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Evidence for the Neogene small-volume intracontinental volcanism in Western Hungary: K/Ar geochronology of the Tihany Maar Volcanic Complex

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Abstract: The Tihany Maar Volcanic Complex (TMVC) consists of several eruptive centres and is made up mostly of pyroclastic rocks. It belongs to the Bakony-Balaton Highland Volcanic Field (BBHVF), which is an extensive Late Miocene–Pliocene alkaline basaltic volcanic field in Western Hungary. The TMVC is the only known location in the BBHVF where volcanic rocks are in a stratigraphically fixed position near the boundary of the *Congeria balatonica–Prosodacnomya* Zones. Since 1985 this stratigraphic importance motivated repeated efforts to obtain unquestionable radiometric data with sufficient accuracy for the volcanic phases. Due to the difficulties of dating basaltic pyroclastic rocks (detrital contamination, excess argon, argon loss during hydrothermal alteration, high atmospheric argon content, etc.), this is for the first time a fully acceptable age of 7.92±0.22 Ma has been obtained for the onset of volcanic activity of the TMVC at the location Monk's cave. This age is a key datum for the boundary of *Congeria balatonica–Prosodacnomya* Zones and it agrees well with the start of alkali basaltic volcanic activity in Central Slovakia. 7.35±0.45 Ma is obtained for Diósteto. The youngest ages, showing the greatest argon loss were measured for the location Gödrös. An analysis of the isochron diagrams suggests here an interval from 6.24±0.73 Ma to 5.92±0.41 Ma for the time of volcanic activity. This age sequence is in agreement with volcanological field observation and in spite of some uncertainty of the younger age limit, it is indicated that volcanism at Tihany was not a single event of the same volcano, but rather a result of longer lived eruptions from a closely spaced, nested volcanic system.

Key words: Pannonian Basin, K/Ar geochronology, phreatomagmatic, scoria, monogenetic, maar, tuff ring, alkaline basalt.

Introduction

The Tihany Volcano is a maar volcanic complex (Németh et al. 2001) and belongs to the Bakony-Balaton Highland Volcanic Field (BBHVF) considered to be an extensive Neogene intracontinental alkaline basaltic volcanic field in Western Hungary (Fig. 1) (Jugovics 1968, 1969; Jámbor et al. 1981; Németh & Martin 1999b). This volcanic field consists of maars, tuff rings, scoria cones, mesa flows as well as long (km-scale) lava flows (Martin et al. 2003), all characteristic of an intracontinental "so called" monogenetic volcanic field (Connor & Conway 2000). The volcanic landforms are strongly modified, and often eroded back to the level of crater and/or vent filling pyroclastic and coherent lava facies (Németh & Martin 1999a; Németh et al. 2003) giving perfect exposures to study the sub-surface architecture of small-volume intracontinental volcanoes. The remnant of an unusual maar volcanic complex (Tihany Maar Volcanic Complex — TMVC) on the eastern margin of the BBHVF consists of several eruptive centres (Németh et al. 2001). Base surge and fallout deposits were formed during an initial phreatomagmatic explosion, caused by interaction of water-saturated sediment (Pannonian sand) and karst water stored in fractures of Mesozoic and Paleozoic rock units (Németh et al. 2001). The rapidly ascending intraplate alkali basalt magma often carried peridotite lherzolite xenoliths as well as pyroxene and olivine megacrysts (at localities Diósteto and Gödrös) accumulated in various lapilli tuff and tuff breccia units often associated with rock units assigned to be deposited in the final stage of the volcanic eruptions (Németh et al. 1999). The phreatomagmatic interaction between ascending magma and complex sources of ground water resulted in deeply excavated maars, which functioned as local sediment traps, where scoriaceous tephra washed into and deposited, building up Gilbert-type delta sequences (Németh 2001). Maar volcanoes reconstructed in the western and central areas at Tihany Peninsula (Fig. 1) are interpreted to have been formed due to phreatomagmatic explosions of magma mixed with water saturated clastic sediments (Németh et al. 2001). The unusual east maar had a special combination of water source from both the porous media aquifer and fracture-controlled aquifer, the latter one was probably the dominant supply (Németh et al. 2001).

On the basis of previous K/Ar determinations (Balogh et al. 1982; Balogh et al. 1986; Balogh 1995; Harangi et al. 1995) TMVC is though to be one of the oldest volcanic erosion remnants in the BBHVF (Balogh et al. 1986) and therefore it bears

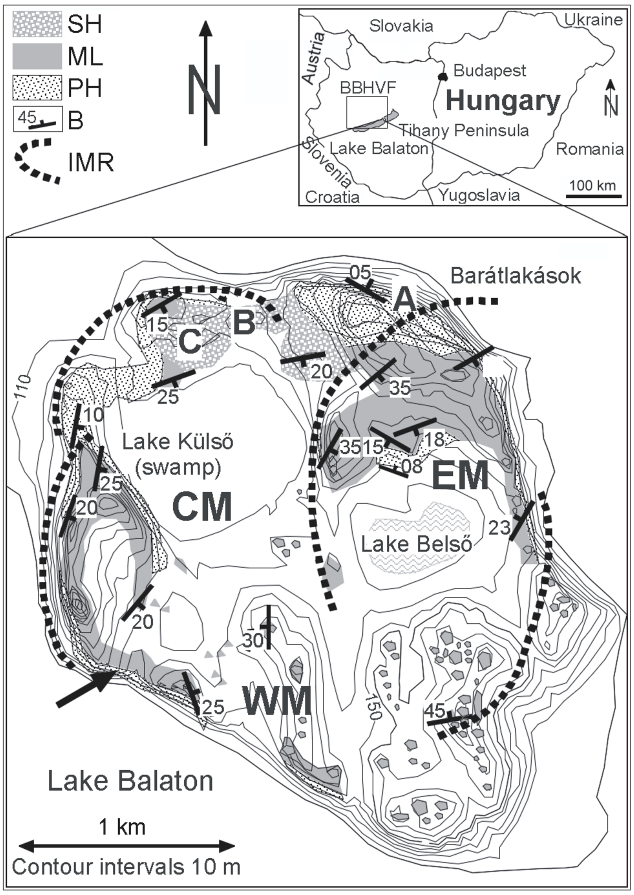

Fig. 1. Simplified geological map of the Tihany Peninsula showing the distribution of volcanic rocks on the surface. **SH** — Strombolian and/or Hawaiian style explosive eruptive products, **ML** — undifferentiated maar lake sedimentary rocks, **PH** — undifferentiated phreatomagmatic pyroclastic rocks, **B** — bedding, **IMR** — inferred position of maar rims, **A locality** — Monk's cave (Barátlakások), **B locality** — Diós, **C locality** — Gödrös. **CM**, **EM** and **WM** — Central, Eastern and Western Maar.

special significance in understanding the onset of the Neogene small-volume intracontinental volcanism in Western Hungary. The TMVC almost entirely consists of pyroclastic rocks, in Western Hungary this is a unique feature of the TMVC. The pyroclastic rocks are lapilli tuffs and tuff breccias with a phreatomagmatic origin. These rocks form the basal rock units and they are often capped by volcaniclastic units interpreted to be a result of remobilization of pyroclastic fragments from a crater rim surrounding a maar basin (Németh 2001). At Tihany no significant volume of coherent lava has been preserved, however, feeder dykes are known from the northern part of the complex (Németh et al. 2001). The basal phreatomagmatic rock units overlie Pannonian (Late Miocene) shallow marine (brakish) fluvio-lacustrine marly sand-silt and clay units with an erosional contact, however, contacts between volcanic and non-volcanic units are poorly exposed (Müller & Szónoky 1989).

The pyroclastic rock units overlie the *Congeria balatonica–Limnocardium decurum* Zone (Lóczy 1913; Jámbor 1980, 1989; Müller 1998). Moreover, in a large (1 m size), angular sedimentary block embedded in the basal phreatomagmatic pyroclastic unit (Fig. 2) *Prosodacnomya carbonifera* fossil has been found (Müller & Magyar 1992) strongly suggesting that volcanic eruption started near to the boundary of *Congeria balatonica* and *Prosodacnomya* Zones. Thus, the age for the Tihany Volcano is a key datum both for the beginning of the alkaline basaltic volcanic activity of Western Hungary and for the determination of the age of the boundary of *Congeria balatonica* and *Prosodacnomya* Zones.

Fig. 2. Large accidental lithic fragments from the basal phreatomagmatic pyroclastic rock units derived from the pre-volcanic shallow marine to fluvio-lacustrine Pannonian (Late Miocene) siliciclastic rock units. Note the intact bedding of the clast.

Finer-grained pyroclastic material contains detrital contamination that during eruption did not release the previously accumulated radiogenic Ar, therefore K/Ar ages measured on it are very uncertain. Reliable ages could be expected only when using volcanic blocks, bombs (e.g. cauliflower bombs) and lapilli (Fig. 3) which are free of contamination. Unfortunately, excess Ar and also Ar loss have been detected even in these samples, Ar loss is likely to be caused by hydrothermal alteration. The aim of the present study was to define a more accurate and reliable K/Ar isotopic age for the eruption of the Ti-

Fig. 3. Cauliflower bomb in a massive, accidental lithic rich phreatomagmatic lapilli tuff. Such bombs have been selected for K/Ar age determination since their eruption history related to the magma/water interaction of uprising magma and ground water, therefore its age inferred to be the age of the formation of the maar/tuff ring at Tihany.

hany Volcano. This purpose has been achieved by applying the isochron method to fractions produced from a single piece of rock and using the criteria for checking the reliability of K/Ar isochron ages by the method elaborated for the neck of Šomoška-hill (Nógrád (Novohrad) — Southern Slovakia Volcanic Field, on the border between Hungary and Slovakia) and the refined techniques for producing fractions from basaltic rocks (Balogh et al. 1994).

Methodology and problems in interpretation of the data

During the past decades intensive geochronological researches on young alkaline basaltic rocks from the Pannonian Basin has confirmed that K/Ar data on these rocks mostly give the correct geological age and the most frequent error is caused by the presence of excess Ar (Balogh et al. 1981; Balogh et al. 1986; Borsy et al. 1986). Even when excess Ar was detected, the real geological age could be obtained by applying the isochron methods as introduced by McDougall et al. (1969) and Harper (1970) and analysed by Shafiqullah & Damon (1974) and Hayatsu & Carmichael (1977). In spite of the successes of isochron methods it still remained impossible to measure reliable age on a part of the basaltic rocks. The reasons for the occasional failures were variable and included:

1 — It is very difficult to distinguish real isochrons and "mixing lines", especially when samples with similar K contents are plotted in the isochron diagram (Hayatsu & Carmichael 1977; Bowen 1988). It is usually difficult to collect samples with highly variable K concentrations from a single basalt body. Therefore the isochron methods were applied as suggested by Fitch et al. (1976) using fractions of a single piece of rock for fitting the isochron. These fractions are not monomineralic, but differ in their mineral composition. The successful separation, that is the production of fractions with highly differing K content, depends on the texture of the rock and also on applying the optimum process for preparing the fractions.

2 — Isochrons fitted to samples with remarkable differences in their K content can still be erroneous, if there is a correlation between the K and excess Ar content of the rocks. This error can be recognized and corrected by using fractions selected according to their atmospheric argon concentrations (Balogh et al. 1994).

3 — It is very difficult, in most cases impossible, to date pyroclastic rocks of phreatomagmatic origin such as the volumetrically largest rock unit in Tihany. During especially phreatomagmatic explosive eruption the fragmented lava mixes with disrupted accidental lithic clasts or minerals derived from deposits where magma intruded. The fast explosive eruption and cooling does not allow the resetting of the K-Ar clock efficiently, a great part of the radiogenic argon will be retained in the detritus. This unreliability can be recognized by highly scattering ages and random distribution of the fractions in the isochron diagrams. In addition, the permeability of the pyroclastic rock units promotes water circulation and alteration of the volcanic material.

Reliable radiometric dating of pyroclastic rocks could be expected only, if larger blocks or bombs were available for dating. These samples must have been completely molten before eruption and free of macroscopic detrital material.

Dating the pyroclastics of the Tihany Volcano has been repeatedly attempted since 1985 (Table 1), but these attempts were only partly successful. Either the poor accuracy or the questionable geological reliability of age data limited the value of the previous efforts. Because of these uncertainties only 7 K/Ar ages and an isochron age of 7.56±0.50 Ma for the onset of volcanic eruption has been published up to now in a widely accessible form and with proper discussion (Balogh et al. 1986), but, in the light of later results, the interpretation even of these ages has to be revised now.

The published isochron age (7.56±0.50 Ma, Balogh et al. 1986) was not satisfactory: the error was too large and the K content varied in the samples only from 1.53 % to 1.87 %. Thus, there was a chance that our isochron is only a mixing line and the real age is significantly younger. Efforts to determine an accurate and convincing age for the Tihany Volcano were renewed after the criteria for testing the reliability of isochron ages were elaborated (Balogh et al. 1994). These new efforts failed to improve the previous results because a part of the newly collected samples proved to be altered and contained excess argon in an irregular distribution. The results were published only in a conference abstract (Harangi et al. 1995) and in a manuscript (Balogh 1995).

Here we present the first set of data that allow to assign a reliable and sufficiently accurate age to the first eruption of the Tihany Volcano. At the same time, this is the best datum for the onset of alkaline basaltic volcanism of the BBHVF. In the light of the new result a short evaluation of previous, mostly unpublished age data will be given too.

K/Ar geochronology of Tihany Volcano

The first K/Ar age determinations of the alkaline basalts in the BBHVF aimed to determine the relationship between the age of the volcanism and the timing of the Pannonian shallow marine to fluvio-lacustrine sedimentation (Balogh et al. 1982, 1986; Borsy et al. 1986). The first K/Ar ages on the Tihany Volcano were published by Balogh et al. (1986) in a review summarizing the results and experiences of K/Ar dating the post-Sarmatian alkaline basalts in the Carpathian basin. The first 7 K/Ar ages and an isochron age measured on the basal phreatomagmatic alternating lapilli tuff and tuff units of the Tihany Volcano, sampled at the Monk's cave (Table 1) have also been published in this paper. The analytical ages varied from 9.73 Ma to 7.35 Ma and the isochron age was 7.56±0.50 Ma.

K/Ar ages from the BBHVF suggested that the Tihany Volcanic Complex may be the earliest manifestation of the Neogene intracontinental monogenetic volcanism in Western Hungary. These preliminary results confirmed that further refinement and discussion of obtained age data from Tihany is desirable.

The oldest ages in the BBHVF were obtained from a basaltic neck (Ragonya at Mencshely, approximately 10 km away from Tihany, 7.92±0.33 Ma) and on the oldest eruption of the Tihany Volcano (at Monk's cave, 7.56±0.50 Ma) measured

Table 1: Previous K/Ar ages on the Tihany Volcano.

No.	Dated fraction	K %	40Ar$_{rad}$ 10^{-7}cm^3/g	40Ar$_{rad}$ %	Age Ma (±1σ)	Ref.
Samples from Monk's caves						
958	w. r.	1.79	5.852	0.52	8.40±0.36	1
958	M_1	1.84	5.524	0.36	7.72±0.38	1
958	M_3	1.87	5.428	0.65	7.46±0.30	1
1000	w. r.	1.75	5.796	0.25	8.51±0.45	1
1000	M_1	1.53	5.797	0.19	9.73±0.75	1
1000	M_2	1.76	5.686	0.20	8.30±0.61	1
1000	D_1	1.79	5.120	0.17	7.35±0.64	1
3378	w. r.	1.72	4.647	0.15	6.92±0.65	4,3
3379	w. r.	1.78	5.970	0.24	8.60±0.55	3,4
3380	w. r.	2.06	6.234	0.48	7.78±0.33	3,4
3382	w. r.	1.81	5.868	0.34	8.31±0.42	3,4
3442	w. r.	1.96	5.646	0.42	7.41±0.34	4
3443	w. r.	1.65	6.078	0.42	9.43±0.43	4
3381	w. r.	2.04	5.379	0.33	6.78±0.35	3,4
3381	D_1M_2	2.39	6.927	0.33	7.44±0.38	4
3381	D_1M_4	2.15	6.820	0.82	8.14±0.31	4
3381	D_2M_1	0.82	3.305	0.16	10.34±0.90	4
3381	D_2M_2	0.91	3.118	0.41	8.78±0.40	4
3381	D_2M_3	1.11	3.832	0.52	8.83±0.37	4
3381	D_2M_4	2.26	6.036	0.35	6.86±0.34	4
3381	D_2M_5	2.17	7.632	0.38	9.03±0.39	4
Samples from Diósteto						
1347	w. r.	0.80	2.305	0.12	7.40±0.86	2
1350	w. r.	1.20	3.647	0.053	7.83±1.45	2
1349	w. r.	1.77	5.117	0.21	7.42±0.52	2
1349	M_1	0.22	1.249	0.26	13.00±1.00	2
1349	M_2	1.85	5.394	0.27	7.49±0.44	2
3344	w. r.	1.40	4.914	0.078	9.03±1.64	4,3
3345	w. r.	1.85	5.065	0.124	7.03±0.73	4,3
3346	w. r.	1.77	3.880	0.075	5.64±1.04	4
3347	w. r.	1.55	3.867	0.26	6.39±0.39	4,3
3445	w. r.	1.72	4.427	0.38	6.62±0.31	4
3445	M_3	1.77	4.551	0.24	6.60±0.31	4
3445	D_1	1.62	4.648	0.13	7.37±0.79	4
Samples from Gödrös						
3341	w. r.	0.88	1.802	0.21	5.24±0.39	4,3
3342	w. r.	1.52	3.349	0.25	5.64±0.36	4,3
3342	M_1	0.115	1.172	0.074	26.0 ±5.5	4,3
3342	M_2	1.57	3.385	0.358	5.53±0.27	4,3
3342	M_3	1.66	3.720	0.452	5.77±025	4,3
3343	w. r.	1.35	3.191	0.186	6.07±0.47	4,3

References: **1** — Balogh et al. 1986, **2** — Balogh et al. 1985, **3** — Harangi et al. 1995, **4** — Balogh 1995.

from a volcanic bomb, a block and their rock fractions from the basal phreatomagmatic lapilli tuff units (Balogh et al. 1986). Unfortunately, these isochron ages were obtained from rocks and rock fraction with insufficiently differing K concentrations, therefore the age of eruption and also the datum for the beginning of basaltic volcanism of the BBHVF remained questionable.

These initial measurements were followed by repeated efforts in order to improve the accuracy and increase the reliability of ages of the Tihany Volcano. Dating has continued with measurement of large, often vesicular, fluidally shaped coherent lava bombs interpreted as lava spatters (Németh et al. 1999) from Diósteto (Balogh et al. 1985). Three whole rock samples (No. 1347, 1349, 1350 in Table 1) and 1 fraction defined an isochron age of 7.35±0.45 (0.1) Ma and the K content in these samples varied from 0.80 to 1.85 % (Fig. 4). The error of this isochron age is defined by the errors of individual measurements, and the error given in parentheses is calculated from the scatter of points around the straight line. The good fit of points may indicate an overestimation of individual errors, but could also be only casual. This datum was in line with the previous results, but the error of age could not be reduced significantly. Some other uncertainties also remained: the isochron was obtained on different samples, so the assumption of uniform isotopic composition for the initial Ar remained questionable and, due to the greater atmospheric argon content in these samples, the error of individual age data was also greater, therefore attempts to determine an accurate and reliable age for the Tihany Volcano have been given up for a time.

Efforts on dating the Tihany Volcano were resumed only after recognizing the criteria for checking the reliability of K/Ar isochron ages. Most reliable isochron ages are those measured on fractions with **1** — highly differing K content, **2** — similar and low atmospheric argon concentration (Balogh et al. 1994).

Encouraged by the successes of this method new samples have been collected from the Monk's cave (cauliflower bombs from phreatomagmatic lapilli tuff), Diósteto (lava spatter) and Gödrös (fluidal vesicular spindle bomb). The last location is thought to represent the youngest eruption of the Tihany Volcano on the basis of the general volcanic field relationships (Németh et al. 1999; Németh et al. 2001).

For all samples from the pyroclastic rocks from the Monk's cave, excluding only one sample with obvious excess Ar content, an isochron age of 7.80±1.07 (0.38) Ma was obtained, where 1.07 Ma is the deviance and 0.38 Ma is the error. The poor fit of points to the straight line shows that conditions, which allow the use of the isochron method, are not met properly. In order to preclude the possibility of a significantly younger age, it has been carefully tested, if the isochron age could be caused by the correlation of excess Ar and K. Fractions with remarkably different K concentrations were prepared from sample No. 3381 from the same locality. The fitted line indicates again a similarly old age: 7.91±1.01 (0.65) Ma. The plot of atmospheric Ar against K concentration does not

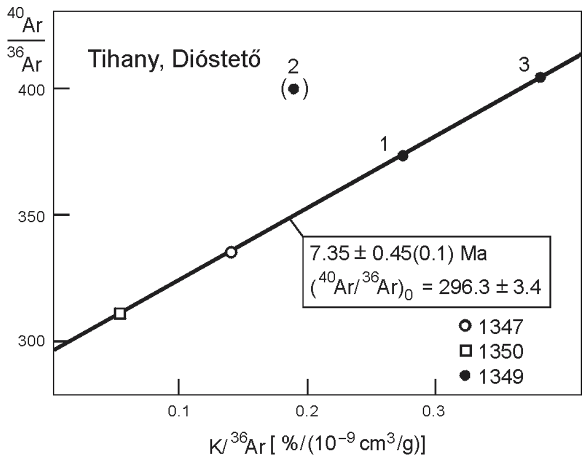

Fig. 4. Isochron of the coherent lava fragment of spatter cone from the Diósteto (C locality in Fig. 1) volcanic sequence.

show correlation, which is an argument for the reality of the age. As an additional test an isochron has been fitted to the fractions with low ($^{36}Ar < 3 \times 10^{-9} cm^3/g$) atmospheric argon content. An age of 7.93±1.00 (0.55) Ma has been obtained. *These investigations proved for the first time the reality of the old age of Tihany, but the unfavourable character of the samples collected from the phreatomagmatic pyroclastic rocks prevented the determination of an accurate age* (Balogh 1995).

New volcanological observations suggested that lava spatter deposits at Dióstető might be the results of a younger volcanic phase in the evolution of TMVC than the basal phreatomagmatic unit (Harangi et al. 1995; Németh et al. 1999; Németh et al. 2001), this did not confront with the K/Ar ages (7.35±0.45 Ma) published first for this deposit (Balogh et al. 1986). The new attempt to improve dating of Dióstető was unsuccessful. The K concentration in the samples collected in 1995 did not show great differences, their atmospheric Ar content was mostly too large, and the too young ages of samples No. 3346 and 3347 indicated greater partial loss of radiogenic argon.

Due to its relatively high K concentration and radiogenic argon enrichment, sample No. 3445 has been selected for fractionation. However, because of the homogeneity of this sample no fractions with different K concentrations were obtained. Omitting the sample with too great an excess of Ar content (No. 1349 M_1) and those with too much Ar loss (No. 3346 and 3347), the fitted line defines an age of 6.64±0.71 Ma. This means that newly collected samples, most likely due to their more altered character, yielded a less valuable age, which was obtained previously by Balogh et al. (7.35±0.45 Ma, Balogh et al. 1985).

The youngest phase of volcanic activity is represented by the basaltic spindle bomb bearing lapilli tuff and tuff breccia at Gödrös (Fig. 1) (Németh et al. 1999, 2001). The precise dating of this occurrence would help to establish the duration of volcanic activity. Mostly young ages have been obtained falling between 6.07 Ma and 5.24 Ma, however, one fraction gave too old an age due to the great amount of excess Ar or detrital contamination. The younger ages define an isochron age of 5.92±0.41 Ma (Fig. 5a), which is close to the oldest analytical age of 6.07±0.47 Ma. This suggests that at Gödrös younger ages may be caused by Ar loss. Plotting the 5 younger ages in the Ar(rad)-K diagram, an age of 6.24±0.73 Ma is obtained (Fig. 5b), this also suggests partial loss of radiogenic Ar at Gödrös, therefore an age older than about 6 Ma can be accepted for the pyroclastic rocks at Gödrös. However, contrasting the ages measured for the locations Monk's cave and Dióstető, ages older than 7 Ma (disregarding the highly contaminated fraction 3342 M_1) are missing: this is another argument for assuming a longer time span for the volcanism of the TMVC.

Summarizing the previous chronological work on the Tihany Volcano, it has been proven that volcanic activity started before 7 Ma (Table 1), however, a more accurate datum was still missing. This fact, together with the Ar loss characterizing the samples from the lapilli tuff at Gödrös, also prevented the estimation of the duration of volcanic activity. A renewed age determination survey therefore needed to give a more accurate and reliable datum for the start and the length of the volcanic activity. The refined techniques of preparing fractions for K/Ar dating from the coherent basalt lavas as well as the careful sampling with insignificant excess Ar content with minimum degree of alteration made a new K/Ar survey promising.

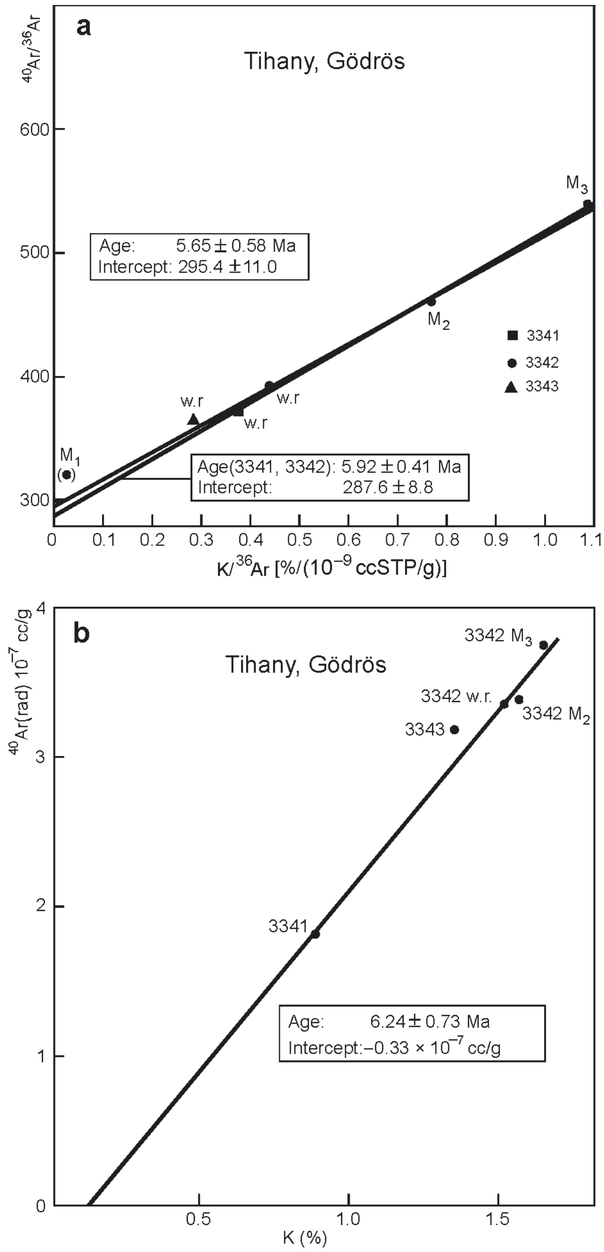

Fig. 5. $^{40}Ar/^{36}Ar$-$K/^{36}Ar$ (**a**) and ^{40}Ar(rad)-K diagram (**b**) of samples from Gödrös.

New K/Ar data from Tihany as a refinement of the old ages

Methods

New dating has been performed on a part of a basalt block of 100–150 mm size collected from the locality Monk's cave. The size fraction of 0.125–0.063 mm has been chosen for producing a set of magnetic and density fractions. The size-fraction was first washed, treated with 20% acetic acid to remove calcium carbonate and washed again. Density fractions were produced by using tetrabromoethane and diluted methylene iodide, so that $D_1 < 2.94 g/cm^3 < D_2 < 3.05 g/cm^3 < D_3$. Three magnetic fractions (marked with M_i, where greater i shows greater magnetic susceptibility) were produced from each density fractions using first a permanent magnet and running the samples repeatedly on a magnetic separator.

The unseparated size fraction (w.r.) and 8 D_iM_j fractions were dated, results are shown in Table 2. In line with our general observation (Balogh et al. 1986) excess argon causes the greatest age increase of the densest and least magnetic fraction, in which olivine is concentrated. Figure 6 shows that D_3M_1 is the only point not fitting the straight line. Omitting D_3M_1 an isochron age of 7.92±0.22 Ma is defined by the rest of the points with an initial $^{40}Ar/^{36}Ar$ ratio of 299.8±5.2, so that a significant amount of excess argon is not indicated. K content in the used fractions ranges from 0.49 % to 2.65 %, thus, the possibility that our isochron is only a mixing line is negligible. K and atmospheric argon do not correlate, therefore this isochron age is regarded as the most likely datum for the eruption of the Tihany Volcano (Fig. 6).

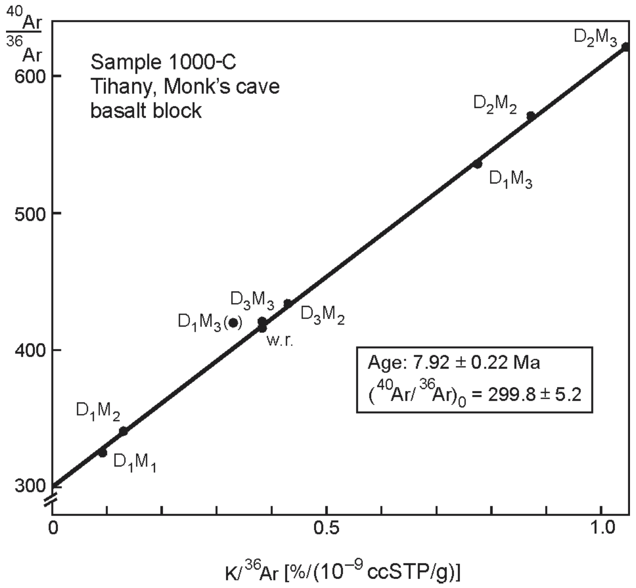

Fig. 6. Isochron of the 1000-C sample derived from the phreatomagmatic rock units of the Monk's cave (Barátlakások — A locality in Fig. 1.)

Discussion on the timing of volcanism and the duration of volcanic activity at Tihany

Three main volcanic stratigraphic units have been identified at Tihany on the basis of textural characteristics, field relationships as well as areal distribution of volcanic rocks (Németh et al. 1999, 2001). These rocks represent erosion remnants of volcaniclastic rock units, lava spatter accumulation zones as well as feeder dykes all associated with at least three maars and a Strombolian scoria cone (Németh et al. 1999, 2001). The identification of strong negative gravity anomalies in three well-distinguished areas at Tihany is in good agreement with the location of reworked volcaniclastic rock units inferred to be part of Gilbert-type delta fronts built in a volcanic depression, presumably a maar (Benderné et al. 1965; Németh 2001; Németh et al. 2001) (Fig. 1). In two areas, maar lake Gilbert-type delta front deposits cover alternating, well-bedded, accidental lithic clast-rich phreatomagmatic lapilli tuffs and tuffs. These rocks exhibit textural features for radial transportation direction from the central areas of the Tihany Peninsula. The presence of the large negative anomaly, and the uniform characteristics of this basal phreatomagmatic unit indicate that there must be a central maar, erupted first, which produced extensive pyroclastic sheets around the maar basin (Central Maar) (Németh et al. 2001). Previously it has been interpreted that the samples collected for the K/Ar age survey from the Monk's cave area have been derived from this initial unit, so from the stratigraphical point of view their age must represent the time of onset of volcanism at Tihany. There are two other gravity anomaly zones and accompanied capping maar lacustrine sequence indicating that there are two other maars post-dating the central maar (Németh et al. 2001). The presence of a large amount of scoriaceous detritus in volcanic rock units inferred to represent gravity driven mass flow deposits in the maar lakes suggests, that a source zone, a ready to be eroded scoria cone, must have existed close to the central areas at Tihany. In this stratigraphical framework it is inferred that the oldest maars are the Central and East Maars. The West Maar is inferred to be the youngest phreatomagmatic vent (Németh et al. 2001). Magmatic explosive activity post-dates production of each maar.

Table 2: K/Ar ages on fractions of basalt No. 1000-C from Monk's cave (Barátlakások), Tihany.

Dated fraction	K %	$40Ar_{rad}$ $10^{-7}cm^3/g$	$40Ar_{rad}$ %	$^{40}Ar/^{36}Ar$	^{36}Ar $10^{-9}cm^3/g$	$K/^{36}Ar$ $[\%/(10^{-9}cm^3/g]$	Age Ma (±1σ)
w. r.	1.89	5.92	28.9	415.6	4.93	0.383	8.03±0.45
D_1M_1	2.31	7.72	9.24	325.4	25.6	0.090	8.56±1.29
D_1M_2	2.31	8.19	13.2	340.4	18.2	0.127	9.09±0.97
D_1M_3	2.65	8.20	44.7	534.4	3.43	0.773	7.95±0.35
D_2M_2	1.76	5.58	48.3	571.6	2.02	0.872	8.13±0.35
D_2M_3	2.02	6.28	52.4	620.8	1.93	1.044	7.99±0.33
D_3M_1	0.449	1.62	29.4	418.6	1.32	0.333	9.48±0.52
D_3M_2	0.49	1.61	32.0	434.6	1.15	0.429	8.36±0.44
D_3M_3	1.14	3.78	30.0	422.1	2.98	0.383	8.50±0.46

The present K/Ar age survey, which measured cauliflower bombs, vesicular spindle-shape lava bomb and/or spatter as well as co-genetic volcanic lithic fragments gave two distinct age groups in good concert with the volcanic stratigraphical position of the host rock units; **A** — 7.92±0.22 for Monk's cave and 7.35±0.45 for Dióstető, and **B** — from 6.24±0.73 Ma to 5.92±0.41 Ma range for the minimum age of eruption of Gödrös. This age data distribution is in good agreement with the identified volcanic stratigraphy.

Most of maar-diatreme volcanoes are the phreatomagmatic equivalent of scoria cones and their lava flows and thus may have been active for days, weeks, months and perhaps up to 10–15 years (Vespermann & Schmincke 2000; Walker 2000; Lorenz 2003). Similar to scoria cones maar-diatreme volcanoes grow in size the longer their phreatomagmatic activity lasts (Kienle et al. 1980; Vespermann & Schmincke 2000; Lorenz 2003). Short-lived maar-diatreme volcanoes have a small maar crater and thus can serve as a small depot centre whereas longer-lived maar-diatreme volcanoes have a larger maar crater and thus can serve as a larger and deeper depot centre for a much longer period of time (Lorenz 1986, 2003).

From historic observations scoria cones are active for days, weeks, months, or years. Paricutin in Mexico erupted for 9 years (20.2.1943–4.3.1952) (Luhr & Simkin 1993). In 1759 the scoria cone Jorullo erupted in the neighbourhood of Paricutin and after 15 years (1759–1775) of activity it reached a final height of 350 m and its associated lava field reached 1.25 km^2 in size (Luhr & Simkin 1993). The activity of most scoria cones is over within one year (Luhr & Simkin 1993).

In historic time only a few maar-diatreme volcanoes erupted, thus there is a very little information on the duration of maar volcanism. The two Ukinrek Maars erupted in 1977 for 3 and 8 days, respectively (Kienle et al. 1980; Self et al. 1980; Büchel & Lorenz 1993; Ort et al. 2000). Ukinrek West Maar erupted for 3 days and finally had a 170 m wide (rim to rim) and 30 m deep maar crater (Kienle et al. 1980). Its tephra ring had a maximum thickness of 10 m (Kienle et al. 1980). In 1954 the Nilahue Maar erupted in Chile during almost half a year (Müller & Veyl 1956; Illies 1959), however, the active phase of eruption varies according to different authors. The main eruptive phase ended after 10 days (Illies 1959) producing a maar crater 300 m in diameter. In summary it can be concluded that maar-diatreme volcanoes, similarly to scoria cones, may be active for days to months, perhaps in exceptional cases up to more than 10 years (Lorenz 2003). In this respect the well-distinguished age groups from the newly obtained K/Ar ages indicate that volcanism at Tihany was not a single event of the same volcano, but rather a result of a longer lived eruption from a closely spaced, nested volcanic system. The identified stratigraphical changes in the pyroclastic rock units at Tihany clearly demonstrate a gradual transition from phreatomagmatic to magmatic explosive fragmentation of uprising alkaline basaltic magma (Németh et al. 2001). These changes seem to coincide with the age variation identified on the basis of the new K/Ar age determination survey. However, the errors of the individual K/Ar age data are too large to demonstrate clearly the separation of volcanic events at Tihany, though their value is good enough to show that volcanism was a longer lived event at Tihany, at least longer-lived than the length of a single volcanic eruption of a common monogenetic intracontinental volcano (tuff ring, maar, scoria cone).

The newly obtained and reconfirmed K/Ar age data from Tihany clearly suggest that other old (older than 5 Ma) age data obtained from the eastern part of the BBHVF might also be true geological ages, and further researches may need to refine the timing of the Neogene volcanism. At Tihany, as the oldest manifestation of the Neogene intracontinental volcanism in Western Hungary, field evidence as well as the textural characteristics of the volcaniclastic rock units indicate that these rocks have been derived from volcaniclastic deposits that accumulated in subaerial conditions. However, deposition has occurred in a fluvio-lacustrine basin with a large quantity of surface water and near-surface water-saturated siliciclastic sediments (Németh et al. 2001; Martin et al. 2003). The age data from juvenile lithic clasts separated from basal phreatomagmatic lapilli tuff units as well as its capping stratigraphical position in relationship to the Pannonian (Late Miocene) siliciclastic units indicate that sedimentation in the Pannonian Lake must have been ended by this time in this region. This interpretation is in good concert with other considerations on the basis of paleontological evidence (Magyar et al. 1999). However, the age of the basal phreatomagmatic units does not imply that the Pannonian lacustrine sedimentation lasted up to this date, because the contact between the basal phreatomagmatic rock units are rather erosional, discontinuous (Németh et al. 2001). The pyroclastic rocks have been interpreted as representing near vent, and/or intracrater as well as diatreme filling rock units, which cut through the pre-volcanic stratigraphy. Therefore the obtained ages should be viewed as a minimum value of the finishing stage of the Pannonian lacustrine sedimentation at Tihany.

In respect to evaluation of the value and validity of the newly obtained age data, it is inferred that sample collection is absolutely critical. In general age determination on pyroclastic rocks of phreatomagmatic origin is difficult, and carries significant possibilities of errors. In a volcanic field, where volcanism is long-lived and/or sills and dykes may have intruded the pre-volcanic rock formations, a potential error is always present. The separation, and/or differentiation between syn-volcanic juvenile lithic clasts from volcanic accidental lithics from the same co-genetic feeding system is difficult. This problem may cause a greater scatter of the ages and older ages may be obtained for certain units than they are. In this work we tried to reduce this risk by selecting carefully samples showing clear signs of cauliflower and/or spindle texture and common textural relationship with other similar clasts in the same beds.

Conclusion

It has been shown that reliable K/Ar ages on basaltic pyroclastic rocks can be determined, if **1** — blocks and/or bombs coeval with the eruption are used for dating, **2** — the isochron method is applied to fractions of a single piece of rock (Fitch et al. 1976) and, **3** — if the criteria elaborated for checking the reliability of isochron ages are fulfilled (Balogh et al. 1994).

An isochron K/Ar age of 7.92±0.22 Ma has been determined on a whole rock sample and its fractions for the onset of eruption of the Tihany Maar Volcanic Complex at the locality Monk's cave (Barátlakások). This age meets all the requirements worked out checking the reliability of K/Ar isochron ages. It is a key datum for the boundary of the *Congeria balatonica* and *Prosodacnomya* Zones and it is very close to the start of alkali basaltic volcanic activity in Central Slovakia (Konečný et al. 1999). An isochron age of 7.35±0.45 Ma has been obtained for the basalt at Dióstető. This younger age is in agreement with volcanological field observation. However, the isochron is less convincing being fitted mostly to whole rock samples. An analysis of isochron and analytical ages suggests an interval from 6.24±0.73 Ma to 5.92±0.41 Ma for the youngest volcanic phase at Gödrös. Although the rejuvenating effect of post-volcanic hydrothermal alterations is strongest at this locality, the lack of analytical ages older than 7 Ma (in contrast to the basalts at Monk's cave and Dióstető) suggests that there is a significant age difference (at least a longer time than it requires to solidify an average feeder dyke of a small-volume intracontinental volcano) between the phases of volcanic eruption of the Tihany Maar Volcanic Complex. This implies that volcanism at Tihany was not a single event of the same volcano, but rather a result of a longer lived eruption from a closely spaced, nested volcanic system. Thus Tihany is another good example from Western Hungary to demonstrate that small-volume intracontinental volcanoes tend to form nested volcanic systems where eruption may recur more-less in the same site after significant time delay similarly to other sites where such delays have been clearly demonstrated (Martin & Németh 2002a,b; Martin et al. 2003).

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