REvPAMS: an integrated REsearch of a volcano with Potentially Active Magma Storage, the youngest volcano (Ciomadul, E Carpathians) of the Carpathian-Pannonian Region

Running time: 2015-2020

Consortional partners: MTA-ELTE Volcanology Research Group and the Geodetic and Geophysical Institute (Sopron) of the Research Centre for Astronomy and Earth Sciences Hungarian Academy of Sciences (CSFK GGI)

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Short summary

Scientific studies during this research project contributed significantly to our knowledge about the behaviour of Ciomadul, a typical long-dormant volcano, the youngest one erupted in the Carpathian-Pannonian Region. A detailed eruption chronology was constructed based on thorough zircon U-Th-Pb and U-Th/He dating and we pointed out that the volcanic activity was characterized by long (several 10's of thousand years, even longer than 100 thousand years) repose periods and even after such prolonged quiescence, volcanic activity was rejuvenated. The latest eruptive stage was dominantly explosive. A multiple criteria approach involving precise geochronological data, petrological and geochemical fingerprinting of volcanic products was effectively applied to characterize the distinctive features of Ciomadul tephras that help to recognize them in a timespan when several volcanoes were active in the Mediterranean and resulted in far-reaching distal tephra layers. Our crystal forensic study revealed that a low temperature high crystallinity magma reservoir (crystal mush) emplaced in the continental crust beneath the volcano and melt-bearing magma was continuously present over 1 million year above the solidus. Eruption triggering was caused principally by magma recharge resulting in fast heating up and partial remelting of the crystal cargo. Carbon-dioxide emanation is relatively high. Isotopic composition of the gases suggests significant magmatic component and derivation of the primary magmas from a strongly metasomatized lithospheric mantle region. Partial melting could be initiated by decompression melting due to the local thinning of the lithosphere. Preliminary results of magnetotelluric study indicate that the lithosphere-asthenosphere boundary (LAB) beneath Ciomadul is relatively shallow (70-90 km) compared with the surrounding areas.

Although the covid pandemia caused some difficulties at the end of the research project, we could complete almost all the planned scientific tasks. The scientific results have been already published in 11 peer-reviewed papers, 8 of them are in high-quality Q1 journals and they provided a strong basis to initiate a further research project to understand better how, why, and when crystal mush-bearing magma reservoirs can be rejuvenated after tens of thousands of years of quiescence and lead to eruptive events.

Introduction

Following the submitted proposal, the principal aim of the research project was to conduct a cutting-edge collaborative study applying state-of-the- art methodologies to constrain the behaviour of long-dormant and seemingly inactive volcanoes, focusing on the Ciomadul, the youngest volcano of the Carpathian-Pannonian Region, eastern-central Europe. The relevance of this study was to increase our knowledge how such volcanoes work. Long-dormant volcanoes pose a particular, but underestimated hazard on society since the long quiescence decreases the awareness. Such volcanoes erupted more than 10 thousand years ago, are considered as already inactive by many people, including scientists. Harangi et al. (2015) suggested a new term (volcanoes with Potentially Active Magma Storage or PAMS volcano, i.e., PAMS volcanoes) for those volcanoes, which erupted last time more than 10 thousand years ago, but their reactivation cannot be excluded based on the presence of melt bearing crustal magma reservoir. This project aimed to gather leading scientists from Hungary as well as internationally recognized top-scientists (from Switzerland, Germany, Italy and Romania) to study Ciomadul, a typical PAMS volcano in detail to understand better its behaviour as well as its present state. In particular, this was a consortional project between the MTA-ELTE Volcanology Research Group (MTA TKI) and the Geodetic and Geophysical Institute (Sopron) of the Research Centre for Astronomy and Earth Sciences Hungarian Academy of Sciences.

The key-questions of the research projects were the following:

1. Refinement of volcanology of Ciomadul with particular attention on the correlation of distal and proximal tephras.
2. Geochronology, i.e. constraints on the eruption ages
3. Petrological mapping of Ciomadul’s volcanic plumbing system (magma residence timescale, characterization of the open-system petrogenetic processes involving the pre-eruption conditions and the eruption triggering processes)
4. Composition and origin of the gas emanations
5. The state of the present magma reservoir and the lithosphere-asthenosphere boundary beneath Ciomadul based on magnetotelluric survey

Results

During this research project, we conducted detailed field works, petrological, geochemical and geophysical measurements to answer the proposed key-questions. We produced hundreds of back-scattered images combined with optical microscopic pictures to characterize the textures and the mineral phases, performed spot analysis and high-resolution profile analysis by electron-microprobe equipped with WDS detectors. Trace element content of selected mineral phases was determined by laser-ablation ICP-MS. We determined the bulk rock composition of almost all the eruption products in Ciomadul and also, the youngest volcanic rocks of the Piliske volcano. These data helped us to get an insight into the petrogenetic processes, recognize the main character of the Ciomadul volcanics and also, to quantify the crystallization condition. We analysed the U-Th-Pb-He isotopic composition of zircon from the entire suite of the Ciomadul volcanic rocks and also from the youngest rocks of Piliske to determine the zircon crystallization ages and calculate the eruption times. We measured emission fluxes at several places in and around Ciomadul in the field and determined the C-Ne-He isotope composition of the CO_2 gases. Fluxes and composition of the methane gases were also analysed. New sites for magnetotelluric measurements were selected and data collection was performed in two field campaigns.

The obtained data and their interpretations were published in 11 peer-reviewed papers (8 papers in Q1 journals):

Harangi Szabolcs, Lukács Réka: A Kárpát-Pannon térség neogén-kvarter vulkanizmusa és geodinamikai kapcsolata, ***Földtani Közlöny*** 149: (3) pp. 197-232., 2019

Harangi, Sz., Molnár, K., Schmitt, A., K., Dunkl, I., Seghedi, I., Novothny, Á., Molnár, M., Kiss, B., Ntaflos, T., Mason, P., R., D., Lukács, R.: Fingerprinting the Late Pleistocene tephras of Ciomadul volcano, eastern–central Europe ***Journal of Quaternary Science***, 35. 1-2, pp 232-244. (2020) https://doi.org/10.1002/jqs.3177

Italiano, F., Kis, B. M., Baciu, C., Ionescu, A., Harangi, Sz., Palcsu L.: Geochemistry of dissolved gases from the Eastern-Carpathians-Transylvanian Basin boundary, ***Chemical Geology***, 469, 117-128., 2017

Kis B.M., Ionescu, Artur; Cardellini, Carlo; Harangi Szabolcs; Baciu, Calin; Caracausi, Antonio; Viveiros, Fátima: Quantification of carbon dioxide emissions of the Ciomadul, the youngest volcano of the Carpathian-Pannonian Region (Eastern Carpathians, Romania), ***Journal of Volcanology and Geothermal Research***, 341, 119-130, 2017

Kis B.M., Caracausi A., Palcsu L., Baciu C., Ionescu A., Futó I., Sciarra A., Harangi Sz.: Noble gas and carbon isotope systematics at the seemingly inactive Ciomadul volcano (Eastern-Central Europe, Romania): evidence for volcanic degassing, ***Geochemistry Geophysics Geosystems*** 20: (6) pp. 3019-3043., 2019

Kis B. M., Baciu C., Zsigmond A. R., Kekédy-Nagy L., Kármán K., Palcsu L., Máthé I., Harangi Sz.: Constraints on the hydrogeochemistry and origin of the CO2-rich mineral waters from the Eastern Carpathians – Transylvanian Basin boundary (Romania) ***Journal of Hydrology*** Vol. 591. (2020) https://doi.org/10.1016/j.jhydrol.2020.125311

Laumonier M., Karakas O., Bachmann O., Gaillard F., Lukács R., Seghedi I., Menand T., Harangi S.: Evidence for a persistent magma reservoir with large melt content beneath an apparently extinct volcano, ***Earth and Planetary Science Letters*** 521: pp. 79-90., 2019

Lukács R., Guillong M., Schmitt A. K., Molnár K., Bachmann O., Harangi Sz.: LA-ICP-MS and SIMS U-Pb and U-Th zircon geochronological data of Late Pleistocene lava domes of the Ciomadul Volcanic Dome Complex (Eastern Carpathians), ***Data in Brief*** Volume 18, June 2018, Pages 808-813, 2018

Molnár Kata, Dunkl István, Harangi Szabolcs, Lukács Réka: A cirkon (U-Th)/He kormeghatározás módszertani alapjai és alkalmazása fiatal (<1M év) vulkánkitörések datálására, ***Földtani Közlöny*** 147/3, 225-244., DOI: 10.23928/foldt.kozl.2017.147.3.225, 2017

Molnár K., Harangi Sz., Lukács R., Dunkl I., Schmitt A. K., Kiss B., Garamhegyi T., Seghedi I.: The onset of the volcanism in the Ciomadul Volcanic Dome Complex (Eastern

Carpathians): Eruption chronology and magma type variation, ***Journal of Volcanology and Geothermal Research*** 354: pp. 39-56., 2018

Molnár Kata, Lukács Réka, Dunkl István, Schmitt Axel K., Kiss Balázs, Seghedi Ioan, Szepesi János, Harangi Szabolcs: Episodes of dormancy and eruption of the Late Pleistocene Ciomadul volcanic complex (Eastern Carpathians, Romania) constrained by zircon geochronology, ***Journal of Volcanology and Geothermal Research*** 373: pp. 133-147., 2019

In addition, 1 TDK, 1 MSc and 1 PhD dissertation were submitted and successfully defended closely belonging to the OTKA project:

Mészáros Kata: A csomádi dácit kitörés előtti magmatározójának jellemzői Fe-Ti-oxidok alapján. ***TDK dolgozat***, ELTE TTK, Budapest, 65 p., 2017

Mészáros Kata: Bálványos és Nagy-Hegyes lávadómjainak petrogenetikai elemzése. ***MSc diplomadolgozat***, ELTE TTK, Budapest, 102 p., 2019

Molnár Kata: Eruption chronology of the Ciomadul Volcanic Complex based on zircon (U-Th)/He geochronology. ***PhD Thesis***, ELTE TTK, Budapest, 161 p., 2019

The results of the research project were presented in posters and talks at various conferences (34 abstracts) such as EGU General Assembly, IAVCEI General Assembly, VMSG Annual Meeting, Goldschmidt conference, Kőzettani és Geokémiai Vándorgyűlés, ECROFI, INTAV Tephra meeting, among others. In the final report, only those abstracts are shown, which contain still unpublished results.

In the following, we summarize briefly the main outcomes of the research project following the initially addressed key-questions.

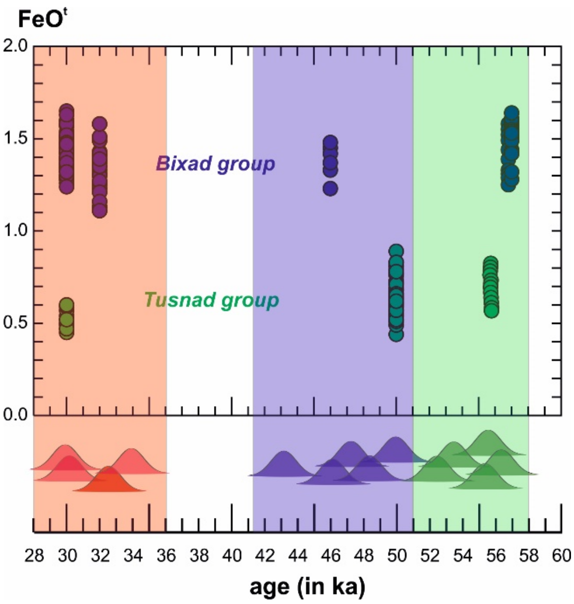
Volcanology

In this research project, we focused primarily on the characterization of distal tephras and their correlation with the proximal ones. The results were published in Harangi et al. (2020). Furthermore, we described several tephra localities within the Ciomadul volcanic complex in detail (e.g., Mohos, Bolondos, Tusnad, Torja), these were partly included in the published papers (Molnár et al., 2018; Harangi et al., 2020).

Distal tephras were described around the Ciomadul volcanoes at distances ~20-25 km from the eruption centres. Northwest of Sânmartin (Csíkszentmárton, lower Ciuc or Csíki basin), a well-preserved tephra bed is found within a Pleistocene gravely sequence. Southeast of Ciomadul two distinct tephra units occur in Pleistocene fluvial-alluvial basin-filling deposits. They are found at three localities northwest and south of Turia (Torja) and northwest of Târgu Secuiesc (Kézdivásárhely) in the NE Brasov (Háromszéki) basin. These tephras were resulted by violent explosive eruptions triggered by magma-water interaction and by vesiculation of magmatic volatiles (subplinian eruption).

We demonstrated that multiple criteria involving precise geochronological data, petrological and geochemical fingerprinting of volcanic products could be effectively used to characterize the distinctive features of a volcano and/or a volcanic eruption and correlate distal tephras with their source volcanoes. Using (U-Th)/He zircon geochronology combined with U-Th in-situ rim dating and complementing it with luminescence and radiocarbon dating, we could constrain the eruption ages of the largest explosive eruptions of Ciomadul that yielded distal tephra layers, but no preserved proximal deposits. The results suggest multiple large explosive eruptions of Ciomadul during its latest eruptive episode at 29-33 ka.

The specific petrological character (ash texture, occurrence of plagioclase and amphibole phenocrysts and their composition), the high-K calc-alkaline major element composition and particularly the distinct trace element characteristics provide a strong fingerprinting of the Ciomadul volcano. We showed that glass compositions, equivalent to bulk rock data, represent two main erupted magma types (called Bixad and Tusnad, following the earlier suggestions by Vinkler et al., 2007 and Harangi et al., 2010) and that there is no systematic compositional variation in the glass composition with time. In turn, eruption of these two main magmas occurred repeatedly during the 57-30 ka eruptive epoch of Ciomadul with its mostly explosive eruptions. Furthermore, during the youngest eruption stage (33-29 ka), both magma types can be recognized in the glass compositions. Thus, major element compositions of Ciomadul glasses alone cannot be used to distinguish single eruption events, but they may be useful to identify the Ciomadul source during its eruption epoch between 57 ka and 30 ka.

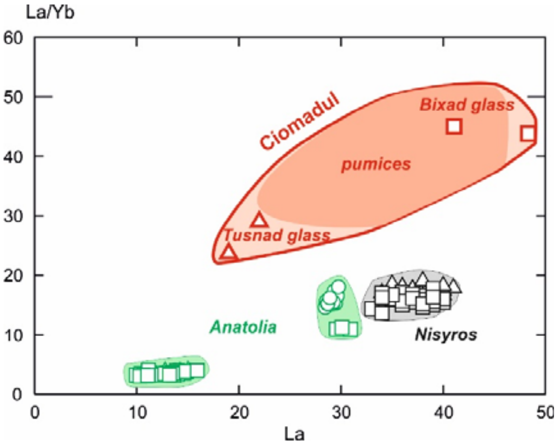


Eruption ages (shown in the lower panel with probability density curves from Molnár et al., 2019) vs. FeO^t in glass (data are from Karátson et al., 2016 and from Harangi et al., 2020). Note absence of systematic changes in erupted melt/magma composition with time. Magmas with Tuşnad- and Bixad-type affinity erupted repeatedly and occasionally coeval.

from Harangi et al. (2020)

We pointed out that application of glass major element composition as a tephrostratigraphic tool is highly questionable, and the presence of Ciomadul tephra at the Roxolany location (Wulf et al. 2016) cannot be validated. Mineral assemblage and mineral chemical data are important proxies in correlation of distal tephras. Ciomadul explosive volcanic products have a typical phenocryst assemblage containing plagioclase, amphibole (hornblende and pargasite), and biotite. In this regard, the Roxolany tephra differs significantly from Ciomadul, since it contains clinopyroxene (Wulf et al., 2016) instead of amphibole and therefore the Roxolany tephra is unlikely to be derived from Ciomadul.

Remarkably, there were several volcanic eruptions produced tephras with similar glass major element composition in the Mediterranean within the timeframe of 57-30 ka. However, the Ciomadul tephras differ from them by glass trace element abundances, ratios of strongly incompatible trace elements and distinctive mineral cargo that serve as discrimination tools.

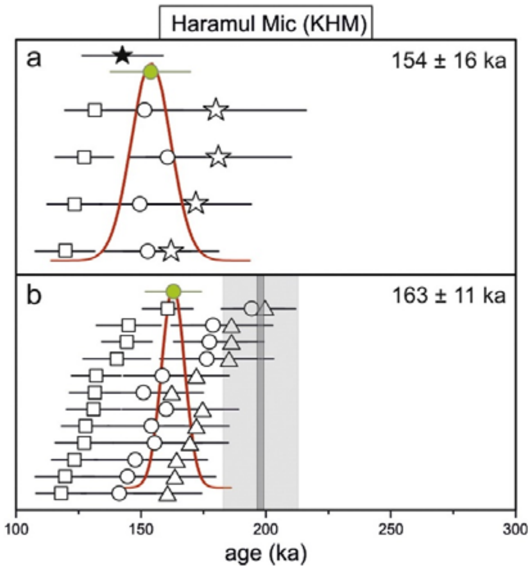


Trace element abundances and ratios of Ciomadul tephras can be readily distinguished from Anatolian and Nisyros tephras erupted during the same period in the Mediterranean and which have similar major element compositions.

from Harangi et al. (2020)

Eruption chronology

Ciomadul is a volcanic complex in the Carpathian-Pannonian Region, eastern-central Europe where the last known eruption occurred at around 30 ka (e.g., Vinkler et al., 2007; Harangi et al., 2010, 2015; Karátson et al., 2016). Understanding the frequency of eruptions in long-lived volcanic complexes is important to evaluate their potential hazards especially when these systems remained dormant for protracted periods. During this research project, we conducted a combined zircon U-Th-Pb and (U-Th)/He geochronology study and refined the eruption chronology of Ciomadul in a great detail (the results were published in Molnár et al., 2017; 2018; 2019 and in Harangi et al., 2020). We pointed out that this methodology is particularly suitable in dating rocks formed during Late Quaternary (<1 Ma) eruption events, where other geochronologically suitable mineral phases such as K-feldspar are lacking. U-Th geochronology was applied both on crystal surfaces (i.e., rim) and interiors (i.e., mantle) in order to have input data for the disequilibrium correction. Double-dating (Danisik et al., 2017) was performed for zircon crystals from lava dome rocks and pumices of a set of localities.

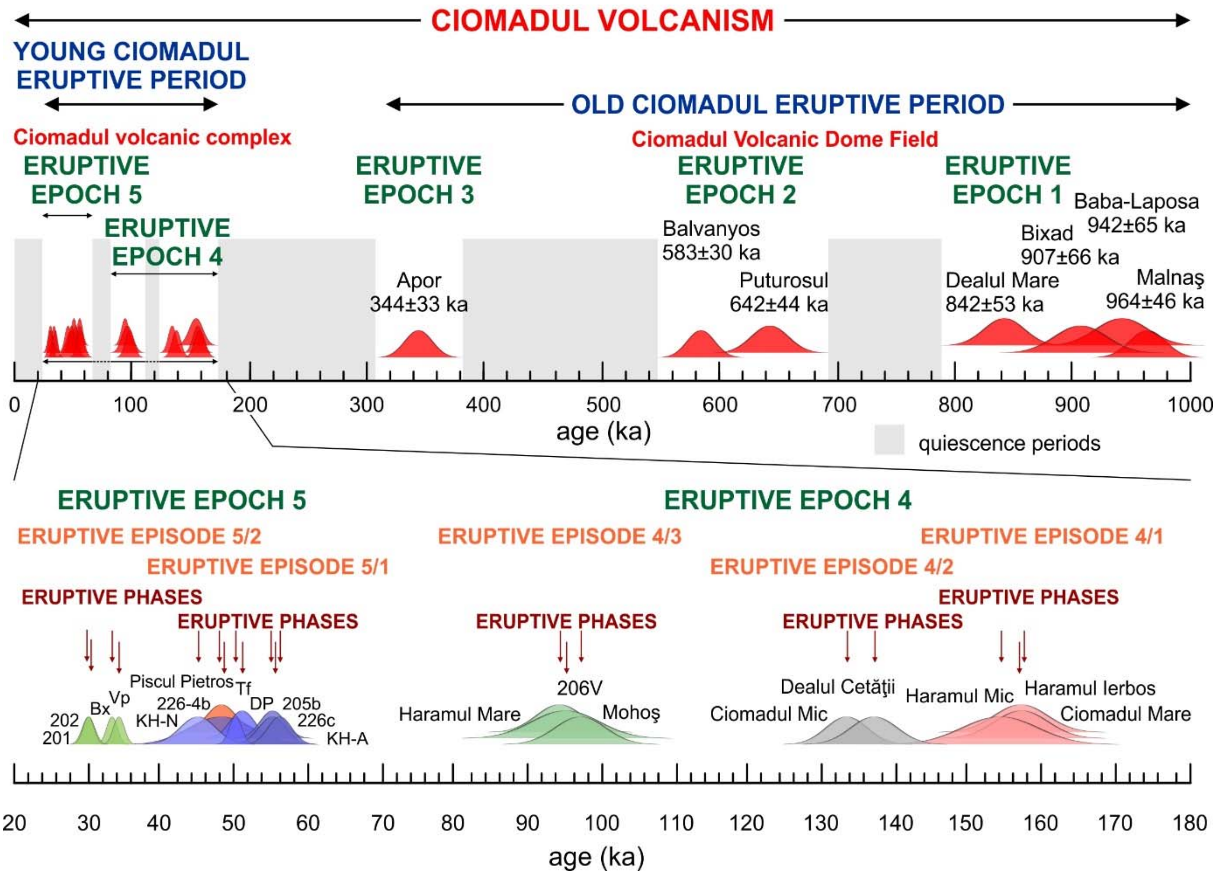


Zircon (U-Th)/He eruption ages determined by double-dating (a) and the average crystallization age correction (b) methods for the Haramul Mic (Kis-Haram) lava dome. Note, that previous K-Ar dating resulted in 850 ka age for this rock (Casta, 1980; Szakács et al., 2015), while our results suggest much younger eruption time.

from Molnár et al. (2018)

The very detailed eruption dating by combined zircon U-Th-Pb and (U-Th)/He method presented in Harangi et al. (2015; 2020) and Molnár et al. (2017; 2018; 2019) enabled us to develop a conceptual model (Molnár et al., 2019) for the eruptive history of the entire Ciomadul volcanism. This is fundamental to understand the behavior of the volcanic system which could be a base of further evaluation of its volcanic hazards.

The ca. 1 Myr-long Ciomadul volcanism was divided into two main stages, which differed largely in their style of volcanic activity: initially scattered small-volume lava domes developed separated by long repose times and resulting in a volcanic dome field. Then the eruption centres focused into a more restricted area and the eruptions built the Ciomadul volcanic complex with much higher eruption flux. Thus, we defined an Old Ciomadul Eruptive Period (OCEP) from 1 Ma to 300 ka followed by the Young Ciomadul Eruptive Period (YCEP) from 160 ka to 30 ka.



Conceptual eruption chronology model with volcanic activity units for the Ciomadul volcanism based on the determined eruption ages (Harangi et al., 2015; 2020; Molnár et al., 2017; 2018; 2019) and the division scheme of Fisher and Schmincke (1984), refined further by Lucchi (2013). From Molnár et al. (2019)

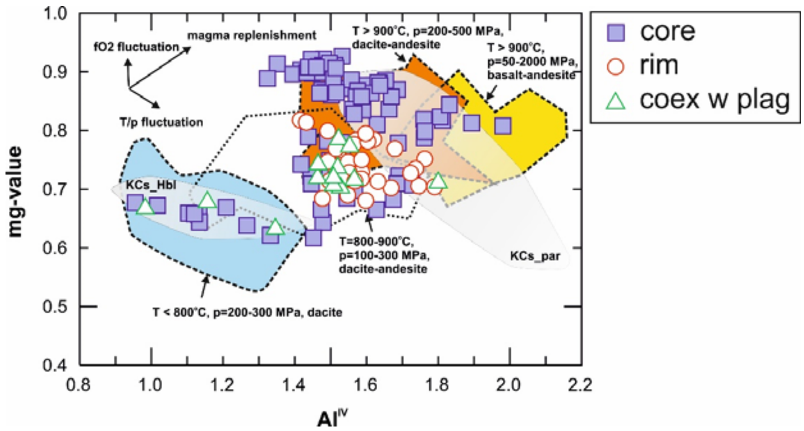
During the OCEP, lava dome extrusions occurred in three stages separated by >100 kyr long repose periods. Importantly, we showed that the two cryptodomes (Malnaş and Bixad) are significantly younger than previously thoughts based on K-Ar dating results (Szakács et al., 2015). Furthermore, their eruptions occurred coeval with the extrusion of the Baba-Laposa lava dome, the first one with typical Ciomadul chemical composition. The contemporaneous eruption and the similarities in mineralogy and chemical composition all suggest that these shoshonitic bodies also belong to the Ciomadul volcanism. Construction of the Ciomadul volcanic complex during the YCEP occurred between 160 and 30 ka by amalgamation of several lava domes followed by an explosive volcanic stage resulting in twin-craters. We found another relatively long (ca. 40 kyr) repose time between the lava dome extrusion stage (160–95 ka) and the younger, mostly explosive volcanic stage (57–30 ka). Noteworthy, we pointed out that this volcanism was much younger than the previous K-Ar age data (Szakács et al., 2015) showed. As an example, eruption of Haramul Mic (Kis-Haram) occurred at 154±16 ka instead of 850 ka inferred from the formerly published K-Ar date (Casta, 1980; Szakács et al., 2015). The latest eruptions were violent explosive ones at 29-33 ka (Harangi et al., 2020) and the volcano has been again in a long quiescence stage since that time.

The long-lasting history of volcanism (ca. 1Myr) and the long repose times (up to 100 kyr) between the active phases of Ciomadul are not rare in andesitic-dacitic volcanoes worldwide. Our geochronological studies with detailed eruption ages and constraints on quiescence periods suggest that volcanic eruption could occur even after several 10s of kyr of quiescence (even after 100 kyr repose time!). Thus, the capability for a volcano to erupt again depends primarily on the state of the subvolcanic magma storage rather than the length of the repose time. If a melt-bearing magma storage can be detected beneath a long-dormant volcano, the potential of reawakening cannot be excluded.

Ciomadul's volcanic plumbing system and petrogenesis

Magma reservoirs beneath volcanoes are considered to subsist dominantly at high crystallinity ("crystal mush"), surviving over 10's or 100's thousands of years. Zircon U-Th-Pb dating results of zircons from Ciomadul eruptive products clearly show that the subvolcanic magma body existed >1 million years and was active even in the long quiescence periods (Harangi et al., 2015; Lukács et al., 2018). Mineral-scale petrological studies of the erupted products of Ciomadul provide constraints on the storage conditions prior to the latest eruption. Both plagioclases and amphiboles show complex zoning in the lava dome rocks as well as in the youngest explosive volcanic rocks. In particular, amphiboles cover a wide compositional range that distinguishes three groups: low Al-Mg ($Al^{iv}<1.4$, i.e. $Al_2O3<10$wt%; MgO <14wt%) hornblende, high Al-Mg ($Al^{iv}>1.4$, i.e. $Al_2O_3>10$wt%; MgO >16wt%) pargasite/Mg-hastingsite and an intermediate group ($Al^{iv}>1.4$, i.e. $Al_2O_3>10$wt%; MgO =13-16wt%). Note that these latter intermediate group amphiboles are most common in the explosive volcanic products, whereas in the older lava domes, mostly bimodal hornblende-pargasite amphibole occurs (Kiss et al., 2017; Harangi et al., 2017). Furthermore, the intermediate composition amphiboles occur always at the outer zone of the phenocrysts and appear to be in equilibrium with the erupted melt.

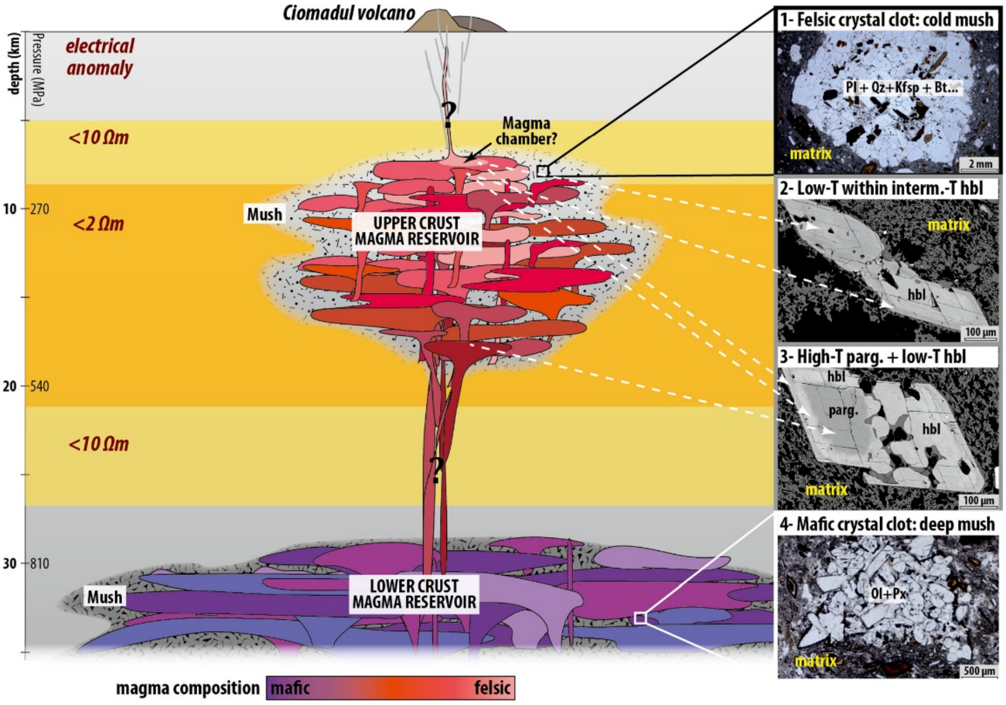
Pressure and temperature of the magma storage were determined using the amphibole and plagioclase compositions on coexisting mineral pairs and using single amphibole compositions as described in Kiss et al. (2014) and in Laumonier et al. (2019). We obtained temperatures above 900◦C and pressure from 230 to 420 MPa for the high-Al amphiboles, which could crystallize from more mafic magma than the erupted dacites. The low-Al amphiboles yielded temperature between 720◦C and 780◦C and a pressure between 210 and 280 MPa. The latter p-T values are comparable with those got for the felsic crystal clots found in lava dome rocks (Kiss et al., 2014). This is consistent with a crystal mush condition with more evolved melt (represented by interstitial glasses in felsic crystal clots and glass inclusions in plagioclase phenocrysts) residing at near-solidus, low-temperature environment. The intermediate amphiboles could have crystallized at similar pressure as the low-Al amphiboles, but at higher temperature (and from a slightly more mafic melt); plagioclase and coexisting intermediate-Al amphibole pairs provide crystallization temperature of 815±20◦C. Using the pre-eruption thermobarometric results, the water content of the melt was estimated using the plagioclase-liquid hygrometer as calibrated by Waters and Lange (2015). Plagioclases coexisting with intermediate-Al amphiboles yielded melt water contents ranging from about 4.7 to 6.3 wt%, whereas the interstitial melt in the felsic crystal mush could have had a little bit more elevated water content of 6.0-7.7 wt%.



Compositional variation of amphiboles from one of the youngest explosive eruption products (Bixad locality) compared to the bimodal amphibole assemblage from the Kis-Csomád lava dome rocks (KCs-hbl and KCs_par) and experimental data compiled by Kiss et al. (2014). Note, that three compositional groups of amphiboles can be distinguished and the intermediate-Al amphiboles represent mostly the rims.

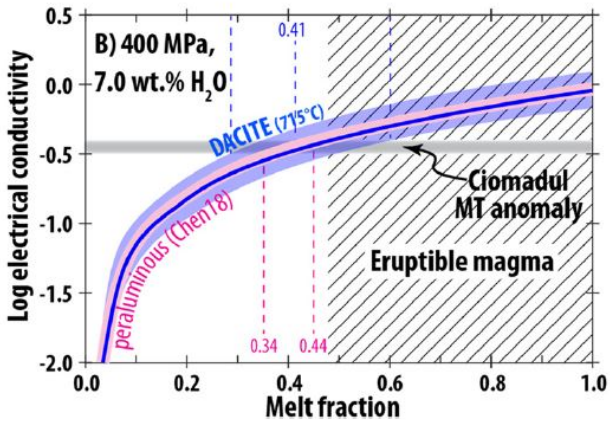
High-resolution profiles for plagioclases were analysed to determine the composition of plagioclase with special focus on trace elements such as Sr and Mg. These elements have faster diffusion than the major elements and therefore, they can be used to calculate diffusion timing and thus, the timescale of eruption triggering. The preliminary results indicate sudden change of these elements at the rim of the plagioclase phenocrysts and suggest fast (in scale of months) reactivation time (Harangi et al., 2019 and 2020 conference presentations), but to get a more constrained results, we need further analysis and model calculations.

In order to better constrain the current state of Ciomadul volcano, we proposed a direct modelling of the geophysical signal of its plumbing system: a petrological analysis is used to build numerical simulations of the thermal evolution of the magmatic reservoir that is converted into electrical conductivity distribution. The integration of this modelling with geophysical observations indicates that a significant amount of water-rich silicic melt (at minima 15%) must still be present in the upper crust beneath the volcano, implying that the reservoir is likely to have been kept in warm enough conditions to preserve sizeable domains in near-eruptible state. The results were published in the paper of Laumonier et al. (2019).



Petrological and magnetotelluric inference for the trans-crustal magma plumbing system beneath Ciomadul (from Laumonier et al., 2019).

We used a two-dimensional thermal model modified from Karakas and Dufek (2015) and Karakas et al. (2017) to quantify the magma evolution and magma lifetime beneath the Ciomadul volcano. The model results confirm the longevity of the magma storage existence and show that a crystal mush with about 10 to 30 vol% melt could have been present beneath Ciomadul even presently. By combining petrologic observations, geophysical results, experimental conductivity data of its last volcanic products and thermal modelling for the development of its magma storage, we were able to decipher the present-day nature of the subvolcanic magmatic plumbing system beneath the long-dormant Ciomadul volcano. Although it is generally considered as extinct (last eruption is ca. 30 ka), the significant average melt fraction determined in the upper crustal magma storage makes the volcano still potentially active (PAMS volcano). All the simulations predict that the magma reservoir could still contain some melt fraction, although the relative volume of the melt content is model-dependant. Using the electric conductivity values coming from the magnetotelluric model presented by Harangi et al. (2015) and the combined petrological, thermal calculations and experimentally determined conductivity data, Laumonier et al. (2019) concluded that the water-saturated felsic melt fraction could be even 20-58%, which is close to the eruptible state in some parts of the magma reservoir. Further constrain of this model could come from the refinement of the magnetotelluric model, which was also one of the principal aims of this research project. Nevertheless, the existence of a melt-bearing magma reservoir is consistent with the proposed seismic tomography model of Popa et al. (2012) and also the relatively high flux and composition of the CO_2 degassing at Ciomadul.



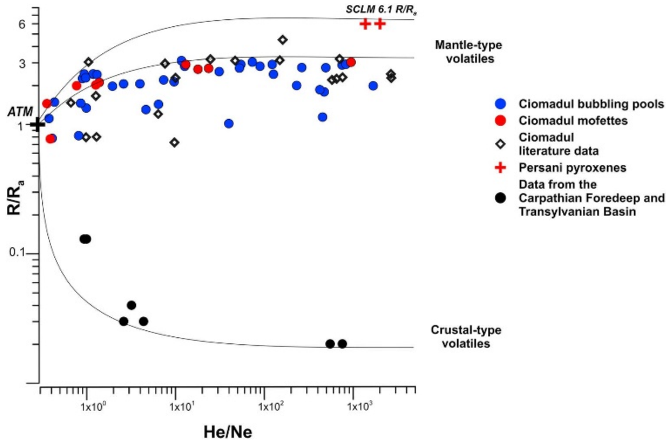
Electrical conductivity vs. melt fraction of the Ciomadul dacite and a peraluminous rhyolite similar to the glass observed in Ciomadul felsic crystal clots. Note that the melt fraction in the magma reservoir depends on the magnetotelluric (MT) anomaly result.

from Laumonier et al. (2019)

Origin and flux of gas emanations

Determining the fluxes and composition of gases in active and dormant volcanoes could help to constrain their origin. At Ciomadul, significant CO_2 emanation occurs as mofettes and bubbling pools. These gases pose an underrated hazard for animals and people, particularly in caves and morphological depressions. We investigated >50 gas emission localities at Ciomadul and in the surroundings to constrain their origin. Results were published in Kis et al. (2017; 2019). Furthermore, chemical and isotopic composition of gases dissolved in mineral waters circulating over 200 km-long transect across the Transylvanian basin and Eastern Carpathians was also determined and these data were used to constrain better the anomalies detected at volcanic areas (Kis et al., 2020). Our findings prove that presence of mantle-component, dissolved in the fluids may be present also at ~50 km distance away from the volcanic centres.

We provided the first high-resolution CO_2 flux data for the Neogene to Quaternary volcanic regions of the entire Carpathian-Pannonian Region, Eastern-Central Europe, and estimated the CO_2 emission at the Ciomadul volcanic complex. Our estimate included data from focused and diffuse CO_2 emissions from soil. The CO_2 fluxes of focused emissions range between 277 and 8172 g/day and overall, it takes a relatively high gas output rate, with a minimum CO_2 emanation of 8.7×10^3 t/year, which is consistent with dormant volcanoes worldwide. The $\delta^{13}C$–CO_2 and $^3He/^4He$ compositions suggest the outgassing of a significant component of mantle-derived fluids and can be explained by the existence of a degassing magmatic intrusion beneath Ciomadul. If no interaction with crustal fluids occurred, the magmatic component in the gases could exceed even the 80%. Remarkably, we obtained such high values for the areas having a larger diffusive CO_2 flux. This high magmatic He content of the gases is not unique and is comparable with that found at Colli Albani volcanic complex, central Italy, another long-dormant volcanic field. The magmatic gases could be derived either from a deep mafic magma and/or from the volatile accumulation zones developed in the shallow crustal felsic-crystal mush body. Since the largest gas emanation is detected at the periphery of the volcano, we infer that the CO_2 gases come from the lower crustal hot zone, where mafic magmas are accumulated.

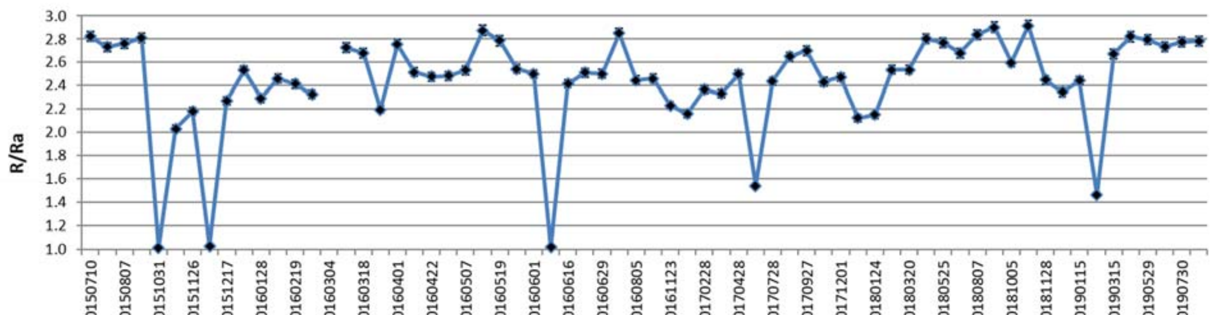


Helium isotopic ratios (R/R_a values) and $^4He/^{20}Ne$ relationships. The theoretical lines represent binary mixings of atmospheric He with mantle (magma)-derived and crustal-derived He. The mantle source end-member of the gases could be metasomatized lithospheric mantle.

from Kis et al. (2019)

Correlation diagram plotting He isotopic ratios (R/R_a) versus $^{13}C_{CO2}$ (VPDB) of Ciomadul gas emissions compared to various volcanic areas, worldwide.

The He isotope signature in the outgassing fluids (up to 3.10 R_a) is lower than the values in the peridotite xenoliths of the nearby alkaline basalt volcanic field (R/R_a 5.95 $R_a \pm 0.01$), which are representative of a continental lithospheric mantle and significantly lower than MORB values. Considering the chemical characteristics of the Ciomadul dacite, including trace element and Sr–Nd and O isotope compositions, an upper crustal contamination is less probable, whereas the primary magmas could have been derived from an enriched metasomatized lithospheric mantle source. The low He isotope content could be due to infiltration of subduction-related fluids and post-metasomatic ingrowth of radiogenic He. Our results imply a heterogeneous lithospheric mantle in a small spatial scale.



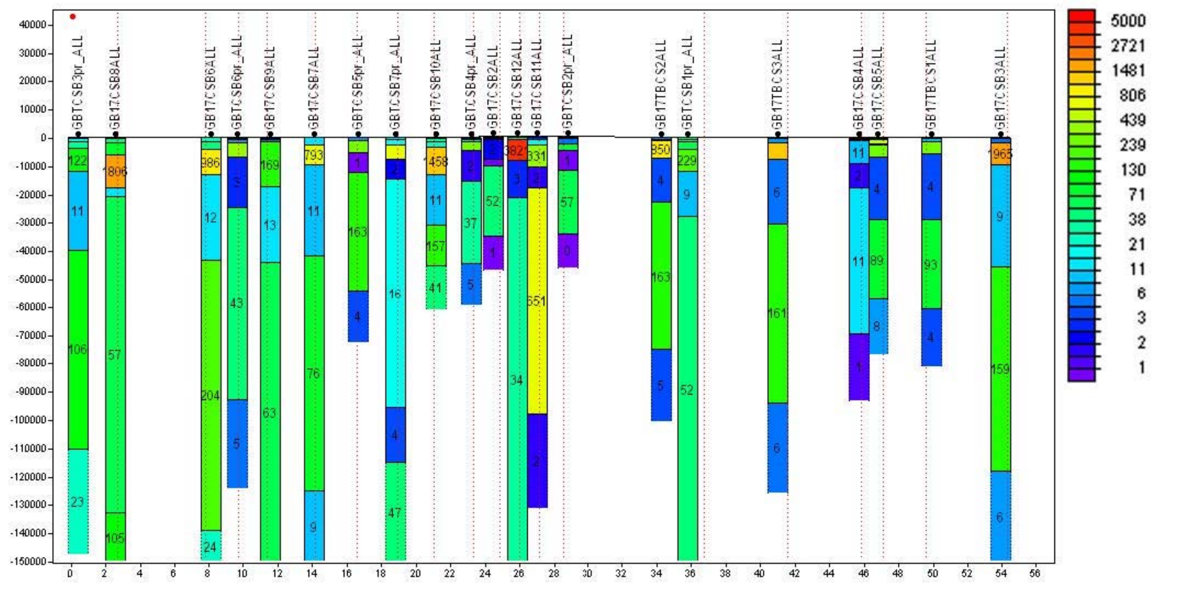
Variation of He-isotope composition (in R/R_a) for 5-years at a stable CO_2 gas sampling point (Büdös-hegy). Data is provided by B.M. Kis

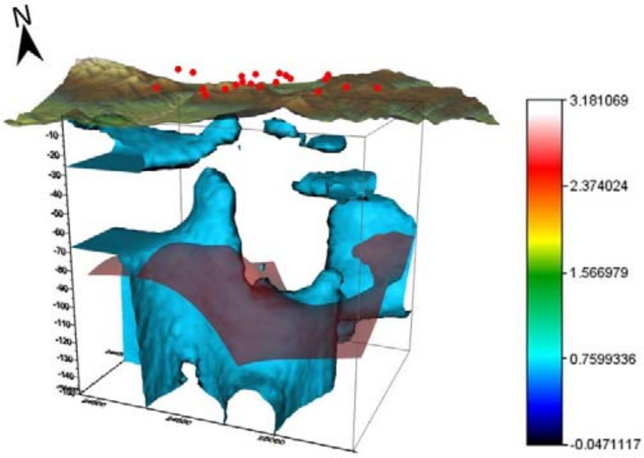
During the research project, we installed continuous gas sampling site at Büdös-hegy, where we have collected the emitted CO_2 gases each month. In the following figure, we show a 5-years long variation in He-isotopic ratio of the emitted CO_2 gases (Kis et al., 2020 EGU presentation). The values remained basically within a narrow range between 2.4 and 2.9 R/R_a. So far, we cannot see any covariations with seismic data (large Vrancea earthquakes with >4 M) and/or meteorological factors, there is a stable, relatively high R/R_a values suggesting static magma degassing at depth. Combining the R/R_a values with He/Ne ratio, two trends can be delineated implying possibly two sources of the CO_2. While the magmatic gas source is the more stable, occasionally, gases with more crustal isotopic signature are emitted. Note, however, that no comparable high-resolution and sensitive seismic data are available. Interpretation of this time-series isotopic variation and data collection is still in progress.

Magnetotelluric results

Magnetotelluric survey what we started in 2010 was extended in this research project to constrain better the electrical conductivity anomaly already presented in the paper of Harangi et al. (2015b). The geophysical measurements, selection of data collection sites and the inversion of the data were performed by the experts from the Geodetic and Geophysical Institute (GGI, Sopron) of the Research Centre for Astronomy and Earth Sciences Hungarian Academy of Sciences as consortium partner. Data collection at new sites was carried out in two field campaigns in 2016 and 2017. Some progresses and results in data evaluation and interpretation have been achieved, but unfortunately, partly due to the supercomputer capacity problems, this has not been completed yet. Therefore, we agreed with the GGI partner that we involve other scientists in this work. We contacted leading experts of magnetotellurics in the Institute of the Czech Academy of Sciences in Praha who were happy to join to this study. The GGI provided and transferred all the raw data and the collaborative work with the Czech colleagues has already started with some preliminary results. In this report, we summarize the main outcomes provided by our geophysicist colleagues from the GGI Sopron.

1D inversion was performed for each local MT sites using WinGLink software layered inversion (integrated) and applied invariant (mean values of TE and TM sounding curves, i.e. the perpendicularly measured sounding curves). Apart from some outrageous data the fitting is available for the required max. 1% RMS limit (root mean square error, differences between calculated and measured data). The figure shows the 1D layered models of the MT data, where the y-axis shows the depth in metre. Colour of layers show the resistivity values down to 150 km depth.





Visualization of 1D inversion results of the MT data. The resistivity isosurface levels represent the 3 Ohmm resistivity region and the red level shows the estimated lithosphere-asthenosphere boundary (LAB). The resistivity values are in 10 based logarithm.

provided by A. Novák (GGI)

The 1D model results appear to confirm our previous interpretation (Harangi et al., 2015b) that an electrical conductivity anomaly can be detected beneath Ciomadul at shallow crustal level and this anomaly continues down to the mantle region. The lithosphere-asthenosphere boundary (LAB) depth was estimated also by the 1D inversion results. Typical values of the electrical resistivity of the asthenosphere are in the range of 1-25 Ωm, where the lithospheric mantle represents a relatively resistive layer (a few hundred to 1000 Ωm) beneath a typically conductive lower crust. During the process we made the following assumption: the condition for the asthenospheric mantle indication was taken into account where the resistivity decreased less than 5 Ωm. As a result, the average LAB depth is at 70-90 km, which is similar what was inferred beneath the nearby Persani volcanic field (Martin et al., 2006; Seghedi et al., 2011; Harangi et al., 2013), but thinner compared with the surrounding areas. This might be explained by local ruptures of the lower lithosphere due to the suction effect of the descending slab beneath Vrancea as hypothesized by Harangi et al. (2013). Thinning of the lithosphere could result in decompression partial melting of the strongly metasomatized mantle regions to yield the primary magmas beneath Ciomadul.

In summary, the data evaluation of the former and new MT sites and the 1D models at Ciomadul appear to support the existence of a melt-bearing crustal magma reservoir characterized by low electrical resistivity. However, a more careful analysis and further data inversion with better and more stable computational background are necessary to constrain better this anomaly. The started fruitful collaboration with the experts from Czech Academy and the preliminary results are promising to get a better picture about the state of the subvolcanic magma reservoir beneath Ciomadul.

Prospects and outlooks

Significant scientific results have been achieved and presented in a number of Q1 publications during the K116528 NKFIH-OTKA consortional research project and further papers could still come out in the near future. These results highlight the importance to understand better how the long-dormant volcanoes work that are characterized by long-lasting melt-bearing subvolcanic magma reservoir and by long quiescence periods between the active phases. Such volcanoes pose an underrated hazard to the society; therefore, we formulated new key-questions to increase our knowledge about their behaviour. In particular, we addressed a challenging question – which is of fundamental importance for understanding crustal magmatism, but also of immediate importance for hazard mitigation – how, why, and when magma reservoirs can be rejuvenated after tens of thousands of years, and lead to eruptive events. We propose to study Ciomadul volcano, Romania, continuing the research that we have started there over a decade ago, but involved other volcanic systems, too. To broaden research perspective and to get a wider international context and impact, we suggested to extend our crystal forensic methodology to another long-dormant volcanic systems. The view that extensive mushy magma storage zones are present beneath active and dormant volcanoes has been supported by various geophysical studies, however, a major remaining challenge is to recognise if, when, and how fast a magmatic system can switch from a state of dormancy into a state of unrest or eruption. This has led to the new research project concept "*From crystal mush to volcanic eruption*", where we aim to answer key-questions such as what are the triggering processes leading to the assembly of eruptible magma in crystal mush reservoirs and what timescales are necessary for reactivation as well as which magmatic processes and/or conditions lead to explosive versus effusive eruptions and what are their warning signals.

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