frontiers

Supplementary Material

Geological background of the studied distal samples

The Ipolytarnóc locality, UNESCO World Heritage Site, is famous for the well-preserved Early Miocene plant remains, mammal and bird tracks assemblage occurring in a fluvial deposit called Zagyvapálfalva Formation (Hably, 1985; Kordos, 1985). It is overlain by ~ 10-30 m thick pyroclastic rocks. This volcanic series was formerly regarded as representing the earliest eruption product of the Miocene silicic volcanism (Gyulakeszi Rhyolite Tuff Formation; Hámor et al., 1980), but palaeomagnetic rotation data implied a younger event and thus, it was distinguished as Fehér hegy Formation (Vass et al., 2006; Márton et al., 2007a). The volcanic materials are overlain by reworked pyroclastics and terrestrial clay, siltstone and sand of the basal Salgótarján Formation. The pyroclastic rock series contains mostly unsorted lapilli tuffs and crystal-rich tuffs, and reworked variations of these. The volcanic suite was divided into 3 volcanic cycles using the intercalated siliciclastic sandstone and conglomerate layers that were interpreted to be channel filling fluvial delta deposits formed in shorter pauses of the eruptions (Korpás, 2003). Age of the 1st volcanic cycle was determined by zircon ID-TIMS and plagioclase Ar-Ar dating by Pálfy et al. (2007). Zircon dates suggested 17.42±0.04 Ma crystallization age, while the single-crystal laser fusion plagioclase $^{40}Ar/^{39}Ar$ dating resulted in 17.02±0.14 Ma cooling and eruption age for the pyroclastic rock. Samples of this study derive from the 1st (IT-BOR1; IT-KKB1, IT-MU2) and 2nd (IT-PUB) cycles (Table 1).

The sample called NEMTI is from an unwelded ignimbrite outcrop at the road-cut between Bátonyterenye and Nemti (Fig. 1). This deposit is considered to belong to the Gyulakeszi Rhyolite Tuff Formation. Age of the deposit was previously determined by Ar-Ar method on plagioclase (Pálfy et al., 2007) which gave 16.99±0.16Ma.

The MSZ sample is from the still active bentonitic lapilli tuff quarry of Mátraszele-Kazár (Fig. 1). The lapilli tuff here resembles to the NEMTI sample, however no fresh glass can be found due to bentonitic alteration. The volcanic material is laying on the Zagyvapálfalvai Formation and covered by the Salgótarján Formation.

The sample SZVG is from an accretionary lapilli-bearing tuff layer within a calcareous shallow marine deposit of Middle Miocene (Badenian) age that belongs to the Lajta Limestone Formation. The accretionary pellets occur in a 20-25 cm thick tuff bed.

Two pumice-bearing ignimbrite samples were involved in this study collected from the vicinity of Tar, NW of Mátra Mts. (Fig. 1; Harangi et al., 2005; Lukács et al., 2018a). The TAR-3 sample is from a ca. 25 m thick unwelded ignimbrite exposed by the Fehérkő quarry. It was dated by Lukács et al. (2018a; 15.0±0.2 Ma) and correlated with the Demjén ignimbrite unit of the BVF based on the similar ages, petrography and bulk rock chemistry. The TAR-Gh-1 sample is from the Gömör hill (ca. 2 km west of the Fehérkő quarry, at western side of the road No. 21). It was dated by K/Ar method (15.9±0.6 Ma) and was considered to be older than the Fehérkő ignimbrite (Zelenka et al.

2004). Thus, Zelenka et al. (2004) suggested that it is one of the type localities of the Tar Dacite Tuff Formation.

In the northern Bükk Mts., samples were collected from a pumiceous lapilli tuff deposit north of Szilvásvárad (Fig. 1), which is mapped as part of the Felnémet Rhyolite Tuff (Less et al., 2005). Although, the volcanic bed seems to be autochthonous, thin section analyses showed reworked features in a shallow marine environment (fine glass-free, crystal-rich tuff texture between pumice lapilli).

References

Hably, L. (1985). Early Miocene plant fossils from Ipolytarnóc, N Hungary. Geol. Hung., Ser. Palaeont. 44–46, 73–132.

Hámor, G., Ravasz-Baranyai, L., Balogh, K., and Árva-Sós, E. (1980). A magyarországi miocén riolittufa-szintek radiometrikus kora. (Abstract in English) MÁFI Évi Jelentése 1978-ról: 65-73.

Harangi, S., Mason, P.R.D., and Lukács, R. (2005). Correlation and petrogenesis of silicic pyroclastic rocks in the Northern Pannonian Basin, Eastern-Central Europe: In situ trace element data of glass shards and mineral chemical constraints. Journal of Volcanology and Geothermal Research 143(4), 237-257. doi: https://doi.org/10.1016/j.jvolgeores.2004.11.012.

Kordos, L. (1985). Footprints in Lower Miocene sandstone at Ipolytarnóc, N Hungary, Geol. Hung., Ser. Palaeont. 44–46, 359–415.

Korpás, L. (2003). New sedimentological model of the Ipolytarnóc sandstone. Chronology of the volcanic event and reconstruction of the eruption centre. Magyar Karszt és Barlangkutató Társulat 1-14. (in Hungarian)

Márton, E., Vass, D., Túnyi, I., Márton, P., and Zelenka, T. (2007a). Paleomagnetic properties of the ignimbrites from the famous fossil footprints site, Ipolytarnóc (close to the Hungarian-Slovak frontier) and their age assignment. Geologica Carpathica 58, 6, 531-540.

Less, G., Kovács, S., Pelikán, P., Pentelényi, L., and Sásdi, L. (2005). Geology of the Bükk Mountains. Geological Institute of Hungary Budapest, 284.

Lukács, R., Harangi, S., Guillong, M., Bachmann, O., Fodor, L., Buret, Y., et al. (2018a). Early to Mid-Miocene syn-extensional massive silicic volcanism in the Pannonian Basin (East-Central Europe): Eruption chronology, correlation potential and geodynamic implications. Earth-Science Reviews 179, 1-19. doi: https://doi.org/10.1016/j.earscirev.2018.02.005.

Pálfy, J., Mundil, R., Renne, P.R., Bernor, R.L., Kordos, L., and Gasparik, M. (2007). U–Pb and 40Ar/39Ar dating of the Miocene fossil track site at Ipolytarnóc (Hungary) and its implications. Earth and Planetary Science Letters 258(1), 160-174. doi: http://dx.doi.org/10.1016/j.epsl.2007.03.029.

Vass, D., Túnyi, I., and Márton, E. (2006). The Fehér hegy Formation: Felsitic ignimbrites and tuffs at Ipolytarnóc (Hungary), their age and position in Lower Miocene of Northern Hungary and Southern Slovakia. Slovak Geological Magazine 12, 2, 139-145.

Zelenka, T., Póka, T., Márton, E., and Pécskay, Z. (2004). A Tari Dácittufa Formáció típuszelvényének felülvizsgálata. (Abstract in English) MÁFI Évi Jelentés 2004-ről, 73–84.

Summary of the condition used during the LA-ICP-MS analysis of zircons performed at ETH Zürich.

Laboratory name	**Department of Earth Sciences, ETH Zürich**
Laser ablation system	
Make, Model & type	ASI Resolution 155
Ablation cell & volume	Laurin Technics 155, constant geometry, aerosol dispersion volume <1 cm^3
Laser wavelength	193 nm
Pulse width	25 ns
Fluence	~2 J cm^{-2}
Repetition rate	5 Hz
Spot size	30 µm
Ablation rate	~75 nm $pulse^{-1}$
Sampling mode / pattern	Single hole drilling, 5 cleaning pulses
Carrier gas	100% He
Ablation duration	40 s
Cell carrier gas flow	0.7 l/min
ICP-MS Instrument	
Make, Model & type	Thermo Element XR SF-ICP-MS
Sample introduction	Ablation aerosol only, squid aerosol homogenization device
RF power	1500 W
Make-up gas flow	~0.95 l/min Ar (gas mixed to He carrier inside ablation cell funnel)
Detection system	Single detector triple mode SEM, analogue, Faraday
Masses measured	202, 204, 206, 207, 208, 232, 235, 238 amu
Integration time per peak	12 ms (masses 202, 204), 20 ms (masses 208, 232, 235, 238), 40 ms (masses 206, 207)
Total integration time per reading	0.202 s
Dead time	8 ns
Typical oxide rate (ThO/Th)	0.18%
Typical doubly charged rate (Ba^{++}/Ba^{+})	3.5%
Data Processing	
Gas blank	10 s prior to each ablation spot

Calibration strategy	GJ-1 (Jackson et al. 2004) used as primary calibration material in all sessions. Validation reference materials used in sessions: session 140815: Plešovice, 91500, Temora2, OD-3 session 140204b, 140205: Plešovice, 91500, Temora2 session 160409p1: Plešovice, 91500, AUSZ7-1, AUSZ7-5 session 160409p2: Plešovice, 91500, AUSZ7-1, AUSZ7-5 session 191204: Plešovice, 91500, AUSZ7-1, AUSZ7-5, AUSZ8-10 References: Plešovice [Sláma et al., 2008; Horstwood et al., 2016], 91500 [Wiedenbeck et al., 1995; Horstwood et al., 2016], Temora2 [Black et al., 2004], OD-3 [Iwano et al., 2013], AUSZ7-1 [Kennedy et al. 2014], AUSZ7-5 [von Quadt et al., 2016] and AUSZ8-10 [this study]
Reference Material info	GJ-1 $^{206}Pb/^{238}U$ 0.09761 ± 0.0002 (weighted mean of ID-TIMS analysis ± 2σ, [3])
Data processing package used	IOLITE v3.4 [Paton et al., 2010, 2011] with VizualAge [Petrus and Kamber, 2012]
Mass discrimination	Mass bias correction for all ratios normalized to calibration reference material
Common Pb correction	No common-Pb correction applied
Uncertainty level & propagation	Ages are quoted at 2 SE absolute, propagation is by quadratic addition. Reproducibility of reference material uncertainty (i.e. external uncertainty) is propagated.

References

S.E. Jackson, N.J. Pearson, W.L. Griffin, E.A. Belousova, The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology, Chem. Geol. 211 (2004) 47-69.

M. Wiedenbeck, P. Allé, F. Corfu, W.L. Griffin, M. Meier, F. Oberli, A. von Quadt, J.C. Roddick, W. Spiegel, Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses, Geostand. Newslet. 19 (1995) 1-23.

J. Sláma, J. Košler, D.J. Condon, J.L. Crowley, A. Gerdes, J.M. Hanchar, M.S.A. Horstwood, G.A. Morris, L. Nasdala, N. Norberg, U. Schaltegger, B. Schoene, M.N. Tubrett, M.J. Whitehouse, Plešovice zircon — A new natural reference material for U–Pb and Hf isotopic microanalysis, Chem. Geol. 249 (2008) 1-35.

M.S.A. Horstwood, J. Košler, G. Gehrels, S.E. Jackson, N.M. McLean, C. Paton, N.J. Pearson, K. Sircombe, P. Sylvester, P. Vermeesch, J.F. Bowring, D.J. Condon, B. Schoene, Community-Derived Standards for LA-ICP-MS U-(Th-)Pb Geochronology – Uncertainty Propagation, Age Interpretation and Data Reporting, Geostand. Geoanal. Res. 40 (2016) 311-332.

L.P. Black, S.L. Kamo, C.M. Allen, D.W. Davis, J.N. Aleinikoff, J.W. Valley, R. Mundil, I.H. Campbell, R.J. Korsch, I.S. Williams, C. Foudoulis, Improved 206Pb/238U microprobe geochronology by the monitoring of a trace-element-related matrix effect; SHRIMP, ID–TIMS,

ELA–ICP–MS and oxygen isotope documentation for a series of zircon standards, Chem. Geol. 205 (2004) 115-140.

H. Iwano, Y. Orihashi, T. Hirata, M. Ogasawara, T. Danhara, K. Horie, N. Hasebe, S. Sueoka, A. Tamura, Y. Hayasaka, A. Katsube, H. Ito, K. Tani, J.I. Kimura, Q. Chang, Y. Kouchi, Y. Haruta, K. Yamamoto, An inter-laboratory evaluation of OD-3 zircon for use as a secondary U–Pb dating standard, Island Arc, 22 (2013) 382-394.

A.K. Kennedy, J.F. Wotzlaw, U. Schaltegger, J.L. Crowley, M. Schmitz, Eocene zircon reference material for microanalysis of U-Th-Pb isotopes and trace elements, Can. Miner. 52 (2014) 409-421.

A. von Quadt, J.F. Wotzlaw, Y. Buret, S.J.E. Large, I. Peytcheva, A. Trinquier, High-precision zircon U/Pb geochronology by ID-TIMS using new 1013 ohm resistors, J. Anal. Atom. Spect. 31 (2016) 658-665.

C. Paton, J. Hellstrom, B. Paul, J. Woodhead, J. Hergt, Iolite: Freeware for the visualisation and processing of mass spectrometric data, J. Anal. Atom. Spect. 26 (2011) 2508-2518.

C. Paton, J.D. Woodhead, J.C. Hellstrom, J.M. Hergt, A. Greig, R. Maas, Improved laser ablation U-Pb zircon geochronology through robust downhole fractionation correction, Geochem. Geophys. Geosyst. 11 (2010) https://doi.org/10.1029/2009GC002618

J.A. Petrus, B.S. Kamber, VizualAge: A Novel Approach to Laser Ablation ICP-MS U-Pb Geochronology Data Reduction, Geostand. Geoanal. Res. 36 (2012) 247-270.