weinstein et al. 1994), but similar to that of nearby older lavas (0.8 Ma, K-Ar age by Mor 1993).

TA-72 and TA-73a were sampled from basaltic flows on the western slope of Mt. Avital (Fig. 2b) as to represent the Lower Avital Basalt (Qβa), the basaltic event that preceded

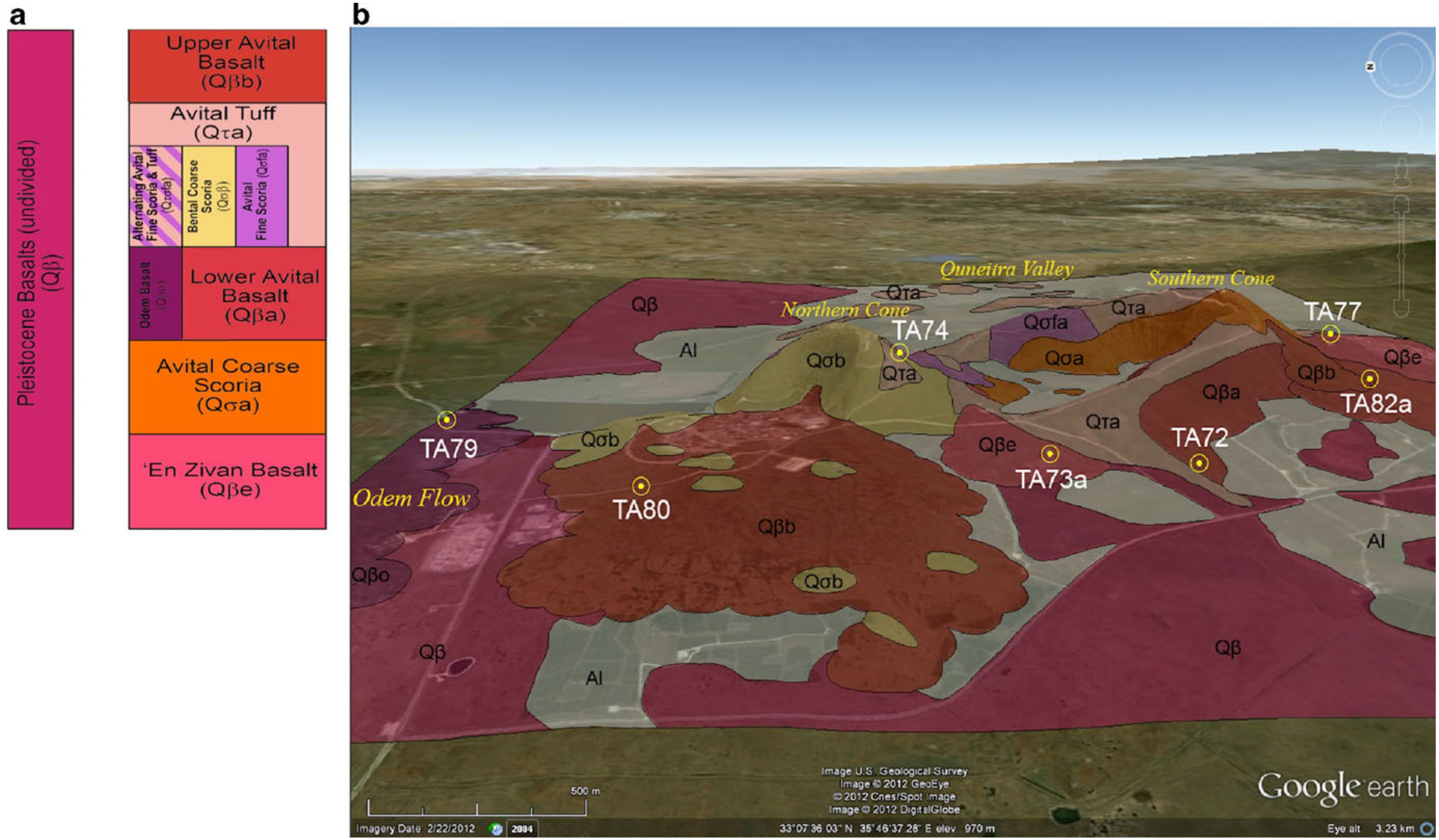


**Fig. 2** **a** Stratigraphy of the Mt. Avital volcanic complex. **b** Detailed geological map of Mt. Avital (modified from Weinstein and Weinberger 2006) draped on a Google Earth image with sample locations (eastward view). TA-72 was taken from a basalt beneath the tuff

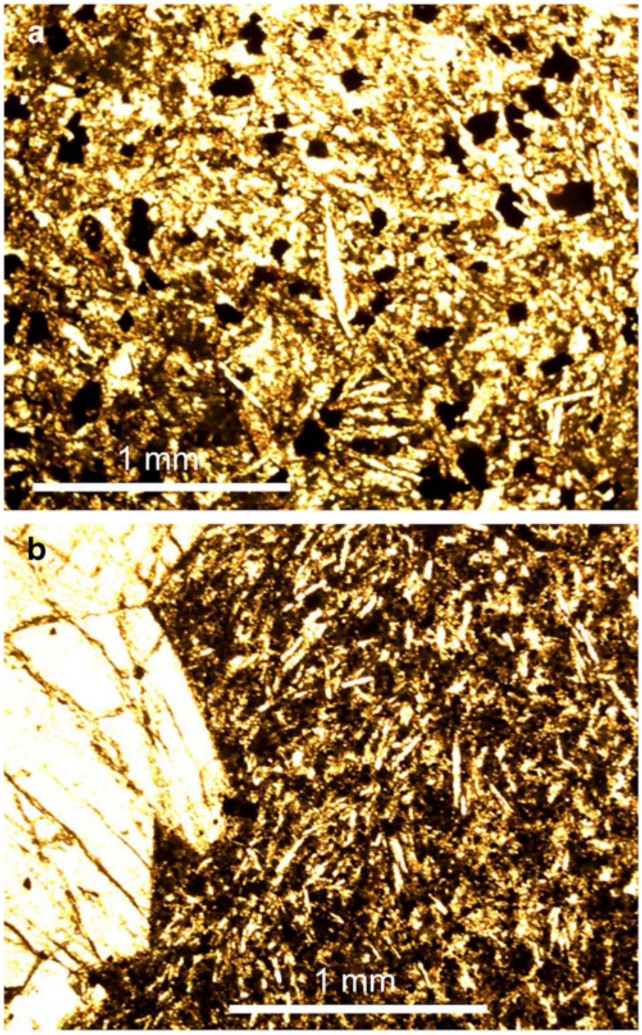


**Fig. 3** Photomicrographs of the groundmass in two holocrystalline samples that were used for $^{40}Ar/^{39}Ar$ age determination in this study. **a** TA-77 (plane-polarized), with relatively coarse groundmass, dominated by micro-crystals of clinopyroxene and plagioclase and a few percent titanomagnetite; **b** TA-79 (cross-polarized), with finer groundmass, similar mineral proportions (plagioclase showing a flow structure), and an aggregate of euhedral clinopyroxene phenocrysts

the dry–wet transition. The flow of TA-72 seemingly erupted from the northern or northwestern flank of the Southern cone (Fig. 2b; no evidence for a specific vent site due to the destruction of the vent area during the phreatomagmatic explosions). Sampling took place in an area where the lava flow is covered by surge deposits of the Avital Tuff. TA-73a was taken from the front of a lava flow located northwest of the tuff ting. Originally, it was thought to be part of the Lower Avital Basalt unit (Qβa). Its stratigraphic position is re-evaluated below based on the $^{40}Ar/^{39}Ar$ results.

TA-74 was sampled from a large (~3 m) volcanic bomb (Fig. 4), embedded in the scoria deposits on the southern slope of the Northern cone (Fig. 2b). Such bombs are very frequent in this scoria cone. Based on its fusiform shape, it is clear that the bomb is syn-genetic with the scoria cone construction event, which allows the determination of the age of the Northern cone (Bental Coarse Scoria, Qσβ). Its relatively dense appearance (relative to the surrounding scoria) made it a good candidate for age determination, which was verified by its holocrystalline texture. The scoria layers that host this bomb intercalate with a tuff breccia (Fig. 4), which is part of the phreatomagmatic deposits (Weinstein and Weinberger 2006). Therefore, the age of the bomb constrains the age of the phreatomagmatic eruption. A volcanic bomb sampled at the Southern cone was found inappropriate for dating, leaving the earlier, southern cone construction (Avital Coarse Scoria, Fig. 2) undated.

TA-80 and TA-82a were taken from flows that breached the scoria cones (Fig. 2b). The Northern cone was undoubtedly coeval with the phreatomagmatic eruption, suggesting that the breaching flow (sampled as TA-80) is either coeval or post-dating the phreatomagmatic events, therefore belonging to the Upper Avital Basalt (Qβb). On the other hand, the Southern cone was constructed earlier in the chain of events (Fig. 2a, b), therefore a flow breaching this cone (sampled as TA-82a) could either precede the phreatomagmatic eruption and be part of the Lower Avital Basalt unit (Qβa) or be part of the culminating volcanic unit (Upper Avital Basalt).

TA-79 was sampled from the front of the Odem Flow (Figs. 1 and 2b), the lava that arrived from the north and supposedly dammed the Quneitra stream (Fig. 1), shifting the course of its water toward the Quneitra Valley. Dating of this sample allows us to better constrain the timing of the damming as compared with that of the events at Mt. Avital.


**Fig. 4** A fusiform volcanic bomb embedded in a scoria layer on the southern slope of the Northern cone. Sample TA-74 was taken from this bomb. The scoria (and the bomb) is covered by a (phreatomagmatic) tuff breccia layer, which is again covered by scoria

### $^{40}Ar/^{39}Ar$ ages

Age spectra of the samples are presented in Fig. 5. Following Calvert and Lanphere (2006) and other authors, we prefer to use the ages derived from the flat portions of the spectra, typically at the middle part of the release spectrum, which shows consistent K/Ca ratios and concordant isochron data. This means that the early steps, often dominated by $^{40}Ar$ loss or recoil loss of $^{39}Ar$, and the latest steps, often dominated by recoil-induced excess $^{39}Ar$ and true excess argon, are excluded from age calculations.

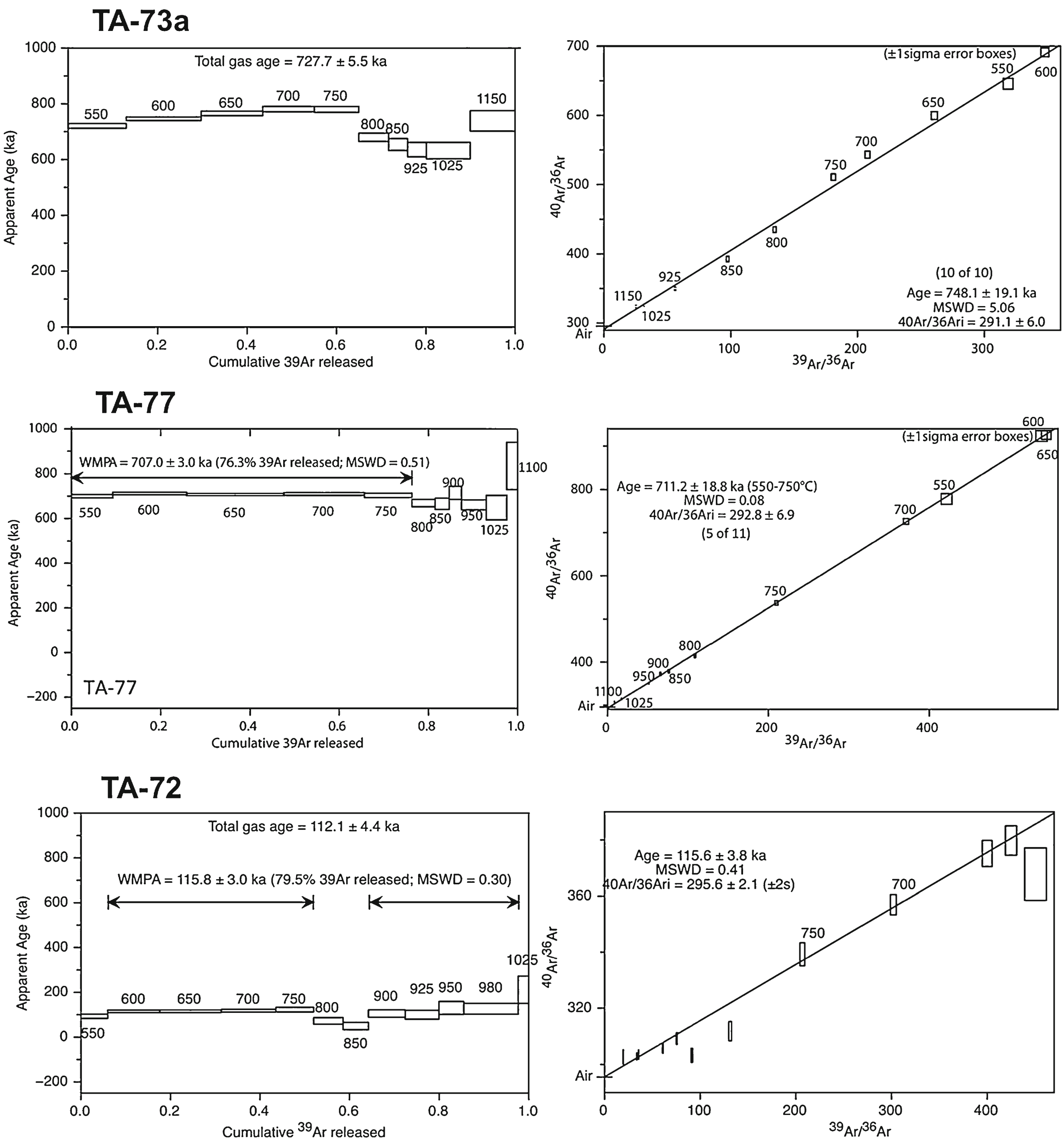


**Fig. 5** $^{40}Ar/^{39}Ar$ age spectra and isochron plots for samples from Mt. Avital. Apparent ages, isotopic ratios, isochron ages, and weighted mean plateau ages (*WMPA*) are all 1σ. Numbers on chart steps are temperature in Celsius

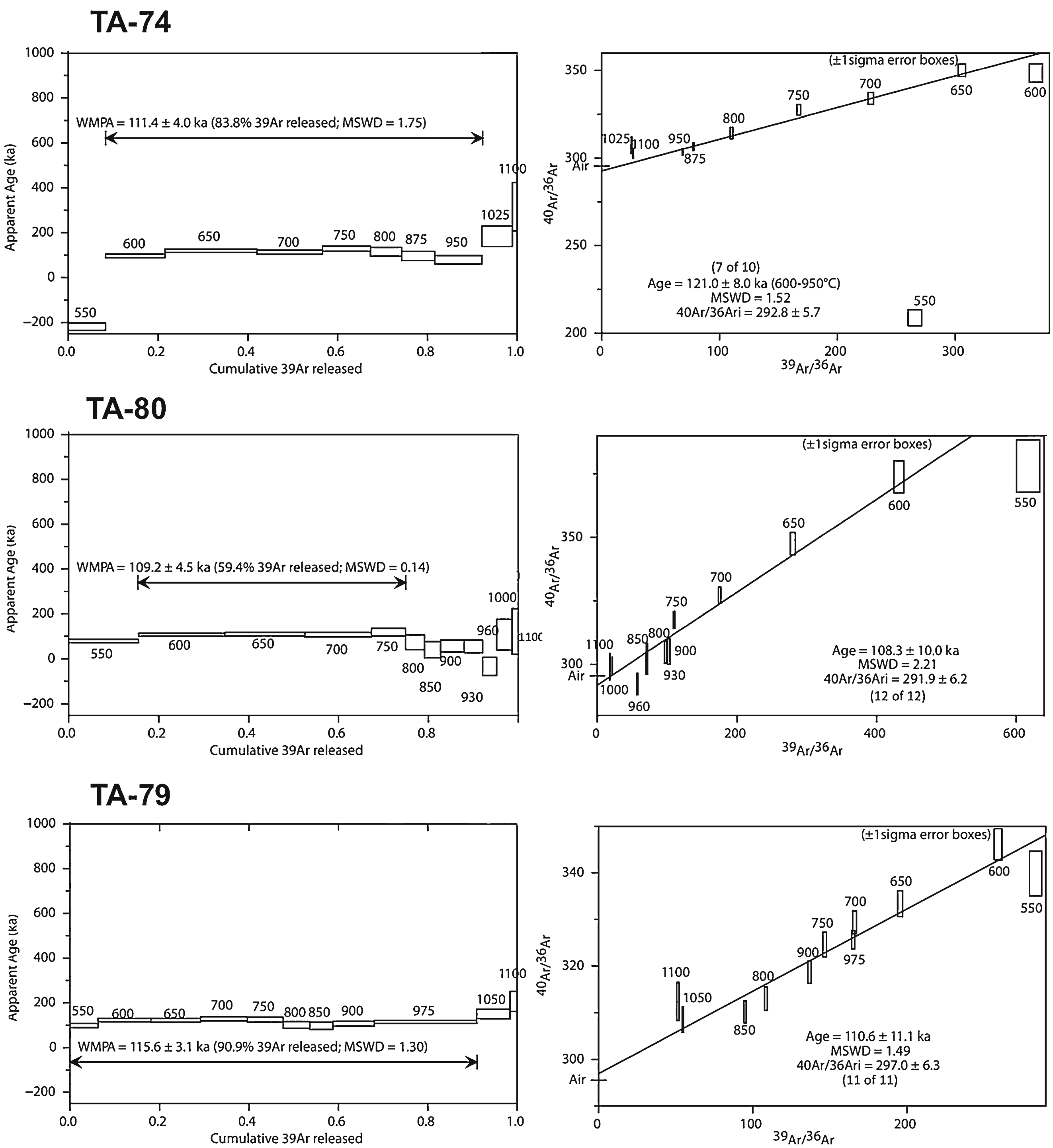


**Fig. 5** (continued)

When plotted on isotope correlation (isochron) diagrams, all our data fall within error of the atmospheric $^{40}Ar/^{36}Ar$ ratio ($^{40}Ar/^{36}Ar$ intercepts of 293.7±2.1 (2σ), compared with 295.5). Samples TA-74, TA-77, TA-79, TA-80, and TA-82a yielded good plateau age spectra. Sample TA-72 contained two intermediate steps with low apparent ages. However, the bulk of the remaining gas is well within analytical error, so it appears reliable. TA-73a yielded a disturbed age spectrum with no plateau and a discordant isochron. All steps lie between 600 and 800 ka, the total gas age is 728±6 ka and the isochron age including all gas fractions is 748±19 ka. While difficult to interpret, we are

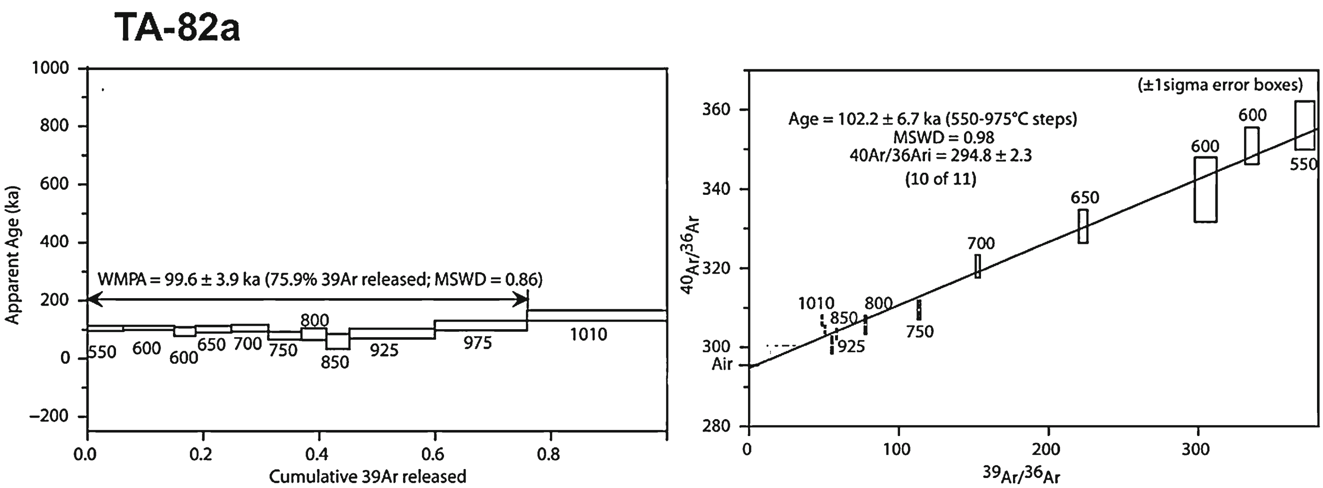


**Fig. 5** (continued)

confident that the eruption age of this sample is between 800 and 600 ka, most likely 800 and 700 ka.

All $^{40}Ar/^{39}Ar$ plateau ages and their 1σ errors are summarized in Table 1. It is evident that the ages cluster around two volcanic periods. Two samples, the En Zivan Basalt (TA-77) together with another flow northwest of the tuff ring (TA-73a, Figs. 1 and 2) define the earliest activity in the complex, 800–600 ka. Four samples from the Mt. Avital volcanic complex yielded ages between 120 and 95 ka. This includes (1) the basanitic flow underlying the tuff northwest of the tuff ring (TA-72, Figs. 1 and 2b), which yielded an age of 116 ± 3 ka (Fig. 4), (2) the basanitic flow that breaches the Southern scoria cone (TA-82a, Figs 1 and 2b) with an age of 100±4 ka (Fig. 4), (3) the volcanic bomb (TA-74, Figs. 1 and 2b), which was sampled from the scoria of the Northern cone and yielded an age of 111 ± 4 ka (Fig. 4), (4) the basanitic flow that breaches the Northern cone (TA-80, Figs. 1 and 2b) with an age of 109±5 ka (Fig. 4). The sample that was taken from the front of the Odem flow (TA-79, Figs. 1 and 2b) was dated at 116±3 ka (Fig. 4), similar to the Avital complex ages and significantly different from the earlier K-Ar age determination of 320 ka (Mor 1993).

## Discussion

### The volcanological history of Mt. Avital

Weinstein and Weinberger (2006) suggested that the complex at Mt. Avital was constructed during two volcanic phases. The early phase included the effusion of basalts that constructed the basal part of the complex (En Zivan Basalt, Fig. 2a). The age of this phase is now constrained by two $^{40}Ar/^{39}Ar$ ages at 800–600 ka, more likely 800–700 ka (TA-73a and TA-77, Table 1). The late volcanic phase included the construction of scoria cones, the effusion of lavas and the phreatomagmatic event. This phase is now also well constrained by the new $^{40}Ar/^{39}Ar$ ages at 120–95 ka (Table 1).

The $^{40}Ar/^{39}Ar$ ages allow a detailed determination of the chronology of the late volcanic phase. The earliest documented event in this phase was the construction of the Southern and the Central scoria cones (Fig. 2a, Avital Coarse Scoria). This event was not directly dated but we note that these cones cannot belong to the early volcanic phase, based on their relief (steep slopes, limited erosion). In the relatively wet climate of the northern Golan (annual

**Table 1** $^{40}Ar/^{39}Ar$ ages (with 1 σ errors) of samples from the Mt. Avital area

| Sample | | Location (Israel Transverse Mercator) | Plateau age (ka) | Isochron age (ka) | Total gas age (ka) |
|---|---|---|---|---|---|
| TA-73a | Early phase | 27262/78074 | No plateau | 748.1±19.1 | 727.7±5.5 |
| TA-77 | | 27505/77910 | 707.0±3.0 | 711.2±5.4 | 701.6±4.4 |
| TA-72 | Late phase | 27253/78014 | 116.3±3.2 | 107.7±7.8 | 112.1±4.4 |
| TA-74 | | 27333/78135 | 111.4±4.0 | 121.0±9.9 | 88.7±6.2 |
| TA-80 | | 27211/78241 | 109.2±4.5 | 108.3±10.0 | 91.8±5.8 |
| TA-79 | | 27315/78358 | 115.6±3.1 | 110.6±11.1 | 119.1±3.6 |
| TA-82a | | 27341/77871 | 99.6±3.9 | 102.2±6.7 | 115.5±5.4 |

See details of age determination in Fig. 5 and the appendix precipitation of 0.9–1.0 m), scoria cones of 800–700 ka are usually preserved as less prominent, often topographically negative structures (Mor 1973).

After the construction of these two scoria cones, the center of activity migrated toward the central part of the complex. This included the effusion of lavas that flowed down the topography to the west (Lower Avital Basalt, Fig. 2a), such as that of sample TA-72, which constrains the time of this stage to 116±3 ka.

The third event includes the construction of the Northern scoria cone (Bental Coarse Scoria), concurrent with the phreatomagmatic eruption at the center of the complex, as is evident by the intercalation of phreatomagmatic tuff breccias with scoria layers on the southern slope of the Northern cone. In particular, the phreatomagmatic deposits directly cover the layer that includes the dated volcanic bomb (TA-74, 111.4±4.0 ka, Table 1). Both tuff rings and scoria cones are monogenetic structures and are usually constructed within a very short time interval (days to months, e.g. Schmincke 2004, 2007; Lorenz 2007). This is clearly manifested in Mt. Avital, where no erosion surface or any other evidence for a pause in the activity was observed, neither in the phreatomagmatic succession nor within the scoria layers of the Northern cone. This means that the phreatomagmatic eruption and the strombolian buildup of the Northern cone concurrently occurred within a short time interval between 115 and 107 ka. The fact that one site experienced dry activity while the other was engaged in a phreatomagmatic eruption probably resulted from the local availability of surface water, controlled by the local palaeo-topography (Weinstein and Weinberger 2006).

The age range of the phreatomagmatic eruption (as well as of the Northern cone construction) can be narrowed by taking into account its relation with a basaltic flow on the western slope of the complex (TA-72). This flow is covered by a flow-top breccia, which in turn is directly overlain by surge deposits of the Avital Tuff (Weinstein 2007). Though vulnerable to erosion, the flow-top breccia is very fresh, with no evidence of weathering or pedogenesis (Weinstein 2007), which implies that the Avital Tuff covered the basalt shortly after emplacement. The age of this flow is 116.3±3.2 ka (Table 1, Fig. 5), which suggests that the Avital Tuff did not erupt much later than 113 ka. Altogether, this means that the phreatomagmatic eruption occurred sometime between 115 and 107 ka, more probably between 115 and 113 ka.

The fourth event includes two flows that breach the scoria cones (Upper Avital Basalt, Fig. 2a). The first flow breached the Northern cone, and considering its age (TA-80, 109±5 ka), it could have erupted immediately following the scoria cone construction. On the other hand, the age of the flow that breached the Southern cone is younger than all other dated units (TA-82A, 99.6±3.9 ka, Table 1 and Fig. 5). In particular, it is significantly younger than the Southern cone, which was built during the first event. Together, the two flows imply a return to the dry style of activity before the complex turned dormant. This change could be a result of the phreatomagmatic activity, where the buildup of the tuff levees prevented access of surface water to the vent. Alternatively, it could be due to a decline in the lake water level in the valley. Another possibility is the migration of volcanic activity to areas not affected by the lake water (Weinstein and Weinberger 2006). Lastly, the wet-to-dry switch could also be due to a change in magma supply rate (e.g., Valentine and White 2012).

### Mt. Avital response to the change in the drainage basin

Common explanations for dry–wet transitions include changes in the conduit magma pressure (Christiansen 1979; Decker and Christiansen 1984; Houghton et al. 1999; Wong and Larsen 2010) or physiographic changes in the volcanic system, such as crater or caldera floor subsidence (e.g., Mastin 1997; Gutmann 2002) or fragmentation of the conduit wall (Tarff and Day 2011), followed by groundwater or surface water influx into the magma system.

Weinstein (2007) argued that the deep groundwater of the regional aquifer in the Mt. Avital area (currently 250–300 m beneath the surface) could not be the source for the magma–water interaction. The climate at 115 ka was very similar to that of today (Bar-Matthews et al. 2003), suggesting that groundwater table was also at a similar depth. Weinstein (2007) suggested that the source of water for the phreatomagmatic eruption at Mt. Avital was a local lake that existed in the Quneitra Valley to the east of Mt. Avital (Fig. 1). It was further suggested that the lake was formed or expanded due to the damming of the Quneitra stream (Fig. 1) by the Odem lava flow that arrived from the north and its course was diverted toward the lake and the eruption site. This was further corroborated by the study of Weinstein and Weinberger (2006), who showed that prior to the phreatomagmatic eruption, there was no topographic high between the eruption site and the Quneitra Valley, so that the water could infiltrate the magmatic system either as a surface flow or as shallow groundwater related to high lake stands.

A similar mechanism was suggested by Brand and White (2007) for the Early Pleistocene Sinker Butte tuff cone from the Snake River Plain (Idaho), where lava flows dammed or disrupted the ancient course of the Snake River, resulting in a shift to phreatomagmatism. A somewhat similar, external mechanism was also suggested by Sohn et al. (2002) for the dry–wet transition at Jeju Island, Korea. In this case, the shift was arguably caused by the Holocene seawater rising and the following raise in groundwater table during the Holocene.

A key factor in the understanding of the circumstances that led to the dry–wet transition at the Mt. Avital volcanic complex is the exact age of the Odem Flow, which dammed and diverted the Quneitra stream to the Quneitra Valley. The earlier K-Ar age of 320 ka (Mor 1993) suggested a long ‘response time’ (ca. 200 kyr) of the Avital volcanic system to the change in the drainage basin (Weinstein 2007). The new $^{40}Ar/^{39}Ar$ age of 115.6±3.1 ka of the damming flow is concurrent with the dry–wet transition at Mt. Avital (113–115 ka). This implies that the lake water reached the eruption site shortly after the damming of the stream, which further suggests that the shift was a direct result of the damming.

The tuff deposits at Mt. Avital lack any palaeosols or erosion surfaces. Hence, it is most likely that the phreatomagmatic eruptions lasted only days or weeks, as is typical in monogenetic volcanoes. Therefore, enough water had to be supplied for the whole eruption to occur within a few weeks. Based on the volume of the phreatomagmatic deposits, Weinstein and Weinberger (2006) estimated the volume of water needed by $0.2–1.5\times10^6$ $m^3$. With a drainage basin (post-diversion) of ~30 $km^2$, and 0.9–1.0 m annual precipitation (at 115 ka, the climate in the study area was very similar to that of today, Bar-Matthews et al. 2003) and 20 % runoff ratio (the current Golan average), the annual inflow to the Quneitra Valley sums at $\sim5\times10^6$ $m^3$. This is also the volume of the two artificial water reservoirs that collect the Quneitra Valley's water at the present. With most of the precipitation occurring during 4–5 months of the year, the required water volume could be certainly supplied within a few weeks or even shorter, during a major storm event.

Such water volumes could not be supplied to the magmatic system prior to the damming event (earlier than 119 ka). With a very small drainage basin (<10 $km^2$), the rainy season precipitation could hardly fill the local shallow depression at the Quneitra Valley and could not supply with significant water volumes to the eruption site.

### Pleistocene volcanism at the northern Golan and adjacent areas

The ages presented above suggest that the Mt. Avital volcanic complex experienced two main phases of volcanic activity at 800–600 and 120–95 ka with a period of volcanic quiescence in between. Volcanic activity was probably common throughout the northern Golan during the period 150–100 ka, as is evident by the 115 ka age of the Odem Flow (derived from Mt. Odem, 10 km to the north of the Avital) and by OSL and $^{40}Ar/^{39}Ar$ ages of 135–100 ka for maar deposits and an overlaying lava at Birket Ram, 13 km to the north of the Avital (Shaanan et al. 2011). An $^{40}Ar/^{39}Ar$ age of 223±3 ka for a lava flow underlying the maar deposits (Feraud et al. 1983) further extends this volcanically active period to 220–100 ka. Ages of the old phase were also documented (K-Ar) in two neighboring volcanic edifices (Mor 1993; Heimann 1990). A recent $^{40}Ar/^{39}Ar$ study of 15 representative samples from the northern Golan (Inbar and Gilichinsky 2009) further confirmed that between ca. 600 and 200 ka the northern Golan was volcanically quiet.

Unlike the above, the K-Ar study of Mor (1993) described a more or less continuous activity (within the K-Ar resolution) from >1.6 to 0.1 Ma. In particular, two of these K-Ar dates, of the Northern scoria cone and the Odem Flow (Mt. Bental and Bab el Hawa, respectively, in Mor 1993, Table 5), with ages of 260±30 and 320±140 ka, yielded $^{40}Ar/^{39}Ar$ ages of 111±4 and 116±3 ka, respectively (this study). It seems that the resolution of the K-Ar methodology in the Geological Survey of Israel geochronology laboratory was not good enough to distinguish between ages <0.5 Ma (Harlavan, personal communication, 2012). This pattern of relatively short volcanically active periods and a long (400–500 kyr) pause in between is similar to observations from other volcanic provinces (e.g., Schmincke 2007).

Pleistocene volcanic activity also occurred in Syria, to the east and northeast of the study area, within the same volcanic field (Harrat ash Shaam). Documented K-Ar and $^{40}Ar/^{39}Ar$ ages spend the whole time interval between 1 and 0.1 Ma (e.g., Giannerini et al. 1988; Trifonov et al. 2011) with no identified pause. However, also in this case, the 0.6–0.2 Ma ages were all determined by the K-Ar method, questioning the resolution of the age determination. A recent detailed K-Ar study (Al Kwatli et al. 2012a, b) of the basalts of the Al Lajat plateau, southern Syria (east of the Golan), yielded ages of 266–56 ka, in agreement with the northern Golan late phase ages. More $^{40}Ar/^{39}Ar$ studies are needed in order to further constrain the timing and the extent of the late phase volcanic period.

The timing of the earlier, Plio-Pleistocene volcanic activity in northern Israel is also less constrained, and K-Ar ages span the whole period from 5 to 1 Ma (Mor 1993; Heimann et al. 1996; Weinstein et al. 2006) with no clear indication of the length of pauses between active phases. This might also be due to the fact that most ages were determined using the K-Ar method, while $^{40}Ar/^{39}Ar$ ages are limited to a few Early Pliocene samples (5–3 Ma) (Heimann et al. 1996). The timing of volcanism and the meaning of the volcanically quiet period in relation with regional tectonics should be further studied using the $^{40}Ar/^{39}Ar$ methodology.

## Main conclusions

1. The Pleistocene volcanic activity in the northern Golan included two main periods (800–600 and 200–100 ka) with a pause of 400–500 kyr in between.

2. In particular, the rocks found at the Mt. Avital volcanic complex erupted in two phases: early (800–700 ka) and late (120–95 ka).
3. The events of the late phase, including the phreatomagmatic activity, probably occurred within a few thousands years or less.
4. The phreatomagmatic eruption, which probably lasted no more than a few weeks, occurred sometime between 115 and 107 ka, probably between 115 and 113 ka, and was coeval with the buildup of the Northern scoria cone.
5. The shift from strombolian to phreatomagmatic activity in part of the complex was an immediate response to the damming of the Quneitra stream by a lava flow that originated from a different site.
6. The consequent change in the drainage basin of the Quneitra Valley resulted in the supply of enough water to produce the phreatomagmatic deposits within a few weeks or less.
7. The phreatomagmatic eruption constructed tuff levees, which in turn may have prevented further access of water to the eruption site (negative feedback) and restored dry activity with basaltic flows that breached both the Northern and the Southern cones.
8. Since abrupt landscape changes are very common in active volcanic areas, damming of streams should be considered in other cases of dry–wet transition.

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