THE CONTRIBUTION OF PETROLOGICAL AND VOLCANOLOGICAL STUDIES OF MAGMATIC ROCKS TO THE INTERPRETATION OF GEODYNAMIC PROCESSES – ACHIEVEMENTS OF THE "ENDOGENOUS PROCESSES, VOLCANOLOGY" LABORATORY BETWEEN 2001 AND 2025

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This year marks the 35th anniversary of the founding of the "Sabba S. Ștefănescu" Institute of Geodynamics of the Romanian Academy. On this occasion, we have prepared a paper on the main volcanological and petrological contributions made during this period by the Endogenous Processes, Volcanology Laboratory. The information contained in the paper presents the achievements of our team, which bring new data and additions to previous scientific knowledge, providing a solid basis for future studies.

Keywords: volcanology, magmatic rock petrology, Carpathian-Pannonian region.

INTRODUCTION

On the occasion of the 35th anniversary of our institute's founding, I will take stock of the activity of the "Endogenous Processes, Volcanology" since 2001, when Mr. Dorel Zugrăvescu, Director at the time, had the kindness and inspiration to welcome us, establishing a new team with the aim of expanding the institute's areas of activity related to geodynamic processes, with specialists in magmatic rocks and volcanology. Since then, our team has made a substantial contribution to the knowledge of geodynamic processes involving magmatic rocks, whether intrusive or volcanic, at local, regional and global levels. This involves a significant number of studies covering both Romania and the Carpathian-Pannonian region, as well as other parts of the world with magmatic rocks. Below is an overview of published works, particularly those published in ISI-rated journals, thematic volumes or books, as well as regional journals. The titles of the chapters refer to the main areas addressed over time in order to resolve or improve knowledge in various fields and areas with magmatic rocks, and take into account the age of the rocks and the territories involved. Most of the reference works, which already have over a hundred citations in the specialised literature, will be indicated with the recent number of citations in the Bibliography; they were the result of international collaborations with several research institutes and universities in Europe and around the world. I would like to mention in particular ATOMKI in Debrecen, ETH Zurich, the Geological Institute of Romania, the University of Vienna, Eötvös Loránd University in Budapest, the University of London, the University of Izmir, the University of Akita, the University of Porto, the University of Liège and the University of Bucharest. Apart from myself, the team included Dr. Ionel Nicolae and Dr. Mihai Tatu, who recently left us prematurely, and currently includes Dr. Alexandru Szakács, Dr. Péter Luffi, Dr. Elena Luisa Iatan, PhD students Violeta Vornicu and Viorel Mirea, and, more recently, Dr. Marian Munteanu. We had as colleagues Dr. Răzvan-Gabriel Popa, currently a professor at ETH Zurich, Dr. Marcel Mărunțiu, retired, and PhD student Gabriel Corneliu Ștefan. This presentation is arbitrarily divided into three chapters: one dedicated to achievements published mainly in the field of magmatic petrology, another to achievements obtained mainly in the field of volcanology, and the third dedicated to synthesis works, mainly focused on the Carpathian-Pannonian area.

 htpps://doi.org/10.59277/rrgeo.2025.68.2

1. MAGMATIC PETROLOGY – BRIEF OVERVIEW OF PUBLISHED STUDIES

1.1. PETROLOGICAL STUDIES OF VOLCANIC AND INTRUSIVE ROCKS FROM PROTEROZOIC, PALAEOZOIC AND MESOZOIC GEOLOGICAL FORMATIONS IN THE CARPATHIAN-PANNONIAN AREA

Between 2006 and 2017, my colleague Mihai Tatu co-authored a series of papers with renowned French researchers on calc-alkaline plutonic intrusive bodies with adakitic affinities in the Southern Carpathians. These papers present their ages (Proterozoic, ca. 600 Ma, and Palaeozoic, ca. 300 Ma) using U-Pb zircon dating and argue their affiliation with the Pan-African and Varisc tectonic domains, respectively (Féménias *et al.* 2006, 2008; Duchesne *et al.*, 2008, 2017). The source of the intrusions is considered to be dominated by mafic and metasedimentary rocks with a volcanic component, with differences observed between Pan-African and Varisc granitoids, both of which are poor in metapelite component (Duchesne *et al.*, 2017).

Permian volcanic rocks have been the subject of a series of studies. Initiated in Romania (Nicolae *et al.*, 2013), the first study focuses on the composition and isotopic characteristics of bimodal volcanism (basaltic and rhyolitic) in the Northern Apuseni Mountains. This is followed by a group of synthetic petrological studies on Permian magmatism in the Carpathian-Pannonian area, including U-Pb dating on zircon under the coordination of Hungarian colleagues (Szemerédi *et al.*, 2020, 2021, 2023). Bonin and Tatu (2016) publish new mineralogical data from the Permian granitoid massif in the Highiș Mountains.

Between 2003 and 2004, Ionel Nicolae and his colleagues in Italy published two reference works on ophiolitic rocks and associated Jurassic calc-alkaline rocks in the Southern Apuseni Mountains, presenting both their petrological and geochemical characteristics (Nicolae and Saccani, 2003) and their geotectonic setting (Bortolotti *et al.*, 2004).

Gallhofer *et al.* (2017) discuss the magmatic and tectonic history of Jurassic ophiolites and associated granitoids in the Southern Apuseni Mountains based on new U-Pb zircon and Sr and Nd isotope dating. The paper confirms a previous hypothesis regarding the formation of the rocks in an intra-oceanic island arc. The new U-Pb ages obtained on ophiolites (158.9–155.9 Ma; Oxfordian to early Kimmeridgian) and granitoids (158.6–152.9 Ma; Oxfordian to late Kimmeridgian) indicate that the two distinct magmatic series evolved within a relatively narrow time frame. It is suggested that the ophiolites and island arc granitoids formed above the same subduction zone over a long period of time.

My colleague Ionel Nicolae is co-author of a paper presenting preliminary geochemical data on Lower Triassic rift basalts in Northern Dobrogea (Saccani *et al.*, 2004).

Upper Cretaceous magmatism, generically known as "Banatitic", has been the subject of several studies focusing on different geographical areas in the west of the country, where intrusions and various volcaniclastic rocks, including lavas, outcrop (Constantina *et al.*, 2009; Bojar *et al.*, 2013; Seghedi *et al.*, 2015; Vornicu and Seghedi, 2025). Petrographic and geochemical data have been published in particular, but also isotopic data (Bojar *et al.*, 2013) specifying the calc-alkaline nature of the rocks and suggesting their post-collisional genesis (Seghedi, 2025; Vornicu and Seghedi 2025). A special note is made of the Paleogene banatitic intrusions in the Poiana Ruscă Mountains, for which an asthenospheric origin has been suggested (Tschegg *et al.*, 2010) and which would end the cycle of magmatic activity in the Upper Cretaceous.

1.2. PETROLOGICAL STUDIES ON NEOGENE/QUATERNARY MAGMATIC ROCKS FROM THE CARPATHIAN-PANNONIAN AREA

Magmatic rocks from the Carpathian-Pannonian area, especially Neogene/Quaternary volcanic rocks from Romania, were the main petrological topic we addressed, in cooperation with colleagues from abroad. These types of rocks are ideal for petrological studies, as they are less affected by hydrothermal or diagenetic alteration processes. I will refer to different geographical areas, which also have specific characteristics (Fig. 1).

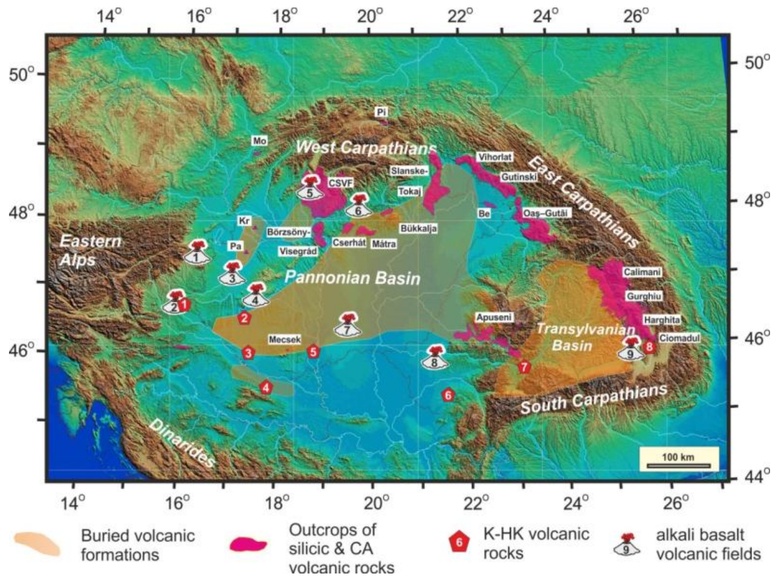

Figure 1. Spatial distribution of the main groups of Neogene-Quaternary volcanic rocks of silicic (felsic) and calc-alkaline (CA); potassic and ultrapotassic (K-HK) and alkaline basaltic types in the Carpathian-Pannonian region. A large volume of volcanic formations is buried by younger sediments. Locations of potassic-ultrapassic volcanic rocks: 1. Styrian Basin; 2. Balatonmária-1 borehole; 3. Szenta borehole; 4. Krndija; 5. Bár; 6. Gătaia; 7. Uroi; 8. Malnas-Bixad, South Harghita. Locations of volcanic fields with alkaline basalts: 1. Burgenland; 2. Styrian Basin; 3. Little Hungarian Plain; 4. Bakony-Balaton; 5. Stiavnica; 6. Novohrad/Nógrád–Gemer; 7. Kecel and surroundings (buried); 8. Lucareţ–Șanoviţa; 9. Perșani. Other abbreviations: Mo = dikes in East Moravia; Pi = dikes in the Pieniny Klippe Belt; Kr = buried Kráľová volcano in the Danube basin; Pa = buried Pásztori volcano in the Little Hungarian Plain; Be = Beregovo Map source: Harangi *et al.*, (2024) with modifications.

The Apuseni Mountains

The Miocene magmatic rocks of the Apuseni Mountains have been the subject of two petrogenetic studies, one concerning the petrology of the rocks according to their age and place of outcrop (Roșu *et al.*, 2004) and another studying the composition and isotopic systematics of the main minerals composing the most representative rocks of the Apuseni Mountains (Seghedi *et al.*, 2007). In both cases, the calc-alkaline composition and characteristic adakitic affinity are noteworthy. Seghedi *et al.*, (2022b) complete the petrological database and suggest that volcanism is the result of tectonic movements involving regional transtensional rotations that led to the formation of a series of horst and graben basins. Magmatic activity ended with a series of transpressive movements (Fig. 2). Crustal extension and asthenosphere uplift created the conditions for the formation of a melting zone at the base of the crust. Crustal melts mixed with mantle melts played an important role in the genesis of the rocks examined.

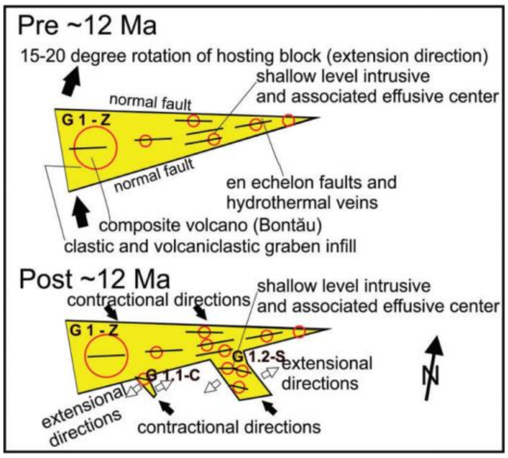

Figure 2. Simplified outline of the extensional model for the Zarand-Brad-Zlatna basin (Zărand Group) in the Apuseni Mountains, suggesting geodynamic control in a tectonic context of intra-continental oblique rift, as a result of the rotational movement of the Tisia tectonic block (in the first phase – pre-12 Ma), followed by a NW-SE oriented compressional/transpressional system (post-12 Ma), with the generation of a wedge-shaped basin (Caraci) and the Săcărâmb sub-basin; Red circles represent volcanic edifices (after Seghedi *et al.*, 2022b).

Crustal assimilation and fractional crystallisation in crustal magmatic chambers characterised the volcanism in each basin.

The Eastern Carpathians

From a geographical point of view, there are three important areas with Neogene magmatic rocks in the Eastern Carpathians of Romania: (1) the Oaş–Gutâi volcanic mountains in the west, (2) a central subvolcanic area dominated by the Rodna and Bârgău mountains, and (3) the Călimani–Gurghiu–Harghita volcanic mountain range to the south-east, dating from the Miocene-Quaternary period. We have important petrological contributions in each of these areas.

The Oaş–Gutâi mountain range is one of the most complex volcanic areas in the Carpathian-Pannonian region, having formed over a relatively long period of time (15.4–7.0 Ma; Pécskay *et al.*, 2006). The evolution of volcanic activity was controlled by the tectonics of the Transcarpathian Basin, which was decoupled from the western part of the ALCAPA block, being contemporary with a counterclockwise rotation and transtensive deformations along the Bogdan–Dragoş–Vodă fault system. During this time, due to the uplift of the asthenosphere, the conductively heated lithosphere progressively melted, involving delamination processes (drip tectonics) (Kovacs *et al.*, 2017, 2021). The lithospheric removal also triggered the melting of the lower crust (generating, for example, the rhyolites in the Oaş Mountains) and subsequently involved additional magma mixing. Thus, early felsic magmas denote a post-collisional tectonic setting, being derived from a mantle source previously modified by subduction components and from the lower crust. The style of volcanism within the eastern Transcarpathian basin system shows spatial variations, with composite andesitic volcanoes (Gutâi Mountains) at the margins and isolated monogenetic andesitic/ rhyolitic volcanoes (Oaş Mountains) towards the centre of the basin.

One of the most controversial petrological situations in the Gutâi Mountains is that of an intrusive body known in literature as the "White Tulip" dacite in the Baia Sprie area. Its complex genesis, characterised by a complex process of mixing strongly hydrated magmas, is discussed based on melt inclusions in various component minerals (Naumov *et al.*, 2014).

The central area is represented exclusively by subvolcanic rocks of intrusive nature. One of these areas, Rodna–Bârgău, due to its petrographic complexity, has been the subject of two petrological studies (Papp *et al.*, 2005; Fedele *et al.*, 2016). Magmatism was deeply influenced by tectonics. The complex geodynamic evolution of the eastern Carpathian Zone probably provided the conditions for the juxtaposition of different mantle domains in the Rodna–Bârgău area, which lies close to the intersection point between the East European, Tisa-Dacia and Alcapa blocks. Following post-collisional extension, the melting of such mantle sources produced calc-alkaline magmas between 17 and 9 Ma. The post-collisional setting in this case has the following characteristics: (a) absence of primitive lithotypes; (b) relatively limited compositional evolution of magmas, from andesites (basaltic) to dacites; (c) compositional interaction between the lower and upper crust; (d) evidence for heterogeneities in the subcontinental mantle; (e) a small volume of magmas generated by crustal anatexis, extruded in peripheral areas opposite in the east-west direction.

The Călimani-Gurghiu-Harghita volcanic chain was intensively studied from a petrological point of view before 2001; more recently, a complex mineralogical study of the most primitive minerals, olivine with spinel inclusions and clinopyroxenes, which concludes that post-collisional magmatism originates in the lithospheric mantle, under the influence of asthenospheric mantle uplift following delamination processes (Bracco Gartner *et al.*, 2020). Recent studies have focused particularly on the complex petrological context of the terminal area of the chain, namely the Southern Harghita Mountains (Figure 3; Seghedi *et al.*, 2011, 2023a) and especially the Ciomadul volcanic massif, which has been the most intensively studied in terms of the magmatic chamber system, considered active even today (Harangi *et al.*, 2015; Molnár *et al.*, 2018, 2019; Laumonier *et al.*, 2019; Cserép *et al.*, 2023, Lange *et al.*, 2023). In addition, I would also like to mention a paper on minerals in magmatic rocks in the volcanic chain (Szakács and Seghedi, 2010) as well as the compilation by Szakács and Gál (2022) on the petrology of the Ciomadul massif.

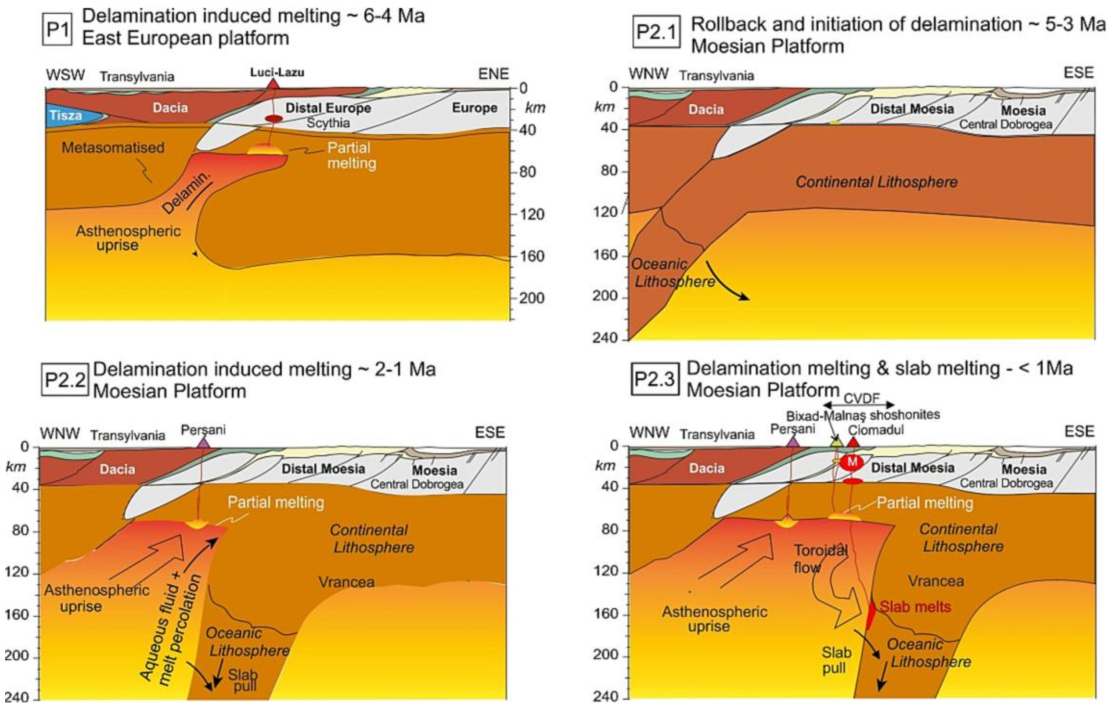

Figure 3. Profiles with magma generation models in the South Harghita and Perşani Mountains: P1 (~6–4 Ma), P2.1 (~5–3 Ma), P2.2 (~2–1 Ma) and P2.3 (<1 Ma) (Seghedi *et al.*, 2023a simplification after Bracco Gartner *et al.*, 2020 and references therein); CVDF – Ciomadul volcano dome field.

A special effort was dedicated to understanding the petrology of basaltic volcanics in the Perşani Mountains, as well as the mantle xenoliths contained therein. Harangi *et al.*, (2013) show that basaltic melts were generated at a depth of 90–60 km, at the base of the lithosphere, from a spinel-bearing peridotite, and demonstrate that they ascended rapidly to the surface within days. Based on the chemical composition of the main minerals in the mantle xenoliths and noble gases in fluid inclusions (Faccini *et al.*, 2020), two main events were recognised within the lithospheric mantle. The first event reveals a pervasive refertilisation of a depleted mantle by the melting of calc-alkaline magmas, leading to the formation of hydrated minerals, amphiboles. The second event is related to the subsequent interaction with an alkaline metasomatic agent similar to the host basalts, which caused a slight enrichment of light rare earth elements (LREE) in disseminated pyroxenes and amphiboles, as well as the filonian precipitation of amphiboles with a composition similar to that of amphiboles in megacrystals.

Kovács *et al.*, (2021), with a group of 15 collaborators, including colleague A. Szakács, put forward the “pargasosphere” hypothesis. The paper discusses the asthenosphere-lithosphere boundary (LAB) and the medium-lithosphere discontinuity (MLD) based on the physical and chemical properties of pargasitic amphibole. The occurrence of partial melts or fluids beyond the stability field of pargasite may explain the geophysical anomalies frequently observed in association with the LAB and MLD. The Vrancea area is suggested to be a suitable location for testing the ‘pargasosphere’ hypothesis to elucidate the origin of intermediate-depth earthquakes (70–300 km) and to explain the delamination of the lower lithospheric mantle.

1.3. STUDIES ON THE ALTERATION AND MINERALISATION PROCESSES OF MAGMATIC ROCKS IN ROMANIA

Since 2008, my colleague Elena Luisa Iatan, either alone or together with collaborators, has been constantly concerned with promoting studies on the mineralisation processes with economic value of magmatic rocks in the metallogenic area of the Apuseni Mountains (Iatan, 2008, 2009, Berbeleac *et al.*, 2010, 2012a,b, 2014; Chernyshev *et al.*, 2015; Iatan, Bilal, 2016; Pintea, Iatan, 2017; Iatan, Berbeleac, 2018, Pintea *et al.*, 2018,2019, 2020, 2021; Udubașa *et al.*, 2025). These papers have been published exclusively in specialised journals in the country and refer to mineralisations or occurrences of gold, silver, lead, molybdenum, porphyritic Cu, platinum and platinum group elements.

1.4. PETROLOGICAL STUDIES OF VOLCANIC AND INTRUSIVE ROCKS IN OTHER AREAS OF THE GLOBE

In collaboration with colleagues from abroad, we have addressed several petrological topics in less researched areas. Most of them concern the petrology of Miocene volcanics in Hungary and Western Anatolia in Turkey (Póka *et al.*, 2004; Seghedi *et al.*, 2015a, Seghedi, Helvacı, 2016; Hencz *et al.*, 2021b; Helvacı *et al.*, 2024), but also a study on mantle xenoliths in alkaline basalts in Spain (Seghedi *et al.*, 2002). I would also like to mention the contribution of my colleague Peter Luffi to a paper (Zhu *et al.*, 2022) dedicated to understanding the migration of the Tengchong arc magmatism in southeastern Tibet during the Cretaceous and quantifying the changes in crustal thickness resulting from this process. Colleague P. Luffi also participated in a synthesis paper on the evolution of the Peruvian coastal batholith (Martínez-Ardila *et al.*, 2023). The paper investigates the geological and geodynamic causes of changes in space and time identified in the composition and rate of arc magma emplacement in a long-evolved subduction zone.

1.5. HISTORICAL AND GEOHERITAGE STUDIES

On the bicentenary anniversary of Charles Darwin, known as the father of evolutionary theory, we contributed to an honorary presentation on his contribution, which is equally important in the field of petrology, where it is largely ignored (Brändle *et al.*, 2010). His contribution is not truly reflected in textbooks and treatises on magmatic petrology, where he is not recognised as the initiator of the theory of fractional crystallisation and gravitational differentiation of magmas.

Recently, I personally contributed to a chapter in the volume “Istoria științelor (History of Sciences)” published by the Romanian Academy on Endogenous Petrology in Romania (Berza *et al.*, 2018; Seghedi, 2018), reviewing the achievements in the field of magmatic petrology in our country from its beginnings (19th century) to the present day.

Our colleague Alexandru Szakács is part of a team that has compiled a list of all localities in Romania with minerals and rocks of potential heritage value (Gál *et al.*, 2024).

1.6. MINERALOGICAL AND HAZARD STUDIES

Such studies, in which colleague L.E. Iatan was mainly involved, consider the negative effects of anthropogenic impact on the environment in which we live. Such investigations concern the harmful effects of waste dumps in various mining areas (Servida *et al.*, 2013), the impact of pollution in areas with uranium mining (Petrescu *et al.*, 2010), or heavy metal pollution in the soil of the Formoso River basin, Buritizeiro, Minas Gerais, Brazil (Freitas de Moraes *et al.*, 2016). Studies on the remediation of polluted mining areas concern the use of freshwater mussels to monitor polluted waters (Bilal *et al.*, 2014 a, b, c) or with the help of phytoremediation (Iatan, 2020, 2025). A remarkable synthesis paper by 25 authors provides an overview of the physicochemical properties of phosphogypsum, a product of sedimentary and magmatic phosphate ores from around the world. The results for phosphogypsum are presented and critically discussed on a large number of samples from 67 industrial storage sites around the world and samples of phosphogypsum synthesized under laboratory conditions (Bilal *et al.*, 2023).

2. VOLCANOLOGY – BRIEF OVERVIEW OF PUBLISHED STUDIES

2.1. GEOCHRONOLOGICAL STUDIES, THE EVOLUTION OF VOLCANISM IN SPACE AND TIME IN THE CARPATHIAN-PANNONIAN REGION

Geochronological studies conducted on magmatic rocks, whether volcanic or intrusive, have been of vital importance for understanding the geodynamic processes in the Carpathian-Pannonian area. Below is an overview of the most important articles on the age of magmatic rocks, starting with the oldest geological formations and ending with the most recent ones.

Members of our team have recently contributed to the development of studies on the U-Pb age of zircon from Paleozoic granitoid plutons in the Southern Carpathians (Duchesne *et al.*, 2008, 2017), or of magmatic rocks (intrusive and effusive) formed during the Permian (Szemerédi *et al.*, 2021, 2023; Fig. 4) and Jurassic (Gallhofer *et al.*, 2017; Fig. 5) periods in the Apuseni Mountains.

Recently, U-Pb analyses on zircon confirmed the Upper Cretaceous (Campanian) age of the Banatite volcaniclastic rocks from the Haţeg Basin (Vornicu *et al.*, 2023). A comparison of K/Ar ages on whole rock with U-Pb ages on zircon performed on the same samples of Upper Cretaceous magmatic rocks (banatites) associated with the Gosau Lăpugiu and Rusca Montană basins reveals similarities, but the U-Pb ages are more accurate (Seghedi and Pécskay, 2024). The K/Ar method on whole rock can be useful when magmatic rocks do not contain zircons.

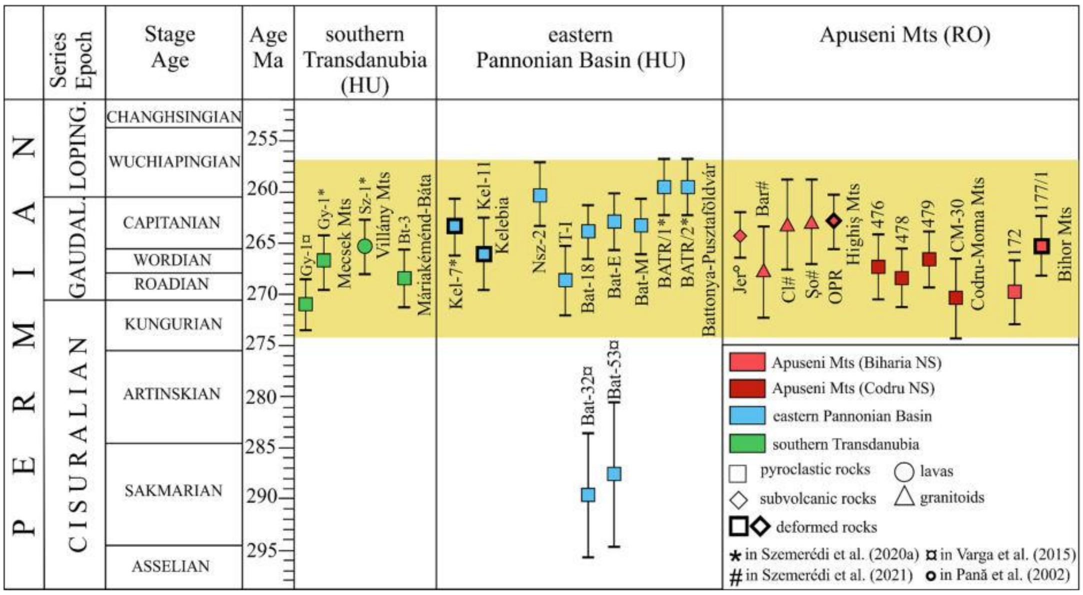

Figure 4. U-Pb zircon age data of Permian felsic volcanic rocks, including previous results from the Pannonian Basin (Szemerédi *et al.*, 2023), as well as those of granitoids from Highiș (SW), Apuseni Mountains (Szemerédi *et al.*, 2021 and references therein).

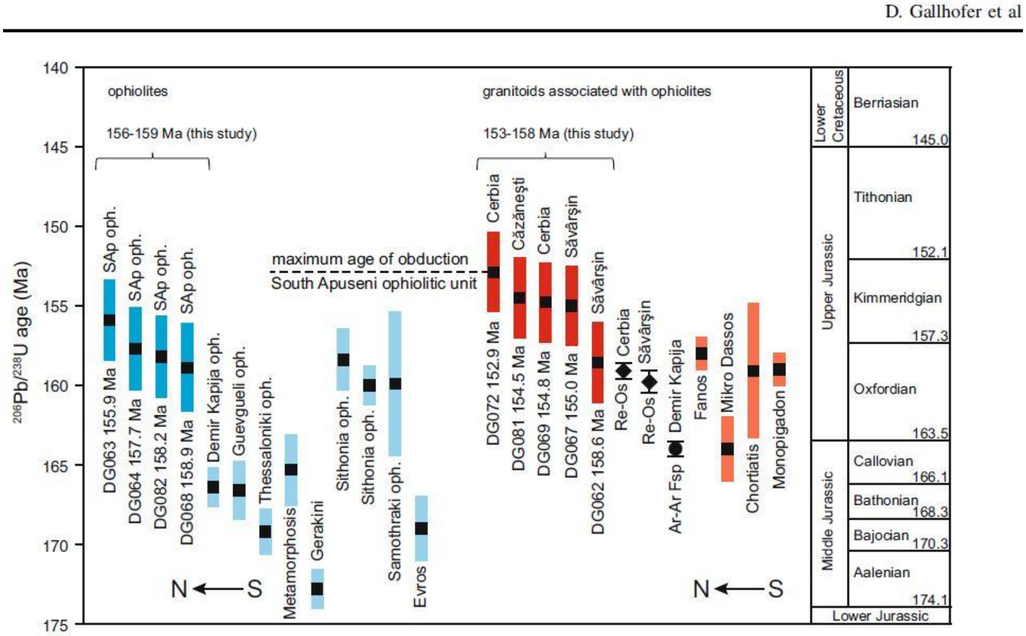

Figure 5. Comparative mean $^{206}Pb/^{238}U$ ages of ophiolites; blue error bars: ophiolites and orange error bars: granitoids associated with the Eastern Vardar in Greece; red error bars: ophiolites and granitoids from the Southern Apuseni Mountains, Romania (after Gallhofer *et al.*, 2017).

In the area of Miocene-Quaternary volcanism, rock dating was mainly performed using the K/Ar method. In 2006, the second synthesis of K/Ar ages of Neogene-Quaternary volcanism in the entire Carpathian-Pannonian area was published (Pécskay *et al.*, 2006; Fig. 6). The paper has become one of the most cited papers internationally in our portfolio. To date, over 1000 age analyses have been accumulated.

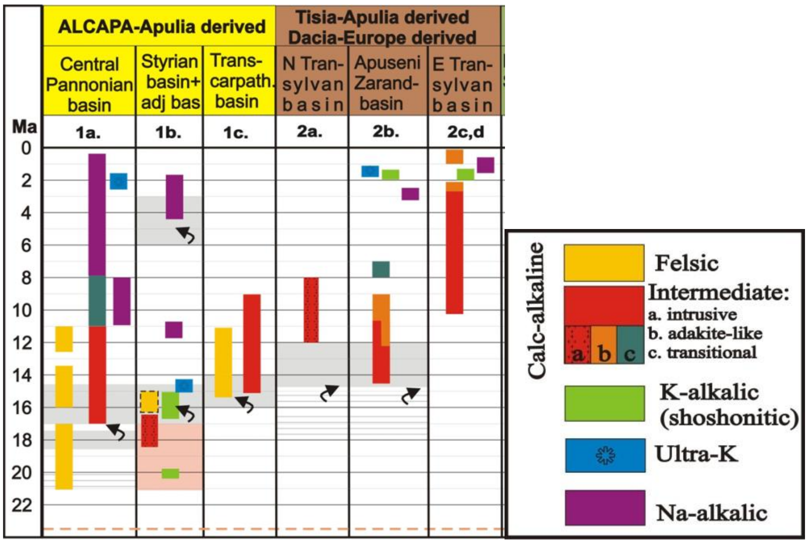

Figure 6. Simplified spatial and temporal distribution (after Pécskay *et al.* 2006, Seghedi and Downes, 2011) with the development of magmatism in the Carpathian-Pannonian area in relation to the main sedimentary basins (Pannonian and Transylvanian).

Based on multiple 40Ar/39Ar dating techniques, Szakács *et al.* (2012) analyzed samples from the rhyolitic Dej tuff complex in the Transylvanian Basin and assigned an age of 14.8–15.1 Ma to the eruptions. For now, the source of this complex remains controversial.

The intrusive rocks in the Subvolcanic Zone of the Eastern Carpathians were dated using K/Ar and U-Pb methods (Pécskay *et al.*, 2009; Fedele *et al.*, 2016), with the ages obtained for their emplacement ranging from 11.5 to 8 Ma, corresponding to the Pannonian stratigraphic interval.

For the andesitic and dacitic volcanoes located at the southern end of the Harghita Mountains, Pilişca, and especially Ciomadul (the youngest volcano in the Carpathian-Pannonian region), K/Ar dating was initially used (Szakács *et al.*, 2015; Pécskay *et al.*, 2006; Fig. 7), and more recently, a combined U-Th-Pb and (U-Th)/He dating on zircon was applied, which led to the refinement of the chronology of eruptions over the last 2 million years (Molnár *et al.*, 2018, 2019; Lukács *et al.*, 2021; Fig. 8).

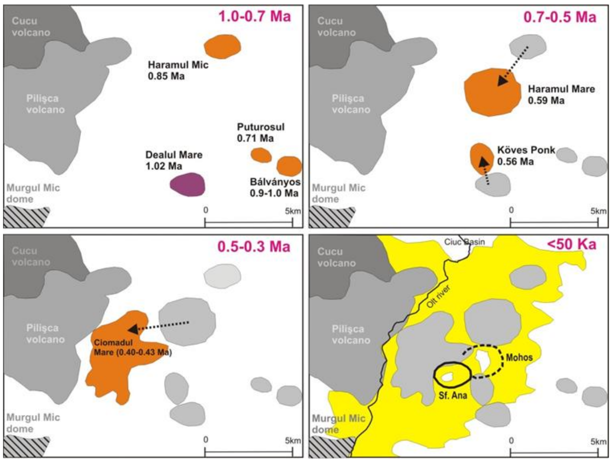

Figure 7. Spatio-temporal sketch with the evolution of Ciomadul volcano in the time intervals of 1.0–0.7 Ma, 0.7–0.5 Ma, 0.5–0.3 kyr, respectively <50 kyr. Petrographic composition of the domes: in purple - andesite and orange - dacite, and in yellow - dacitic volcaniclastic rocks. Extinct volcanism is shown in gray tones. Arrows show the direction of change of volcanic activity from the previous phase (after Szakács *et al.*, 2015).

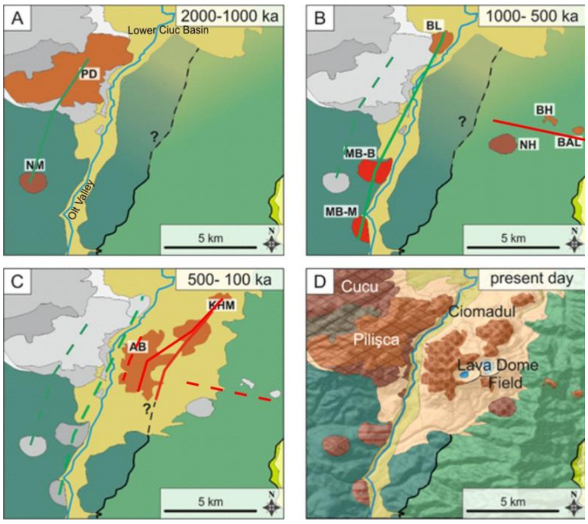

Figure 8. Spatio-temporal sketch of the evolution of the Pilişca and Ciomadul volcanoes in the time intervals: A-2000-1000ka, B-1000-500ka, C-500-100ka and D- present (after Molnár *et al.*, 2018, with modifications). The solid line suggests the active fault system, and the dashed line the inactive faults.

The dating of alkaline basalt rocks in the Perșani Mountains area was initially performed using the K/Ar method combined with paleomagnetic data (Panaiotu *et al.*, 2004) and subsequently refined using the Ar/Ar method (Panaiotu *et al.*, 2013). The dating reveals the formation of volcanic edifices between 1221 ka and 683 ka. Both the new 40Ar/39Ar and paleomagnetic ages suggest the existence of at least five episodes of volcanic activity, the most active belonging to the Jaramillo and Brunhes chronologies. Paleomagnetic data reveal several transitions of virtual geomagnetic poles, which were associated with the Cobb Mountain subchron at 1221 ± 11 ka and an excursion in the Brunhes chron.

2.2. VOLCANOLOGICAL STUDIES IN PALEOZOIC AND MEZOZOIC AREAS IN ROMANIA

There are few volcanological studies in areas with Paleozoic and Mesozoic volcanism in Romania due to limited exposure and difficulties in interpretation caused by the deformation processes to which they were subjected following Alpine tectogenesis. A good example is that of the Permian volcanic formations located on the southwestern banks of the Danube and its tributaries (Seghedi, 2011). Volcanism evolved in an intra-continental basin with (1) the extrusion of underwater domes surrounded by hyaloclastite deposits closely associated with secondary volcaniclastic rocks, (2) effusive and explosive underwater eruptions of the Surtseyan type and shallow subaerial eruptions and emerging domes associated with secondary volcaniclastic deposits, and (3) subaerial extrusive domes. Subsequent fluvial erosion and associated sediment deposition completed the evolution (Fig. 9).

A recent volcanological study conducted by our young colleague Violeta M. Vornicu, highlights the lithology and interprets the genesis of the Upper Cretaceous volcaniclastic deposits in the Hațeg Basin (Southern Carpathians) exposed around the localities of Densuș and Răchitova (Vornicu, 2024). Three different volcaniclastic sequences are interpreted as resulting from multiple explosive volcanic eruptions of stratovolcanoes that occurred in a subaerial environment.

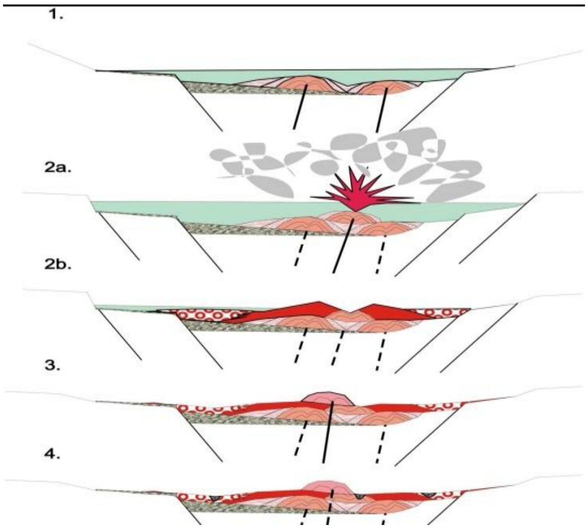

Figure 9. Volcanic evolution model in the Permian Sirinia basin; 1. Increased subsidence along normal extensional faults allowed the generation of underwater effusive domes, whose eruptions generated a hyaloclastic shell and associated secondary deposits; 2a. After subsidence ceased, rhyolite domes were generated accompanied by explosive Surtseyan-type eruptions in a shallow-water regime; 2b. Generation of pyroclastic and secondary deposits that succeeded the formation of the domes by the transition to a subaerial environment; 3. Generation of subaerial effusive domes; and 4. Erosional stage with the accumulation of fluvial deposits (after Seghedi, 2011).

This volcanological study provides the first detailed description of the lithology and lithofacies of these sequences in order to gain a better understanding of the nature of the eruptive processes that led to the formation of these stratovolcanoes and, subsequently, of the dynamics of these large-scale explosive eruptions. All the main types of volcanic formations have been identified in these sequences: primary, secondary, and epiclastic, with each sequence characterized by a specific type of deposit. Intercalated clay deposits accumulated during periods of volcanic inactivity, probably in a lacustrine or deltaic environment. The volcaniclastic sequences were generated by composite volcanoes or high-volume silicic explosive volcanoes that mainly developed phreatoplinian volcanism. The stratigraphic position of the volcaniclastic deposits relative to other lithostratigraphic units and the absence of any volcanic eruption centers in the Haţeg area or its surroundings suggest that volcanic activity took place outside the Haţeg basin.

2.3. VOLCANOLOGICAL STUDIES IN THE NEOGENE/QUATERNARY AGE AREAS OF THE CARPATHIAN-PANNONIAN REGION

Colleague A. Szakács was part of the team documenting a series of volcanic ash layers (tephra) embedded in Pleistocene loess and fluvial deposits of the Lower Jiu and Olt valleys in southwestern Romania (Veres *et al.*, 2013). These were analyzed for the chemical compositions of volcanic glass, which, based on the characteristics of the major and minor elements, document phonolitic and trachytic compositions. The chemical data suggest an origin in the Campi Flegrei volcanic province in Italy and a similarity to Campanian/Y5 ignimbrites, confirming that the volcanic ash layers in southern Romania are distal occurrences of this widespread ash deposit. This is the product of one of the largest explosive events of the late Quaternary in the Mediterranean area and is dated elsewhere to approximately 39–40 ka, constituting one of the most important chronological/stratigraphic markers of Western Eurasia, providing an independent basis for establishing age relationships for the deposits that incorporate them.

Volcanological studies on Miocene-Quaternary volcanism have been the focus of our team's work, especially those carried out in the Călimani–Gurghiu–Harghita volcanic chain. I will now refer to a series of studies carried out in different geographical areas of the Carpathian-Pannonian region.

The Miocene volcanic zone of the Bükk foreland

Colleague A. Szakács participated in three recent volcanological studies conducted by Hungarian colleagues on ignimbrite deposits in the volcanic area of the Bükk foreland (Biró *et al.*, 2020; Hencz *et al.*, 2020, 2021). Biró *et al.* (2020) highlight and study in detail a new sequence of pyroclastic deposits in the volcanic area of the Bükk foreland (BFVA) in northern Hungary, naming it the Jató Member. The succession of stratified pyroclastic deposits is ~8m thick and was deposited in the Middle Miocene, ~14.9 Ma ago, as a result of phreatomagmatic eruption processes. Despite the age of the sequence, granulometric analyses suggest that the deposits accumulated at a distance of approximately 10–50 km from the eruption center.

Hencz *et al.*, (2021), study three tephra deposits from the Lower Miocene in the volcanic area of the Bükk foreland, northern Hungary, and correlate them lithostratigraphically, volcanologically, compositionally, and palaeomagnetically to determine the location of their source region. The results suggest that old pyroclastic deposits (Miocene in this case) – even in relatively small numbers (at least three sections) – can facilitate the identification of the direction of the source region. Subsequently, Hencz *et al.* (2024) document the volcanic evolution of the Miocene silicic volcanism area of the Bükk foreland (BFVA) in northern Hungary on an event scale. Detailed field observations allowed the identification of eleven lithological members corresponding to fourteen eruption events and the establishment of an almost complete lithostratigraphic correlation between fifteen outcrops along the BFVA. A new lithostratigraphic classification scheme has been developed. Favourable conditions for generating explosive silicic phreatomagmatic eruptions are suggested. As paleosol horizons formed after almost every major eruption event or sequence, a subaerial environment is suggested for the deposition of pyroclastic material.

The Apuseni Mountains

In the Apuseni Mountains, we studied the largest stratovolcano in the Zărand basin from a volcanological point of view, previously known as Tălagiu and renamed Bontău by us. In 2010, we published a preliminary study (Seghedi *et al.*, 2010), followed by a comprehensive volcanological and petrological study (Seghedi *et al.*, 2022a). The Bontău volcanic complex, which in addition to the volcano itself also includes a series of three independent domes, is located in the western part of the Zărand graben. Currently, the Bontău edifice is preserved in the form of two N–S-oriented edifice remnants, as parts of the largest andesitic stratovolcano in the Zărand basin. Its activity began at ~14 Ma and ended at ~10 Ma, comprising two stages. The first was effusive-explosive, when a series of independent lava domes were generated at ~12 Ma. The second stage, after ~12 Ma, began with a Plinian eruption and continued with the generation of extrusive domes, which quickly destabilised the volcanic cone, leading to the formation of a series of gravitational collapses around the volcano, widely distributed within the graben, with the formation of volcanic debris avalanche deposits (VDAD). Four VDAD units were separated, corresponding to collapsed structures, the first ones initially directed towards the west and east, and the last ones towards the south and north. The construction and destruction of the volcanic edifice was controlled by tectonic movements of faults oriented E–W and NW–SE.

The Călimani–Gurghiu–Harghita volcanic chain

Documenting and explaining the main volcanological characteristics of the Călimani-Gurghiu-Harghita volcanic chain has been a major, long-term concern for our team.

Based on several approaches, we have developed a new volcanological model for this area, which extends over approximately 160 km (Seghedi *et al.*, 2023b). The most important is the regional volcanological approach, based on segments or volcanic zones, which involved combining volcanological and geochemical observations (Seghedi *et al.*, 2001, 2004a, b, c, 2005a, b, 2017; Szakács and Seghedi, 2003; Molnár *et al.*, 2018, 2019; Karátson *et al.*, 2019; Harangi *et al.*, 2020). The second approach was tectonic, based on geological and geophysical observation data, including paleomagnetism, which is essential for understanding the overall evolution of this unique volcanic chain in Europe (Fielitz and Seghedi, 2005; Szakács and Krézsek, 2006; Panaiotu *et al.*, 2012, 2016; Vișan *et al.*, 2013; Seghedi *et al.*, 2019; Besuțiu *et al.*, 2021).

In the most recent tectonic study (Seghedi *et al.*, 2019), we performed a comprehensive GIS mapping of the Călimani–Gurghiu–Harghita volcanic chain, integrating geological, tectonic, and geophysical (magnetic and gravimetric) data to highlight (i) the interaction between magmatism and volcanic activity, (ii) the development of intramountain basins, and (iii) the large-scale evolution of faults in the post-collisional tectonic setting of the Eastern Carpathians. We confirmed the contemporary formation of intramountain basins with volcanic activity, the two phenomena propagating southward in time, between 11 and 0.03 Ma, parallel to the collision front, in close connection with the initiation and development of fault systems (Fielitz and Seghedi, 2005). The geometry of the fault system and the alignment of volcanic edifices indicate the presence of both strike-slip faults and normal faults, with no evidence of rotation (Panaiotu *et al.*, 2012, 2016; Vișan *et al.*, 2013). Both volcanic centers and intra-mountain tectonic basins evolved along a NNW-SSE transtensional system. The fault zones favored the development of magma ascent pathways and the formation of intra-crustal magma chambers.

An original approach, but without volcanological implications, based on quantitative geomorphology, assesses the growth and erosion rates of volcanic structures in the Călimani–Gurghiu–Harghita volcanic chain (Dibacto *et al.*, 2020); colleague A. Szakács also participated in the study. The study confirms a decrease in the accumulated eruptive volume in the four main successive volcanic segments (910, 880, 279, and 165 km^3 for Călimani, Gurghiu, North Harghita, and South Harghita), totaling 2200 km^3 and an average growth rate of 200 km^3/ Ma for the entire volcanic chain. Such a quantitative morphometric and geochronological approach demonstrates its effectiveness in studying the dynamics of volcanic activity, both construction and erosion, over time.

The most comprehensive volcanological study of the Călimani–Gurghiu–Harghita volcanic chain is recent and highlights the volcanic debris avalanche deposits (VDAD) that have fundamentally contributed to its current configuration (Seghedi *et al.*, 2023b). The work presents a new volcanological model for the entire volcanic chain, which is integrated into a new original cartographic presentation (Fig. 10). By combining data obtained from field observations and GIS analysis with published data and new petrographic, geochemical, and K/Ar geochronological data, this paper demonstrates that VDADs dominate the volcaniclastic deposits at the periphery of the volcanoes. In addition to two previously identified VDADs (Western Călimani and Vârghiș), we have shown that six other VDADs (Eastern Călimani, Fâncel–Lăpușna, Ostoroș, Ivo-Cocoizaș, Luci, and Pilișca) were generated by the partial collapse of a series of volcanoes in the chain, most of which retain the distinctive scar of collapse.

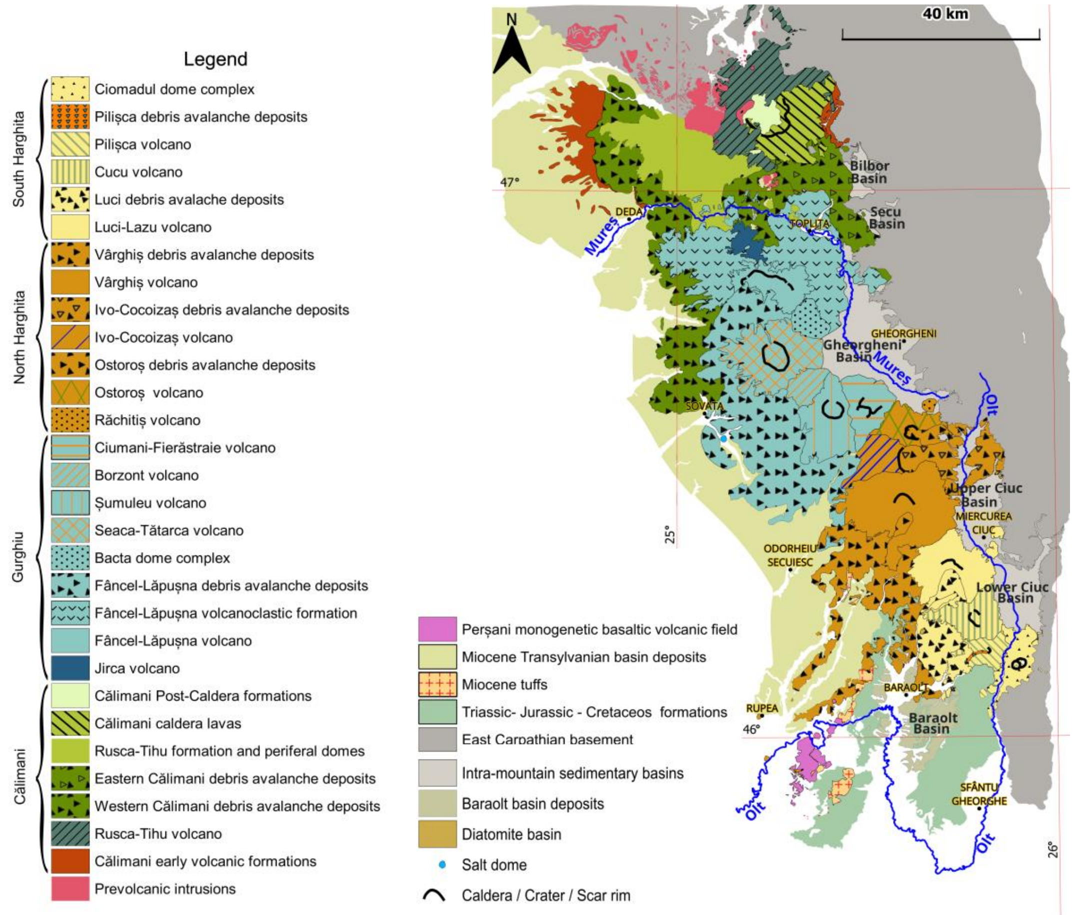

Figure 10. Volcanological map of the Călimani–Gurghiu–Harghita area – CGH (after Seghedi *et al.*, 2023b).

Based on our estimates, avalanche deposits have variable volumes ranging from < 1 km3 to > 100 km3, representing 0.4–39% of the source edifices, incorporating nearly one-third of their cumulative volcanic production. K/Ar age constraints suggest that VDAD formation closely followed, in space and time, volcanic activity that migrated southward between approximately 7.8 and 1.5 Ma. Based on this age model, the orientations of the collapse scars and the directions of VDAD displacement, we proposed a geodynamic model suggesting that the collapse of the volcanic edifices was determined by regional-scale deformation processes of the Dacia block lithosphere, imposed by the progressive detachment of the underlying subducted plate, manifested at the surface as transient tilting of the relief along the volcanic chain (Fig. 11). This process was responsible for the southward tilting of the foundation and led to a progressive destabilisation of the volcanic edifices along a system of shallow faults and is synchronous with the opening of intramountain basins on the eastern flank of the chain (see Seghedi *et al.*, 2019).

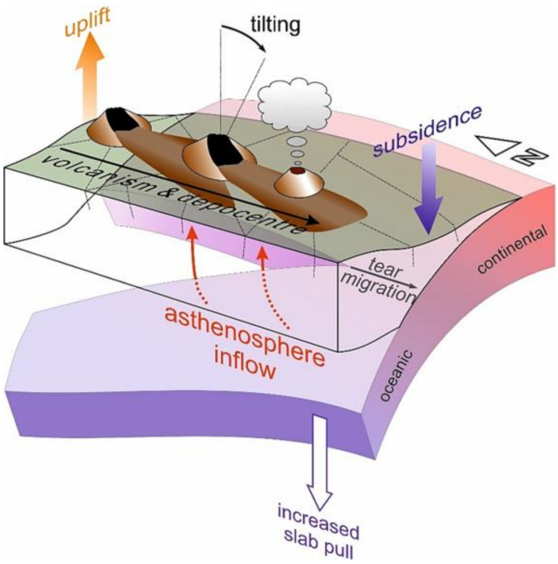

Figure 11. Model showing the geodynamic causes of the instability of the volcanic edifices in the CGH chain following the collision between the East European Platform (pink) and the Dacian Mega Unit (transparent) at ~11 Ma. The propagation of the rupture towards the south-southeast and the unrolling of the subducted plate allowed the progressive influx of asthenosphere and, in turn, a migratory process of melting and deformation of the Dacian lithosphere, as well as the generation of volcanism in the CGH. The tilting of the volcanic edifices and the relocation of the depocenter resulting from the transient subsidence-uplift couple would have led to the formation of several VDADs. The thin dashed lines represent the fault system that facilitated the volcanism and, later, the collapse of the edifices. After Seghedi *et al.*, 2023b.

Another comprehensive volcanological study concerns the field of alkaline basaltic volcanoes in the Perşani Mountains (Seghedi *et al.*, 2016). With an area of ~176 km2 (~22 × 8 km), this is the youngest and most developed monogenetic volcanic field in south-eastern Europe. It consists of 21 monogenetic volcanic centres, most of which were built on a foundation of Miocene rhyolitic tuff and Mesozoic sedimentary rock. 40Ar/39Ar dating shows that the eruptions occurred in five episodes, at 1220, 1142, 1060, 800 and 683 ka. An additional undated episode between 1060 and 800 ka has been identified using volcanological observations. The initial volcanic activity was explosive phreatomagmatic; it was followed by explosive Strombolian/Hawaiian eruptions that deposited proximal bombs and agglutinated ash around the eruption centres, and distal scoria, lapilli and unconsolidated ash. Some volcanoes do not preserve evidence of explosive magmatic activity, while others lack the diagnostic elements of an initial phreatomagmatic phase. In most cases, the final activity was represented by lava flows, which in some cases deformed or partially destroyed the initial volcanic edifices. The volumes of magma expelled varied greatly from one episode to another; the largest volumes, approx. 0.25 km^3, being accumulated in the third pulse (1060 ka). The volcanoes are located near or along faults, and it can be inferred that the regional tectonic stress regime controlled both the timing and spacing of volcanic activity in the Perşani Mountains.

2.4. VOLCANOLOGICAL STUDIES CONDUCTED ABROAD, OTHER THAN IN THE CARPATHIAN-PANNONIAN REGION

In 2007, together with our Spanish colleagues, we published, for the first time internationally, the description and modern volcanological interpretation of the monogenetic volcanoes of ultrapotassic, lamproitic composition in south-eastern Spain (Seghedi *et al.*, 2007a). These formations are associated with extensional basins filled with Neogene deposits from the Betic and Subbetic structural units. The paper describes the volcanic centres of Cancarix, Calasparra and Barqueros, which show initial phreatomagmatic eruptions caused by the interaction between lamproitic magma and groundwater. The tuff rings were formed during this volcanic activity. Subsequent activity consisted of the formation of extrusive domes in the emission areas of Cancarix and Calasparra and explosive to effusive magmatic activity accompanied by lava flows at Barqueros (Fig. 12). Tectonic variations, the extensional regime and local hydrogeological conditions (shallow aquifers) influenced the emergence of these lamproite volcanoes. In the late terminal phase, the magma eruption was dependent on the volatile regime, already degassed at Calasparra and Cancarix, due to the presence of extrusive domes with high viscosity and a high crystallisation rate, located in the centre of the tuff rings, or still rich in volatile substances at Barqueros, displaying a lower viscosity, which generated fountains and then lava flows.

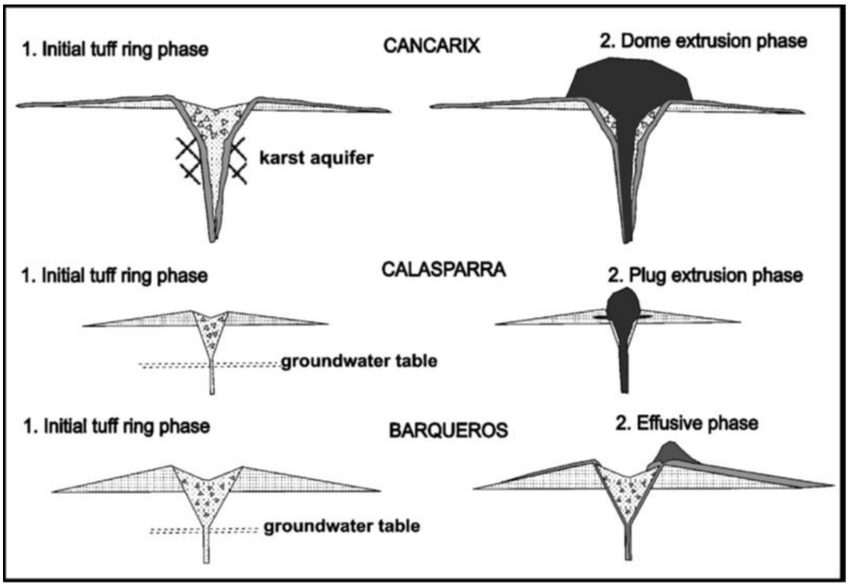

Figure 12. Evolution models of lamproitic volcanoes in southeastern Spain (Seghedi *et al.*, 2007a).

In 2009, we published a novel volcanological study on the Tuzo kimberlite dyke belonging to the Gahcho Kué dyke field in the Middle Cambrian (~540 Ma), located approximately 275 km ENE of Yellowknife, NWT, Canada (Seghedi *et al.*, 2009). The kimberlites cut through 2.6 Ga Archaean granitic rocks of the Yellowknife Supergroup. The Tuzo dyke has a circular outline at the surface and widens towards deeper levels. The filling consists of several types of kimberlite facies, both coherent and fragmentary. The coherent or apparently coherent (possibly welded) kimberlite facies dominates at depth but also occurs at shallow levels. The central and shallower portions of the dyke consist of several fragmentary varieties of kimberlite, which are texturally classified as tuffaceous kimberlites. The definition, geometry and extent of the geological units are complex. The fluid contours of some coherent kimberlite clasts suggest that at least some are the products of fragmentation of magma that was in a semi-plastic or even welded state. The shape and architecture of the Tuzo diatreme facies suggest that the section studied is located at the root–diatreme structural transition level (Figure 13). The coherent kimberlite clasts imply that recycling processes were active over time, while the granitic rocks in the walls were recycled, and the ductilely deformed welded kimberlite clasts indicate the presence of temporary cavities in the root zone. The eruption did not occur in a single violent explosion, but involved repeated volcanic explosions, alternating with periods of relative calm. The observed characteristics are typical of phreatomagmatic explosion processes, which may include, in later phases, less explosive magmatic activity similar to proximal Strombolian processes.

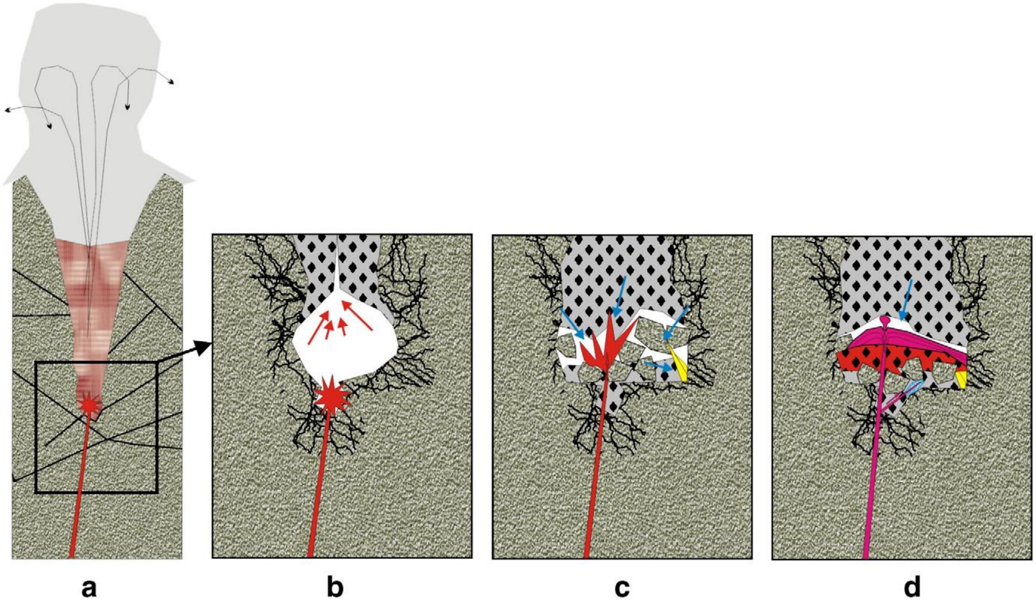

Figure 13. Simplified model of a maar–diatreme phreatomagmatic volcano; the sketches and the framework suggest a cycle of transition from phreatomagmatic manifestations to magmatic eruptions in the root zone/transition zone of the Tuzo diatreme; b. the granitic host rock is strongly brecciated due to the penetration of shock waves and gases, and the explosion chamber is temporarily evacuated by the phreatomagmatic eruption through the supply pipe and consequently a short-lived cavity is formed at the explosion site; c. subsidence of granitic breccias and fragmental kimberlites lithified in the explosion chamber, but also the initiation of a less energetic magmatic eruption; d. the even less energetic magmatic eruption that generates hot fragments with plastic contours, which accumulate and agglutinate rapidly; The associated intrusions generate dikes and peperites (after Seghedi *et al.*, 2009).

In 2015, we published for the first time a description of two composite volcano structures (stratovolcanoes) in the İzmir–Balıkesir area, Western Anatolia, Turkey, which evolved between 17.48 and 14.94 Ma (Seghedi *et al.*, 2015a).

In 2016, we had the opportunity to discover and evaluate, from a volcanological and petrological perspective, one of the largest volcanic calderas in Western Anatolia, Turkey (Seghedi and Helvacı, 2016), which hosts one of the largest boron deposits in the world (Helvacı *et al.*, 2020).

The Kırka-Phrigian caldera is part of the Eskişehir-Afyon-Isparta volcanic zone. Transtensive/distensive tectonics in the NNW-SSE direction 25 Ma ago influenced the approximately elliptical shape of the subsided block that led to the formation of the caldera. With an approximately oval shape (24 km × 15 km) on the surface, it was formed during a series of collapse events (gravitational collapse) starting ~19 Ma, generating a huge volume of extra- and intracaldera ignimbrites (Fig. 14). Post-collapse sedimentation and subsequent volcanism at the northern edge of the caldera (at ~18.6 Ma) were controlled by subsidence-related faults, generating a series of volcanic structures (domes and lavas) with a wide compositional range. The heat resulting from the mantle's ascent produced silicic magmas in large crustal reservoirs; the interaction of these melts with fertile crustal rocks further caused crustal anatexis, resulting in two plinian ignimbrite eruptions of different acidic compositions: Rhyolite-1 and Rhyolite-2. After the caldera was formed, there was a change in composition due to volcanic activity in the northern rim of the caldera, which produced lava domes of varying composition: rhyolitic, basaltic-andesitic-trachytic, trachytic and lamproitic, the latter being the youngest (16.2 Ma), indicating the progressive generation of increasingly primitive magmas, which originated in an enriched lithospheric mantle. The succession of rocks provides a direct picture of the state of the magmatic system at the time of the eruptions that led to the formation of the caldera structure as well as some post-caldera products, and documents an excellent example of magmatic diversity in a post-collisional extension tectonic setting.

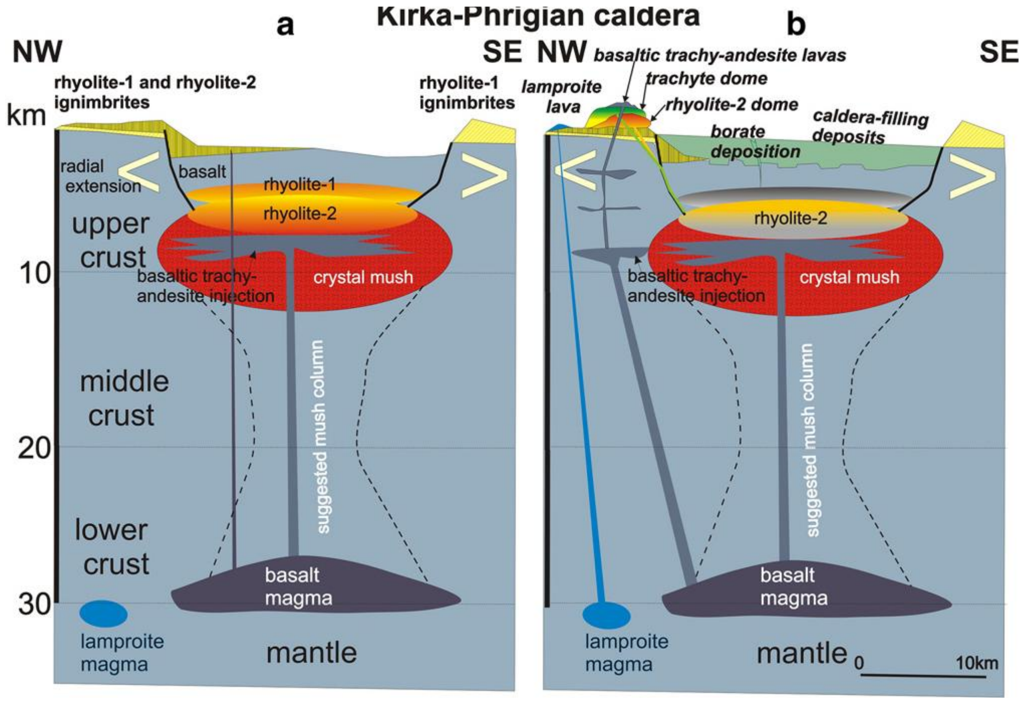

Figure 14. Evolutionary model of the Kırka-Phrigian caldera. a. caldera collapse with the generation processes of Rhyolitic-1 and 2 ignimbrites; b. filling processes with secondary post-caldera volcanoclastic deposits and the generation of lava domes at the northern margin, rhyolites, trachytes shortly after collapse, and then basalts, trachyandesites and lamproites at ~2 Myr after collapse (after Seghedi and Helvacı, 2016).

In the following years, I continued my research in the Kırka-Phrigian caldera, and suggested that the formation of one of the world's largest borate deposits within it was closely linked to the volcanic processes and deposits resulting from the formation of the caldera located in the northernmost part of the Miocene Eskişehir–Afyon volcanic field (Helvacı *et al.*, 2020). Following the collapse of the caldera, its basin filled with lacustrine sediments and volcaniclastic deposits, as well as boron mineralisation deposition processes, which were concentrated in two main sub-basins: Sarıkaya and Göcenoluk. The close spatial and temporal relationship between borate deposition and the extensive ignimbrite deposits inside and outside the caldera (with high concentrations of elements associated with mineralisation) suggests that ignimbrites were the most important source of boron. Boron was transported by geothermal fluids and post-volcanic gases that circulated in the hot water at the base of the caldera-paleolake system and was then concentrated during sedimentation and evaporation cycles, with most of the mineralisation accumulating along a N-S fracture system (Fig. 15).

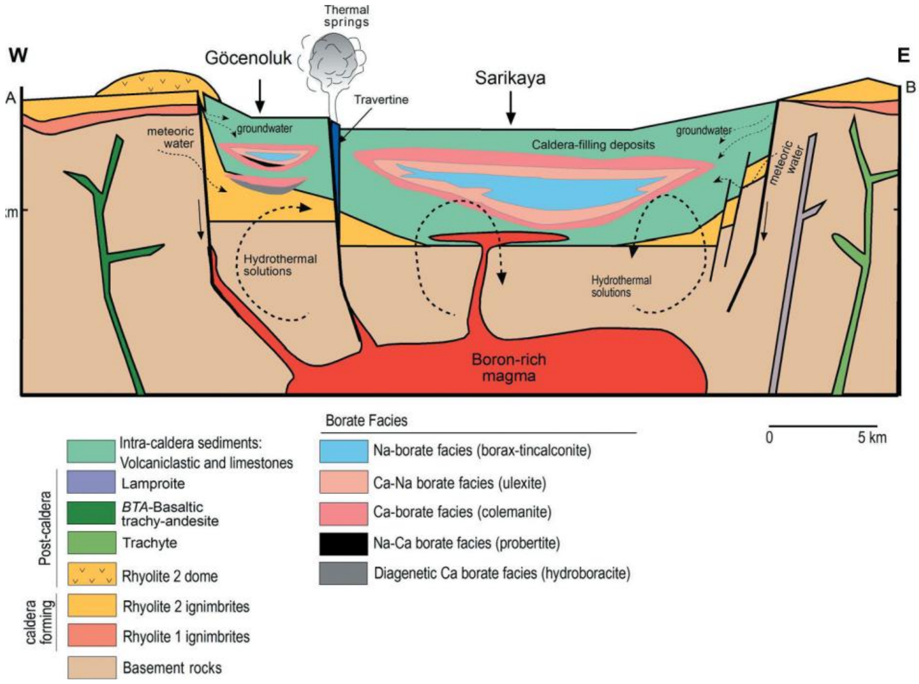

Figure 15. Early Miocene (~16–18 Ma) borate deposit pattern in the Kırka-Phrigian caldera basin of Western Anatolia (after Helvacı *et al.*, 2020).

3.4. HISTORICAL, HAZARD AND GEOHERITAGE STUDIES

In 2022, I published a chapter in a volume of the Romanian Academy with a historical overview of works in the field of volcanology and their role in the history of geosciences in Romania (Seghedi, 2022). I reviewed the most relevant volcanological contributions since the 1970s. The year 1973 is particularly important, as Romania organised an International Symposium on Volcanism and Metallogenesis at the University of Bucharest, coordinated by Professor Dan P. Rădulescu. In 1976, Professor Dan P. Rădulescu published the book "Volcanoes Today and in the Geological Past", which served as a catalyst for many students and significantly increased interest in volcanological studies.

In 2022, we presented a historical overview of the main aspects related to the progress made in mapping the Miocene-Quaternary volcanic chain of Călimani–Gurghiu–Harghita and in understanding its geological structure (Seghedi and Szakács, 2022). The volcanic chain, with a length of over 160 km, attracted the attention of naturalists and geologists from the end of the 18th century to the beginning of the 19th century due to its grandeur and splendour. Knowledge, mainly in petrography, volcanology and cartography, has improved steadily to the present day (Seghedi *et al.*, 2023b).

Szakács (2011) suggests a novel strategy for earthquake prediction. In his opinion, effusive monogenetic volcanic conduits filled with rocks of primitive parental magma composition are best suited to indicate direct ascent from the sublithospheric magma generator zone to surface areas. This could be an innovative research strategy for earthquake prediction, considering that monogenetic volcanoes and deep transcrustal fractures can be considered prime locations for seismic monitoring stations, using a set of physical, chemical and biological sensors designed to detect earthquake precursors. Earthquake prediction systems can be built on the concept of signal emission – transmission-reception system, in which volcanic conduits and/or deep fractures play the role of the most suitable and efficient signal transmission paths through the lithosphere. Seismic structures are expected to be signalled by such 'precursor fingerprints'. Intelligent pattern recognition systems would be included to evaluate the signal ensembles recorded by complex sensor networks. Such strategies are expected to be limited to intermediate depth and deep seismic structures, such as the Vrancea area.

Until the publication of Szakács and Seghedi (2013), volcanic hazards had been ignored in natural hazard studies in Romania, as there are no known active volcanoes on its territory. However, approaches focused on volcanic hazards should be considered, even if the sources of danger may be far from our country. In this study, we have compiled an inventory of potential sources of volcanic hazards for the territory of Romania, regardless of their location inside or outside the country. With regard to external volcanism, sources involving the danger of ash fall from the dispersion of tephra following explosive volcanic eruptions include: the central field of active volcanoes in Italy (e.g., Campi Flegrei and Vesuvius), the active volcanic arc in the Aegean Sea, the Eifel region in Central Europe (Germany), and Iceland. Geological evidence of thick ash deposits from the Campi Flegrei caldera (its Campanian ignimbrite erupted at approx. 39 Ka) found in southern Romania clearly indicates that such a volcanic hazard is real (Veres *et al.*, 2013). On the other hand, the study of the most recent volcanic activity in Romania shows that the last eruptive event, of the explosive Plinian type, took place at the Ciomadul volcano, at the southeastern end of the Călimani-Gurghiu-Harghita (CGH) volcanic chain between 10.7 and 30 Ka, following 10.5 Ma of volcanic activity that migrated southward along the entire CGH chain. A series of distinctive features of the Ciomadul volcano and its surroundings strongly suggest that the magma chamber of this volcano is not frozen, given a well-concentrated and strongest heat flow anomaly in Romania, local subcrustal seismic activity, seismic wave attenuation features recorded in seismic tomography images, and the area with the most intense post-volcanic activity, which includes gas emissions from the mantle. All these symptoms suggest that future eruptions of this volcano cannot be ruled out. The need for dedicated geophysical studies is emphasized in order to obtain more basic information on the current state of the magma generation systems and magma chambers of the Ciomadul volcano, which are crucial from the point of view of volcanic hazard and the assessment of derived hazards.

Laumonier *et al.*, 2019, revisits the idea of volcanic hazard in the Ciomadul structure and provides evidence for the existence of an active magma reservoir with high melt content beneath the volcano. Most active volcanoes have eruption frequencies of 10–1000 years, but some volcanic systems have extremely long dormant periods (>10 Ka) and can be considered extinct. However, some volcanoes resume activity, posing a particular threat due to the way they evolve and come back to life. The reawakening depends primarily on the nature of the subvolcanic magma reservoir, in particular the presence and distribution of melt. By integrating petrological, thermobarometric, thermomechanical models, geophysical data and in situ electrical conductivity measurements, it is demonstrated that the volume of magma beneath Ciomadul, considered an inactive volcano after its last eruption 30 ka ago, may still contain 20 to 58 km^3 of silicon-rich melt, constituting 20–58% of the volume of the crustal magma chamber (crystal mush body). This volume of magma exceeds the volume of lava erupted throughout the entire history of the volcano. This illustrates the longevity of a magma reservoir at a supersolidus temperature, implying that there is still potential for rapid revitalisation of the magma chamber. The fact that an apparently extinct volcano such as Ciomadul is capable of erupting in the future requires a reassessment of the status of "inactive" volcanoes around the world and even a redefinition of the concepts of activity/inactivity.

In 2022, colleague A. Szakács notes that, due to the most recent eruption less than 30,000 years ago, the Ciomadul volcano has been subjected to intense research in recent decades, which has led to increasing questions about a possible resumption of its activity in the future (Szakács, 2022). Various geophysical and petrological investigations as well as previous eruptions are arguments in favor of this situation. However, in the author's opinion, due to the sensational perception in the media, local and international news stations, this issue is often exaggerated and distorted. The author believes that the volume and degree of melting of the residual magma should be estimated with greater precision and in a more reliable way than the figures published by Laumonier *et al.* (2019), which he suspects to be exaggerated. Then, he believes that to more realistically assess the chances of an eruption, the location and spatial development of the eruptive magma storage system should be determined more precisely than it is currently.

Recently, Szakács and Kovács (2023) rhetorically ask whether the most recently potentially active volcano in the Carpatho-Pannonian region, Ciomad, is capable of further eruptions. The authors believe that the debate on the future eruptive capacity of Ciomad, which has recently gained new impetus, has attracted exaggerated media attention. The paper challenges the numerical thermal modeling that estimated that the current magma volume accumulated under the volcano is 20–58 km^3 (Laumonier *et al.*, 2019), because they believe that the applied model does not take into account the initial conditions, the parameters related to the crustal structure and the local radiogenic heat production. The two authors propose an alternative hypothesis, considered more plausible from a geological point of view: the presence of relatively small amounts of fluids percolating from the upper mantle to the surface would explain the conductivity anomalies reported under the volcano. The authors believe that the exaggerated and alarmist media coverage of the research results encouraged by inappropriate wording of the title of Laumonier *et al.*'s (2019) article may have harmful consequences for the credibility of the scientific community and unnecessarily alarm local communities.

The current landforms and volcanic landscapes of the Eastern Carpathians are presented in terms of geo-heritage (Szakács and Kovacs, 2022). Such current landforms have been shaped by various syn-volcanic deformation processes, post-volcanic erosion of various degrees and types (including glacial erosion on the highest elevation parts and relief inversion in peripheral areas) and modern anthropogenic intervention. Developed on this diverse volcanic substrate, the current landscape presents a wide variety of forms due to other factors (original relief, altitude, vegetation cover, distance from settlements, anthropogenic activities and degradation processes. The Oaş–Gutâi and Călimani-Gurghiu-Harghita volcanic mountains host many sites relevant for geoheritage of different spatial extents (from hundreds of km^2 to limited areas of a few 10 m^2) and with protection status (from national parks, natural or scientific reserves, natural monuments and protected areas, or areas without protection). Despite the high heritage potential of the region, geoparks are still absent, geotrails are rare and geotourism is only in its infancy.

The Călimani National Park (PNC), legally founded in 2000 to ensure the highest level of protection for the unique natural and scientific values it hosts, is the largest volcanic protected area in Romania (Szakács and Chirița, 2017). It covers a significant part of the Călimani Mountains, representing the most extensive, highest and most voluminous segment of Neogene volcanism in the Carpathians. The values protected in the PNC include a unique alpine volcanic landscape of over 2000m, hosting glacial and periglacial cirques, lakes and marshes, spectacular rock formations and unique floral elements. Due to their outstanding scientific value, the Juniperus with Pinus cembra botanical scientific reserve, the Iezer Lake scientific geographical reserve and the "12 Apostoli" geological reserve are at the highest legal level of protection. The PNC also hosts damaged or destroyed natural values of geo-heritage importance. This is where the phenomenon of volcanic karst was first described and called "volcanokarst". The open pit for sulfur exploitation destroyed the original features and only poor traces of this phenomenon can be found today. The landscape was also catastrophically affected by mining.

However, remediation and re-cultivation activities in the open pit area have significantly mitigated the damage. Unfortunately, the Park management pays little attention to the evaluation of geological and volcanological features that would deserve higher levels of protection. Most of them are not even known to the general public. Much remains to be done to fully take advantage of the natural values of the geoheritage hosted by the PNC. The actions that should be undertaken to this end, suggested here, include the organization of thematic workshops, conferences, exhibitions, and field practice for students, professionals, and the general public focused on the values of the geoheritage, the placement of geoeducational panels along the tourist routes, the design of terrain, guides, and promotional materials, and the connection of the Călimani Mountains to wider tourist networks.

The volcanological reconstruction study undertaken in the UNESCO Geopark of Țara Hațegului can be used in promoting volcanological geotourism and the remarkable story of the explosive nature of volcanism from the distant past of the Upper Cretaceous geological period which, due to the scarcity of data and the lack of detailed observations, has remained largely unknown until now (Vornicu, 2024). As has been proven many times before, when it comes to volcanoes from the geological past, the description of features and landforms increases their geoheritage value, so the availability of scientific data and the way in which these data are transmitted to the general public can make a significant difference.

3. SYNTHESIS STUDIES BASED ON GEOCHRONOLOGICAL, PETROLOGICAL, VOLCANOLOGICAL AND TECTONIC DATA

A separate group is represented by the synthesis works that concern the geodynamic evolution of some territories in the geological history of the Earth. These reconstructions are based on complex geological, geochronological, petrological, volcanological and geotectonic data. I mention the work of Munteanu and Tatu (2003) which discusses the formation of the crystalline-Mesozoic zone in the Eastern Carpathians as a result of the amalgamation of the Gondwana and East European cratonic lands.

The geodynamic reconstructions of the Carpatho-Pannonian area from the Miocene-Quaternary period, based on the complex analysis of igneous rocks, have been a long-standing concern for our team and our collaborators abroad, through the publication of a series of papers with a special impact (more than a hundred citations) in the specialized literature (Seghedi, 2004; Seghedi *et al.*, 2004a,b, 2005a; Seghedi and Downes, 2011; Harangi *et al.*, 2006, 2024; Szakács *et al.*, 2018). The geodynamic syntheses were then extended to the Anatolian area (Seghedi *et al.*, 2013, Prelević and Seghedi, 2013), revealing similar evolutionary situations of igneous rocks.

The paper by Harangi *et al.*, (2006) discusses the geodynamic context of the Tertiary-Quaternary “subduction-related” magmatism in the different segments of the Alpine-Mediterranean region (Betic-Alboran-Rif provinces, Central Mediterranean, Alps, Carpatho-Pannonic, Dinarides and Hellenides, Aegean and Western Anatolia) and discusses the main characteristics and compositional variation of the igneous rocks. Isotopic data indicate the importance of the contribution of the continental crust in the genesis of this magma. The interaction of mantle melts with crustal material occurred both in the upper mantle during subduction (“source contamination”) and in the continental crust, during the ascent of the magmas (either by mixing with crustal melts or by crustal contamination). From the Neogene to the Quaternary, the convergence of Eurasia and Africa led to a variety of orogenies and collisions, including different styles of subduction. Characteristic features of this area include arcuate orogenic belts and extensional basins, both of which can be explained by the movement of subducted plates and retreating subduction zones. After the cessation of active subduction, plate detachment and post-collisional gravitational collapse of the overthickened lithosphere followed. This complex tectonic history was accompanied by the generation of a wide variety of magmas. Most of these magmas (tholeitic, calc-alkaline, shoshonitic, and ultrapotassic) have minor element and isotopic signatures that reflect enrichment of their source regions by subduction-related fluids. Thus, they can be considered "subduction-related" magmas regardless of the geodynamic context. Alkaline basalts in the region generally postdate "subduction-related" volcanism. The compositions of these mantle-derived magmas have not been significantly influenced by subduction.

In a team of leading volcanologists from Slovakia, Romania and Hungary, in 2010 we participated in the elaboration of the most extensive synthesis of volcanic and subvolcanic activity forms in the Carpatho-Pannonian area (CPR), covering the Miocene-Quaternary period, between 21 Ma and 0.1 Ma, (Lexa *et al.*, 2010). Since most primary volcanic forms were affected by erosion, especially in areas of post-volcanic tectonic uplift, depending on the level of erosion, the following were distinguished: (1) areas eroded down to the level of the prevolcanic basement, where paleovolcanic reconstruction is not possible; (2) deeply eroded volcanic forms, for which limited paleovolcanic reconstruction is possible; (3) eroded volcanic forms, with the original morphology partially preserved; and (4) volcanic forms with well-preserved original morphology. The wide variety of volcanic forms present in the area can be grouped into a) monogenetic volcanoes and b) polygenetic volcanoes and their subterranean/intrusive counterparts that belong to the different rock series found in the CPR, such as calc-alkaline igneous rock types (with felsic, intermediate and mafic varieties) and alkaline types, including K-alkaline, shoshonitic, ultrapotassic and Na-alkaline types. The following volcanic/subvolcanic forms have been identified: (i) domes, shield volcanoes, effusive cones, pyroclastic cones, stratovolcanoes and calderas with associated intrusive bodies for intermediate and basic calc-alkaline volcanism; (ii) domes, calderas and ignimbrite/ash fields for felsic calc-alkaline volcanism and (iii) lava flows and domes, shield volcanoes, maars, tuff cones/tuff rings, scoria cones with or without lava fields and their erosional or subsurface forms (nekurs, dykurs, shallow intrusions, diatremes, lava lakes) for different rock types with K- and Na-alkaline and ultrapotassic magmatism. Finally, the paper presents a summary of the eruptive history and distribution of volcanic forms in the CPR.

Considering the magmatic processes in the Carpatho-Paanonian area, as well as the magmatism at its southern limit, in the Dinarides and the Balkans, from the Early Miocene to the Recent, we have published a new geodynamic view of regional-scale magmatism (Seghedi and Downes, 2011). This geodynamic system was controlled by the subduction and then collision of Africa with Eurasia, from the Cretaceous to the Neogene, especially by Adria which generated the Alps to the North, the Dinarides-Hellenides belt to the East and caused tectonic phenomena of extrusion, collision and inversion in the CPR. This convergence of plates, having a long life, provided the lithospheric mantle with diverse subduction components. The CPR contains igneous rocks with very diverse compositions (calc-alkaline, K-alkaline, ultrapotassic and Na-alkaline), all generated in response to complex post-collisional tectonic processes. These processes formed extensional basins in response to the compressional and extensional interaction of two microplates: Alcapa and Tisza-Dacia. The competition between different tectonic processes, both at local and regional scales, determined variations in the associated magmatism, mainly as a result of differences in the rheological and compositional properties of the lithosphere. The extension led to the disintegration of the microplates that eventually developed into two basin systems: the Pannonian and the Transylvanian. The southern border of the CPR is bounded by the Adria microplate through the Sava and Vardar zones that acted as regional transcurrent tectonic zones during the Miocene until recent times. Major, minor and isotopic geochemical data of the igneous rocks of the CPR suggest that subduction components were preserved in the lithospheric mantle after the Cretaceous-Miocene subduction and were reactivated, in particular by extensional tectonic processes that allowed the uplift of the asthenospheric mantle. Changes in mantle composition over time support post-collisional geodynamic scenarios and processes related to the evolution of the main blocks and their boundary relationships. Lithospheric blocks with weak rheology (Alcapa and western Tisza) generated the Pannonian Basin and, adjacently, the Styrian, Transdanubian and Zărand basins, which are associated with a wide range of magmatic compositions. Rigid lithospheric blocks (Dacia), on the other hand, were deformed only marginally, via strike-slip faults, with extension associated with magmatism. At the Adria and Tisa-Dacia boundaries, extensional tectonics was associated with a small volume of magmas in narrow sedimentary basins or in core-complex detachment systems along older suture zones (Sava and Vardar), accommodating extension into the Pannonian Basin and then Pliocene–Quaternary inversion. Magmas of various compositions appear to have acted as lubricants in a series of tectonic processes.

In 2013, we published a review comparing Neogene volcanic rocks from the Pannonian Basin (PB) and the Menderes Massif (MB) in Anatolia (Seghedi *et al.*, 2013). The magmatic systems in the two regions were active during the same time interval and show many similarities in major and minor element geochemistry. In the PB, the production of large volumes of rhyolite at ~22 Ma indicates the crust as the dominant source of magmas. Later, andesitic volcanism was derived from the mixing of magmas originating from the lithospheric mantle and crust; further, until 11 Ma, the magmas originate from the lithospheric mantle and have increasingly smaller volumes. Over time, the metasomatic components diminished in the lithosphere and this eventually led to the eruption of magmas with a purely asthenospheric intraplate character. At ~10 Ma, magmas of mixed lithospheric and asthenospheric origin generated transitional rocks with basaltic compositions. Intermittent generation of small volumes of Na-alkaline basalts continued at 12–10 Ma in the Styrian Basin and between 8 and 0.13 Ma in the central part of the PB, indicating a long period of asthenospheric magma generation through adiabatic decompression processes. In the MB, volcanic rocks were emplaced in NE-SW-trending basins between 22 and 13 Ma, during the episodic exhumation of the central complex of the Menderes Massif. Rhyolites dominated in the Early Miocene and were followed by andesites, trachytes and lamproites in the Middle Miocene. Between ~10–8 Ma, transitional rocks formed, suggesting the mixing of magmas derived from the lithospheric and asthenospheric mantle. The generation of Na-alkaline basalts in the central part of the MB began at ~1.9 Ma and lasted until recently. The lithospheric mantle was metasomatized during previous subduction events in both regions, but the lithosphere beneath the MB was metasomatized more intensely and heterogeneously. The extension of the lithosphere allowed the penetration and uplift of the asthenosphere, which facilitated the melting of its hydrated parts. In both cases, the extension also led to heating of the lower crust and facilitated its partial melting.

An original paper, based on a synthesis of published geochronological data, addresses the temporal-spatial evolution of Neogene magmatism in the Carpatho-Pannonian region (CPR), with the aim of identifying significant patterns and trends in magmatism evolution (Szakács *et al.*, 2018). The rocks are grouped according to petrochemical criteria (felsic and intermediate calc-alkaline and alkaline) and major geotectonic units (Carpathian and Intracarpathian, in turn divided by lithospheric blocks, Alcapa and Tisza-Dacia). Evolutionary models for the Intracarpathian Zone and the Carpathian Zone are suggested. The Intracarpathian Zone is characterized by (1) an areal spread of magmatic activity, with eastward displacement, more developed on the Alcapa block, involving calc-alkaline and intermediate felsic magmas (21–7 Ma) and alkaline magmas in later stages (11 to < 1 Ma) and (2) a longlasting magmatic activity, concentrated in an area of ca. 200 km diameter, located on the Alcapa block, moving eastward in time. It is suggested that a thermal anomaly due to a mantle plume acted at the site of the development of large-volume, areal-type magmatism in the Alcapa block. In comparison, the Tisza-Dacia block was activated later and, being cooler, is characterized by lower-volume magmatism. Magmatism in the Carpathian Zone presents, in turn, two distinct time-space evolution patterns: (1) long-lived, with the calc-alkaline intermediate magmatic front migrating slowly eastward along the Carpathians, active in the time interval 15–9 Ma, being generated under subduction conditions and (2) a transitory magmatism in time along the Eastern Carpathian segment, in the time interval 11 to < 0.1 Ma, and whose connection with subduction is questionable. Beyond these evolutionary patterns, two regional trends at the CPR level have also been identified: (1) the general eastward shift of magmatic activity over time, regardless of the petrochemical type, and (2) the convergence of magmatism both in time and space towards the southeastern corner of the CPR (i.e. the Carpathian curvature zone in Romania), currently the most active and dangerous geodynamic zone of the entire CPR area, known as the Vrancea seismic structure. The eastward displacement of the asthenosphere is considered possibly related to a mantle plume and responsible for the volcanism associated with the Alcapa block, which could also be at the origin of the aforementioned evolutionary trends.

Colleague P. Luffi participated in the work of Balica *et al.* (2020) which presents a global study focused on the chemistry and geochronology of a large number of zircon crystals extracted from unconsolidated sediments, sedimentary and detrital metasedimentary rocks. Based on a compilation of data from the literature, but also a significant number of new analyses, this archive contains zircon crystals of all ages from 4.4 Ga to the present. The chemistry of the zircons indicates a dominantly magmatic provenance and suggests that most of these crystals, regardless of age, formed in magmatic arcs with thicknesses of 35–45 km, similar to the current continental average. It is considered that, although different subduction processes could have contributed to the formation of the granitoids from which the zircons come, the temperatures, depths and the presence of water, arbitrated by the presence of amphibole, were similar.

Two authors from our laboratory, in collaboration with colleagues from the University of Bucharest, are creating the first petrological database of the Carpatho-Pannonic area in 2021 (Vlăsceanu *et al.*, 2021). The work centralizes the published geochronological, geochemical, and isotopic data on the Mesozoic to Quaternary igneous rocks of the region.

An exceptional paper recently published (Luffi and Ducea, 2022), for which colleague P. Luffi received the "Ştefan Hepites" award of the Romanian Academy, evaluates the chemical paleo-mochometry techniques used to estimate crustal thicknesses in ancient orogenic zones formed in subduction zones and continental collision zones, and develops a new paleo-mochometric method. The complex method proposed in this paper is based on the quantitative correlation between a series of chemical components and their ratio, characteristics of igneous rocks formed in modern arcs in subduction zones, depending on the degree of differentiation of the magmas, and Moho depths at the location of magmatism. Applied to magmatic suites from the geological past, the models developed in the paper allow for the precise estimation of crustal thicknesses in fossil arcs and, thereby, a better understanding of the evolution of the continental crust. Because the arcs are in isostatic equilibrium, mochometers are also useful in reconstructing orogenic paleo-elevation.

The most recent synthesis paper mainly refers to the petrological knowledge on the magmatism of the Neogene-Quaternary interval, accumulated over 35 years, and emphasizes the connection with the tectonic evolution of the

CPR region. The paper refers to the role of early plate tectonic models and how these ideas have developed over half a century (Harangi *et al.*, 2024).

We present below the recently suggested model for the generation of alkaline basalts from the Carpatho-Pannonian area (Fig. 16; Harangi *et al.*, 2024).

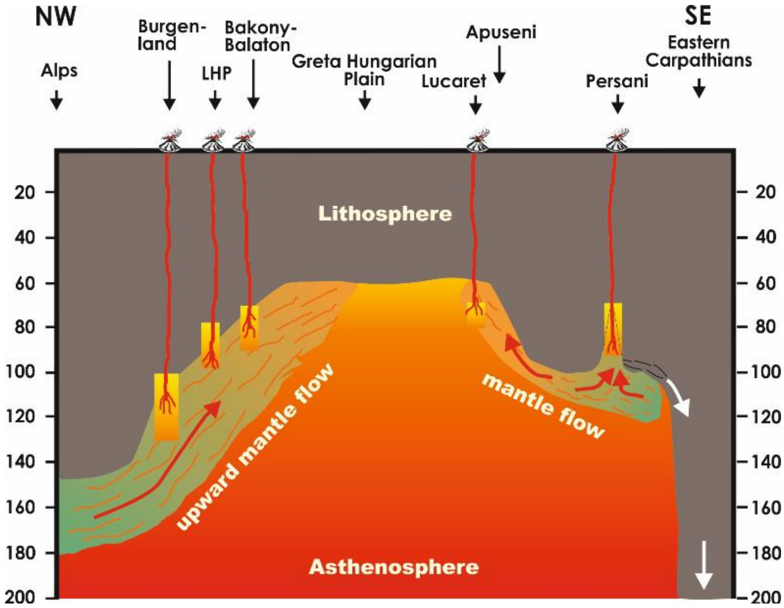

Figure 16. Proposed model for the Late Miocene to Quaternary alkaline basaltic volcanism of the Carpatho-Pannonian area. Decompression of the asthenospheric mantle induced abrupt changes at its boundary with the lithosphere. The melt columns are calculated from the chemical composition of the alkaline basalts (after Harangi *et al.* 2024 and associated references).

Volcanism is a phenomenon of magma generation at the Earth's surface, and the evolution of magmas in the upper mantle and crust is important for understanding this phenomenon. Volcanic rocks formed during eruptions can provide information, such as the time of formation, origin and evolution of magmas. High-resolution studies, investigation at the scale of the crystals of volcanic rocks components provide snapshots of these events, both qualitative and quantitative. Combined with other geological and geophysical data, these allow the formulation of geodynamic models. As has been demonstrated, the volcanic activity in the CPR does not form a classic volcanic arc developed during active subduction. Magmatism in the CPR is different from classic subduction-related volcanic arcs, the magmas forming by melting of a previously metasomatized lithospheric mantle. An intriguing question is why calc-alkaline volcanism occurred during the formation of lithospheric extension and during a post-collisional period and not concurrently and directly related to active subduction. Although there is no classical volcanic arc in the CPR, the term "back-arc" can be used for the Pannonian Basin only from a structural point of view. During the silicic ignimbrite volcanism from 18.1–14.4 Ma, explosive eruptions produced voluminous tephras, which covered large areas of Europe. Neogene calc-alkaline volcanic rocks are found in significant volumes throughout the CPR area between 16–0.03 Ma (Fig. 1). Alkaline basaltic volcanism formed distinct volcanic fields, especially in the peripheral areas of the CPR (Fig. 16). The youngest eruptions occurred at 100–30 Ka, partly in the still geodynamically active Eastern Carpathians. In conclusion, it can be stated that after 50 years of intensive research, many questions remain unanswered. Understanding and integrating the results obtained by different disciplines is crucial for a better constraint on the evolution of this tectonically complex area, and is essential for revealing its resources and assessing its potential natural hazards. The view presented in this paper on the Neogene-Quaternary magmatism in the CPR represents only a transitional stage that we hope will help in the future effort of knowledge.

Thanks

I would like to take this opportunity to thank all my colleagues with whom I have worked so far. Although the future does not seem "rosy", I hope that there will be a future generation of volcanologists and petrologists who will continue the work we started. I would like to thank the directors Dorel Zugrăvescu and Crișan Demetrescu, who supported our work and supported us in the most difficult circumstances, as well as all the other colleagues in the institute with whom I had joint activities and of course the Sabba S. Ștefanescu Institute of Geodynamics of the Romanian Academy, which provided a favorable framework for our activity. I would like to thank my colleague Peter Luffi for his suggestions for improving the text.

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