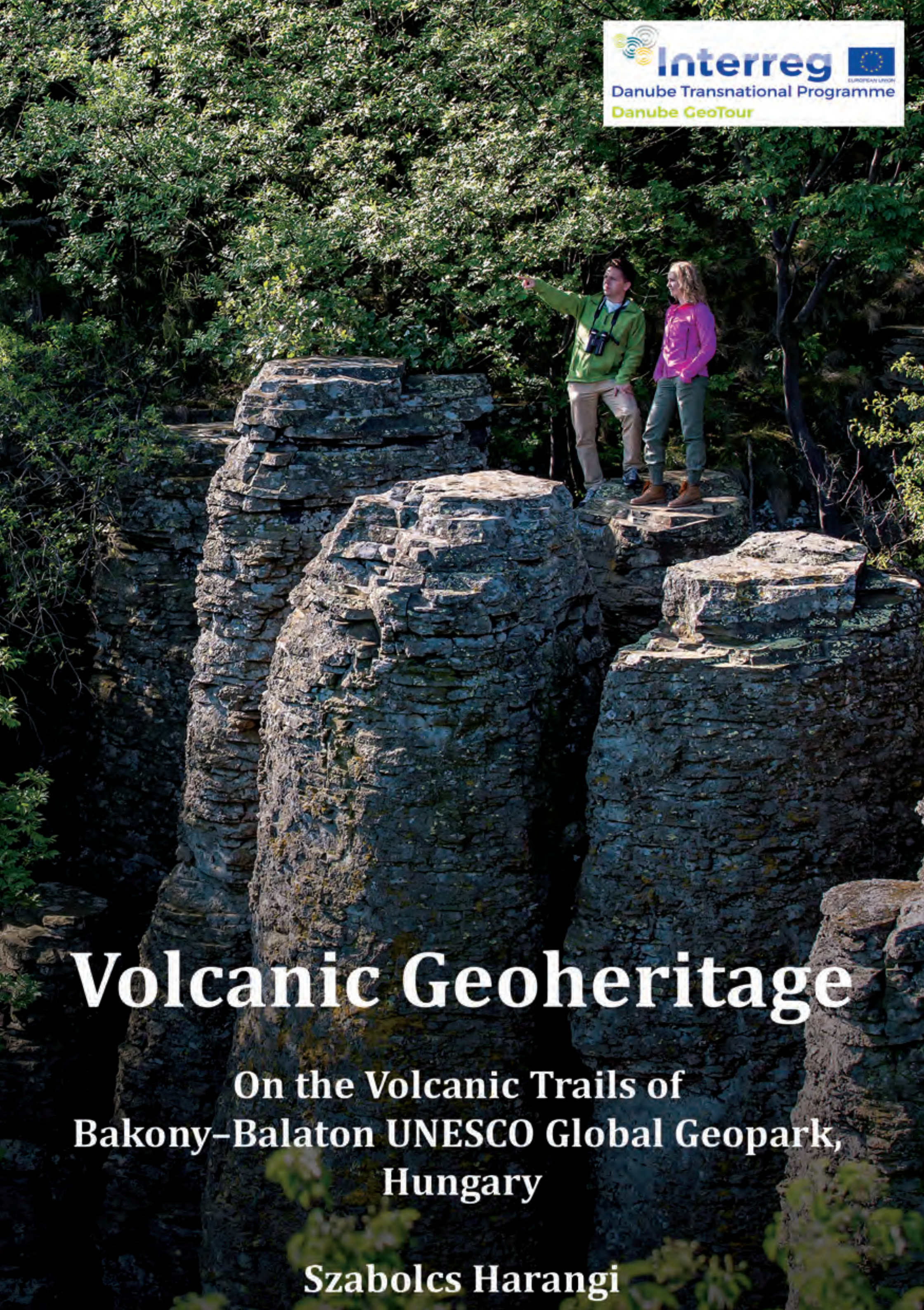


Interreg
Danube Transnational Programme
Danube GeoTour

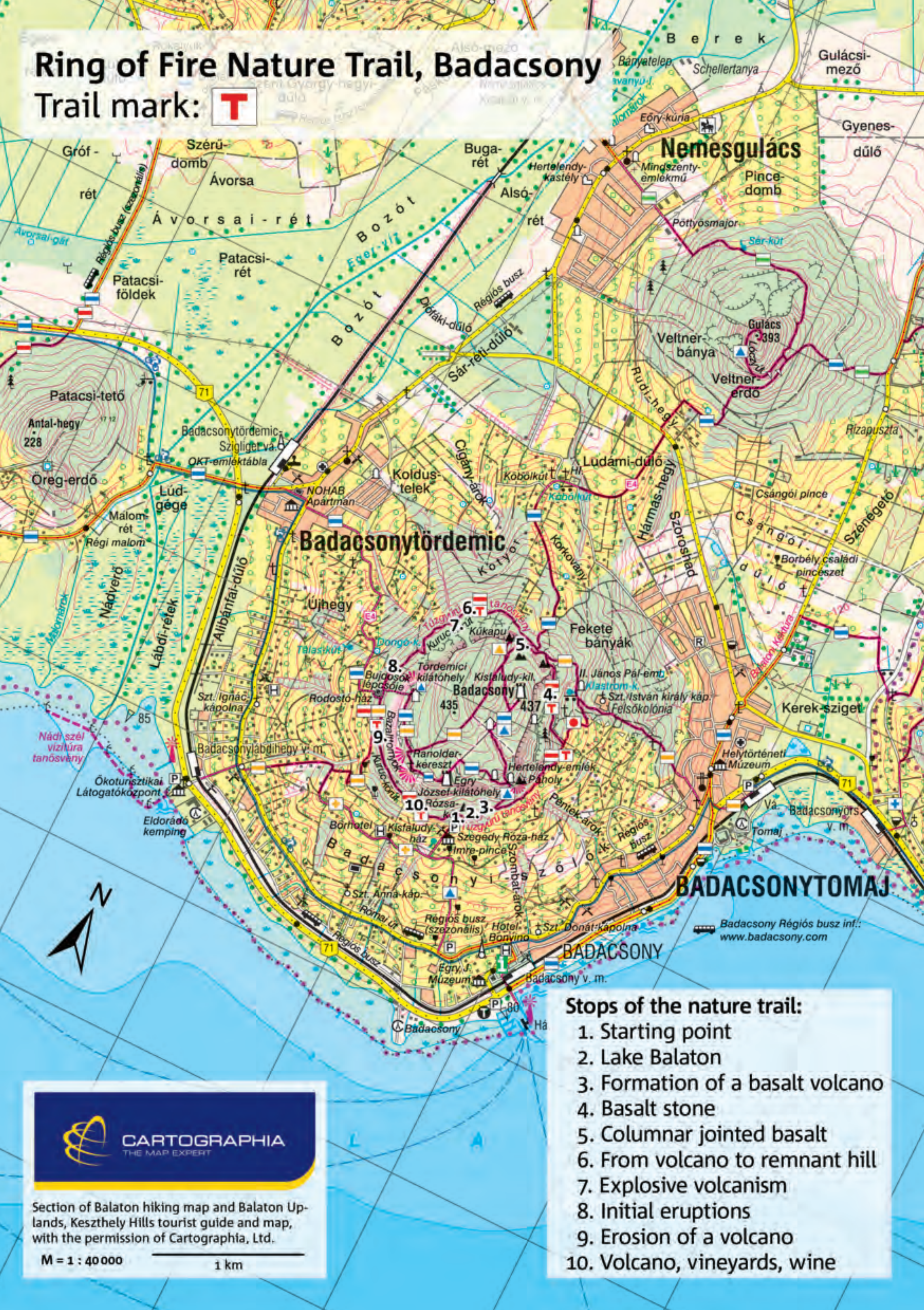
Volcanic Geoheritage

On the Volcanic Trails of Bakony–Balaton UNESCO Global Geopark, Hungary

Szabolcs Harangi

Ring of Fire Nature Trail, Badacsony

Trail mark: T



Stops of the nature trail:

1. Starting point
2. Lake Balaton
3. Formation of a basalt volcano
4. Basalt stone
5. Columnar jointed basalt
6. From volcano to remnant hill
7. Explosive volcanism
8. Initial eruptions
9. Erosion of a volcano
10. Volcano, vineyards, wine

CARTOGRAPHIA
THE MAP EXPERT

Section of Balaton hiking map and Balaton Uplands, Keszthely Hills tourist guide and map, with the permission of Cartographia, Ltd.

M = 1 : 40 000 — 1 km

Szabolcs Harangi

Volcanic Geoheritage

On the Volcanic Trails of Bakony–Balaton UNESCO Global Geopark, Hungary

Photos: Szabolcs Harangi (2,3,4,5,6,7,9,10,11,13,15,17,18,26, 28,30,32,33,35,38,40,41), USGS (12,23,31,39), Károly Németh (1,14,34), Balázs Kiss (8), Eszter Mészáros (16), Goran Pavic (20), Hateg UGGP (21), Barnabás Korbély (29), Ildikó Ipach (30), Éva M. Jankovics (38), Paul Cole (37), Szenthe Zoltán (címlap)

The English text was reviewed by Petra Krasszer

Concept and Design: Lapillus Bt.
Edited by Péter Jacob

Hiking maps: Cartographia, Ltd.

Balaton Uplands National Park Directorate
Editor-in-charge: Zoltán Puskás, Director

Csopak

2019

Innovariant Nyomdaipari Kft., Szeged
ISBN 978-615-80144-7-2


1.


2.

Volcanoes and volcano detectives

The strong arm grabbed the bellows and the delivered fresh air in the forge agitated the coal and sulphur material, while sparks and dense acid smoke emerged from the chimney. The hot, incandescent metal sword blade was placed on the anvil and the hammer fell with a full swing. Each hit triggered large sparks. The smithy in deep of the hill was hidden, but people could see the delighting sparks and felt the suffocating dense gases coming out of the holes on the top of the hills (**1, 2**). Based on these observations, it was clear to them that somewhere deep within the mountain, weapons of gods are carefully prepared with the guidelines of the god of fire, the smith-god, Vulcanus. His smithy was believed to be situated underneath Mount Etna or one of the volcanic hill of the Aeolian Islands. The naturalists documented everything that they could observe and explain the phenomena according to the beliefs of the given era. The present interpretation, however, differs from the ones given by the Greek and Roman naturalists. We know that these phenomena are controlled by the processes occurring in the magma chamber*, but these hills are called '*volcanoes*' all around the world in memory of the ancient beliefs. In the Hungarian language, however, these hills have another name, '*Tűzhányó*', which means a place spewing fire (**1**).

The volcanic processes date back not only till the Greeks and the Romans, but are one of the most important processes of the Earth, to the very beginnings, i.e. to about 4.6 billions of years. Volcanism had a major role in the formation of the Earth's crust*, the hydrosphere and the atmosphere. Volcanic activity has still a major influence on the present environment.

Mankind has always had a close relationship with volcanoes. The footprints of our predecessors, the Australopithecus afarensis, were discovered in a 3.5 million-year-old volcanic ash* deposit at the East African Rift Zone. Well after this era, the modern humans, the Homo sapiens, left Africa around 80 thousand years ago. They migrated towards east when a huge volcanic eruption occurred in Sumatra. That was the largest known eruption in the past several millions of years. The Indonesian Toba volcano ejected a volume of about 2,800 cubic kilometres volcanic material through several tens of kilometre long fissures. There was full darkness for several days and everything was covered with grey pumiceous ash deposit. Several meter thick volcanic material accumulated at many parts of the Malaysian peninsula and in India. Results of genetic research show a severe reduction in the size of the total human population at that time, called genetic bottleneck, that is widely connected to this volcanic eruption. This theory is still strongly debated. It is a fact that human survived this cataclysmic volcanic supereruption and since then the human population has continuously been increasing and has exceeded the number of 7 billion.

3.

4.

However, the strong relationship between humans and volcanoes have not stopped. Presently, 10% of the total human population, i.e. more than 700 million people live close to a volcano, which had a major eruption in the historical time and presumably will erupt again in the future. This would certainly cause a crisis with unforeseeable consequences. Therefore, there is a strong need in people to understand the nature of the volcanic activity better because this knowledge is essential to conduct effective forecast and preparation. The work of volcanologists, the modern naturalist observers of volcanoes, is not only pure basic research into the work of volcanoes, but their studies are aimed at forecasting events and thus saving people and resources. However, a volcanologist's work is not easy. A volcanic eruption lasts for a short time but the quiescence time* is much longer. The point is to understand what the triggering mechanism is. Answers are required, when the magma* starts the ascent, when the eruption occurs, how fast this process is and what precursor signs are given that can be detected by sensitive instruments. Volcanologists have to have an insight beneath the volcanoes (**6**). Presently, there are rapidly growing techniques, near-real time well-deployed instrumental networks and also analytical tools, which can be used to detect subvolcanic magma bodies. However, in order to understand a given volcano better, i. e. how it worked in the past, how many times it erupted, what the eruptions were like, a researcher needs witnesses from the past. These witnesses are the volcanic formations, the products of eruptions. The structure of the volcanic deposits or lava rocks, the chemical and mineralogical compositions, even the texture of the crystals can tell how magma generated in the depth, what happened in the magma chamber* and how the eruption took place. This is a kind of detective work (**7, 8**): collecting mosaic of observations, interpreting them and finally make conclusions, producing a model to explain natural processes that we could not see but are likely to occur again. Such forensic studies interrogate lava rocks and volcanoclastic layers to reveal how magma erupts to the surface, why the eruptive products are so different, what physical processes control the eruption style, why magma explodes many times, while in other cases only lava is poured out from the vent*. The shape of the volcanoes also reflects the style of eruptions characteristic of the given volcano: do they have high, conical shape or nothing else just a deep hole remained? Only one single volcano developed or many small ones in an extended area? Why do volcanoes build up and then collapse? Microscopic study of the rocks can reveal additional information about the evolution of the magma. Describing the appearance of crystals, determining their chemical composition, even the compositional variation with crystals could help to constrain the pre-eruptive condition and the magma chamber processes which led to the ascent of the magma and to the final eruption. Presently researches are also devoted to quantify the timescale of these processes. For this, tiny crystals are analysed and based on the compositional values of isotopes*, the eruption history as well as the lifetime of the magma reservoirs* and also the magma ascent rate can be determined. The volcanic products, i.e. volcanic rocks, cliffs etc. are important witnesses and the object of thorough studies.

The Carpathian–Pannonian Region and the areas of the Danube Region in central Europe have an internationally recognized volcanic heritage formed by various volcanic activities in the last 20 million years. Volcanism is closely connected to the plate tectonic processes and the formation of the Carpathian Basin, or Pannonian Basin as Earth Scientists call it. One of these particular volcanic activities occurred in the area of the Bakony–Balaton UNESCO Global Geopark between 2.5 and 8 million years ago. The unique volcanic landscape along with the volcanic formations provided a strong basis to establish the geopark and it is also a natural laboratory for volcanologists to better understand this style of volcanism.

Within the framework of the Danube GeoTour project two former nature trails have been renewed, a new volcanological trail has been established and altogether 31 new explanation panels (**3, 4, 5**) have been placed along the trails in the Bakony–Balaton UNESCO Global Geopark.

This booklet provides additional information to better understand the background of the volcanic heritage inviting the visitors to a kind of volcano detective work.


PIROKLASZT-ÁR
PYROCLASTIC FLOW
TŰZ ÚTJA TANÖSVÉNY
ROUTE OF FIRE NATURE TRAIL
11.
Interreg

6.


Interreg

7.


EXPLOSIVE VOLCANISM
Interreg

8.

How do volcanoes work?

What does a rock tell us (**10, 11**)? At first glance, one cannot see too much, particularly in case of a basalt*, where only a few larger crystals might be observed in the homogeneous, dark groundmass. In order to understand the origin of the rock, it is crucial to know where it came from, i.e. in what geological unit it can be placed back. The reconstruction of a volcanic process should start with the close investigation of an outcrop (**9**), where contacts of rock units can also be recognized. The structure of the beds, their appearance can reflect their formation. Distinguishing a massive lava rock from a volcanoclastic deposit is quite easy. The latter one contains many small rock fragments which

could have originated from an explosive volcanic eruption and in this case, it is called pyroclastic rock*. Nevertheless, it might have also a secondary origin, i.e. reworking of a set of volcanic rocks during erosional processes.

The pyroclastic rocks have distinctive characteristics: the size and the lithology of the clasts, their distribution in a bed – all of these can be used to reveal

how the volcanic eruption occurred in the past. Among the rock fragments, particular importance is attributed to the ones which came from the magma. These clasts are called juvenile*. The style of the volcanic eruption and as a result, the shape of a volcano is primarily controlled by the physical and chemical properties of the erupted magma. Determination of the chemical composition of the juvenile clasts, description of their crystal content can tell us what kind of magma caused the volcanic eruption. These observations can be used to infer the viscosity of the magma, i.e. the fluid's resistance to flow. Magmas with high SiO_2 and crystal content and low temperature have higher viscosity, which means that they have more resistance and thus flow more slowly. The exsolved gas bubbles can grow and escape harder from a stickier liquid, which results in greater internal pressure leading to a violent explosive eruption. Basaltic magmas, however, are less likely to erupt explosively since gas bubbles can easily leave the less viscous, i.e. more fluid magma. Explosive disruption usually occurs in the upper part of the magma body (**12**), where gas bubbles accumulate. This occurs when the internal pressure of the magma foam exceeds the tensile strength of the solid rocks above. If this is the case, we can see this in the juvenile clasts. There are volcanic materials which look like a petrified sponge (**13**): they contain abundant vesicles separated by thin rock walls. In addition, there are volcanic rocks, called pumice, which are floating on water since they have very low density due to their high vesicularity. Based on the appearance of such rocks, it is no question that they come from a foamy magma, i.e. from the upper part of the explosively disrupted magma body.

However, explosive eruptions may also be triggered by the mixing of hot

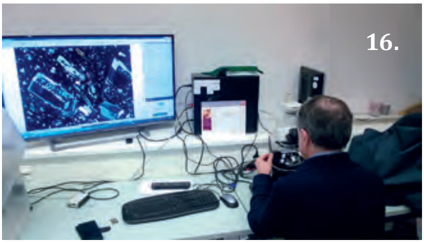
12.

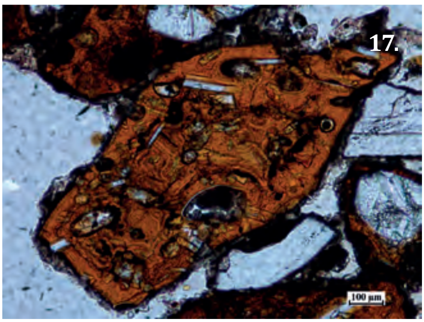
13.

14.

15.

magma and cold water or water-saturated sediment. This process is similar to a severe accident that might occur in a nuclear power plant during a fuel–coolant interaction, i.e. mixing of molten nuclear-reactor fuel rods with water in a nuclear reactor core following a core-meltdown. During such an interaction, water in a superheated condition rapidly transforms into steam that leads to a violent explosion. Such process is associated with major increase in volume and this rapid expansion results in the disintegration of the material at the contact zone, i.e. both the magma and the surrounding rocks fragment into tiny particles and blow out to the surface (**14, 15**). Sometimes no particles representing the magma are incorporated into the erupted material, instead it contains only rock


16.



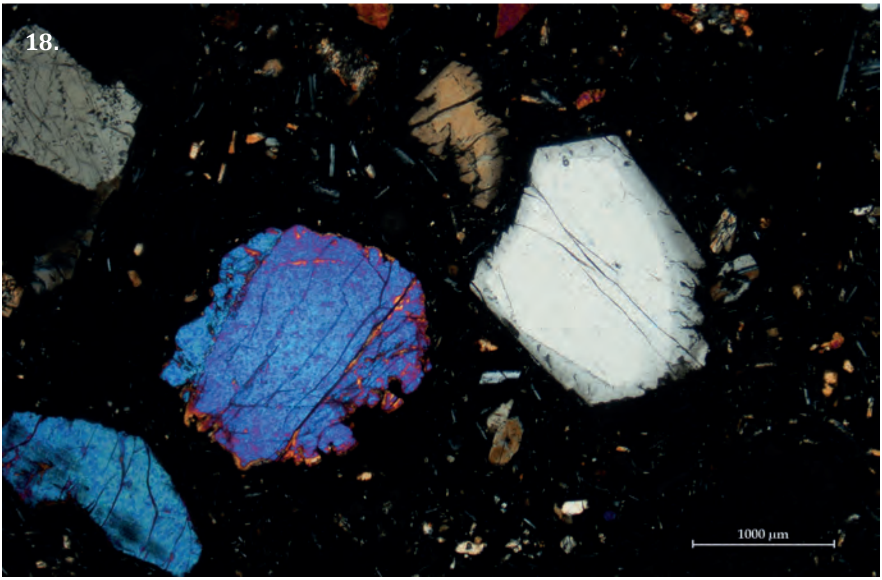
17.

fragments from around and above the magma body. This eruption style is termed phreatic* and is one of the most dangerous volcanic events, because this can happen without any precursor signs (e.g., tragic event at Ontake, Japan in 2014). If the erupted material comprises both juvenile and lithic clasts, it is called a phreatomagmatic* or hydrovolcanic eruption. Since the melt fraction of the magma undergoes rapid cooling during such an interaction, the tiny juvenile particles are often glass shards. The eruption cloud contains abundant vapour, therefore a volcanic deposit with a typically 'wet' structure accumulates on the surface. Using the tools of physical volcanology recognition all of these features help to reconstruct whether such violent explosion occurred in a given area.

Another important part of the volcano detective work focuses on the subvolcanic magma evolution. Understanding the deep processes is as important as revealing the mechanism of the volcanic eruptions. The key-questions are what could trigger the ascent of magma leading eruptions and how physical and chemical processes in the magma reservoir* and the vent control the style of volcanism. There has been major progress in volcanology, which brought scientists closer to answer these questions. Petrology (**16, 17**) is a pillar discipline in which volcanic rocks are carefully investigated and then the observations are linked to processes occurring during eruptions. In basaltic systems, analysing the main mineral phases (**18**), such as olivines* and pyroxenes* can lead to quantify the speed of the magma ascent and to describe what may have been happening in the magma reservoir before eruption. In addition, analyses of the chemical composition of the basaltic magma make it possible to constrain the conditions of the magma generation process, which is fundamental to the birth of a volcano. This is real detective work: nobody could see these processes in the depths so we need observational mosaics to put together the story. We need experimental work to test which minerals at which conditions can be stable in the magma. The theoretical models can be tested and refined by observations and experiments and finally we can get a model to explain the natural processes. For example, we know from the high-resolution chemical variation within crystals that volcanic eruptions could often be triggered by new, hot magma emplacement in an already low temperature, almost solidified magma mush and this can lead to reactivation and eruption. Such processes certainly have precursor signs, which can help in forecasting eruption.

The volcano detective work is not just a pure basic science. Knowing how volcanoes work from the magma generation up to the eruptions is fundamental to evaluate pre-eruption signs and to save people's lives and resources. However, the necessary knowledge can be acquired mostly in peacetime, i.e. during quiescence or by studying inactive volcanoes.

18.

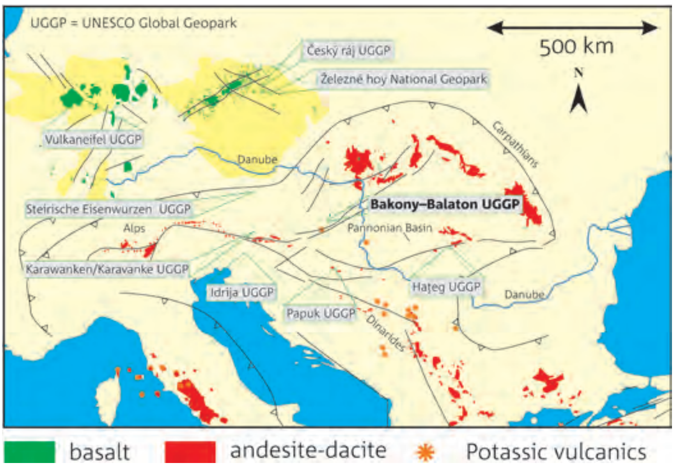


Volcanic eruptions in the Danube region and in the Carpathian Basin

In Europe various volcanic activities have taken place for the last 20 million years (**19**). These were fed by various magmas ranging from basaltic* through andesitic* to rhyolitic*. The largest eruptions in Europe during this period occurred in the Carpathian basin. About 14 to 18 million years ago, large-volume rhyolitic magmas erupted close to the present Mátra—Bükk area. The volcanism must have changed the environment considerably, volcanic ash fall was detected even more than 1000 km away and this volcanic material was preserved in lake sediments. This was followed by the development of andesitic to dacitic* volcanic complexes from the Börzsöny and Visegrád Mts. to the east and then towards southeast down to Harghita Mts. This type of volcanism started around 16 million years ago and eruptions occurred even in the last tens of thousands of years. The youngest volcano of the Carpathian-Pannonian Region is Ciomadul at the southernmost end of Harghita with the latest eruptions about 30 thousand years ago. Besides, there were other, less destructive volcanic activities in the Carpathian Basin, which formed extensive basalt volcanic fields. This long volcanic history along the Danube region can be mostly connected to the thinning of the continental crust and the lithosphere*. One of the best examples of this plate tectonic process is the Carpathian Basin or the Pannonian Basin as the Earth Scientists call it.

This long volcanic history formed spectacular volcanic heritage found at many of the geoparks along the Danube region. The Vulkaneifel (Germany) was one of the founders of the European Geopark Network in 2000. This area is famous for the beautiful rounded lakes,

Fig 19.

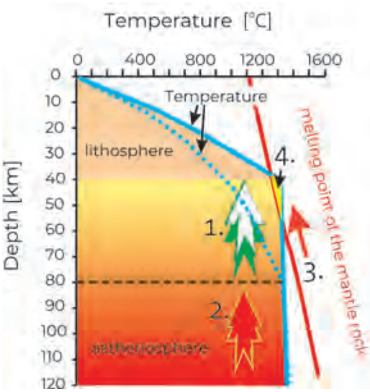


which are actually places of the maar* volcanoes. More than 350 eruption centres were formed here with the last eruption around 10 thousand years ago. A partly contemporaneously volcanic activity took place also in the area from northern Czech Republic to southern Germany and southern Poland. Many of these volcanoes have been strongly eroded and only their root zones, i.e. their necks were exposed. A fine example of them is the Trosky cliffs in the Český ráj UNESCO Global Geopark. Columnar jointed basalts (**20**) with mantle-derived peridotite* xenoliths from this Miocene* volcanism can be found also in the nearby Železné hoy National Geopark.
Another interesting volcanic feature is exposed in the area of the Papuk Geopark (Croatia), where the columnar jointing with quadrangular and pentagonal geometries was formed in a rhyolitic shallow depth magma intrusion. The Haţeg UNESCO Global Geopark's establishment was primarily based on the dinosaur fossils, but a volcano house (**21**) has recently been built in the visitor centre. Exhibitions and outreach activities here help to understand not only the volcanic processes, but also the causes why volcanic eruption in this area occurred in the geological past.
Probably the most varied volcanic activities for the last 20 million years in Europe took place in the relatively restricted area of the Carpathian-Pannonian Region, which makes it a kind of volcanological natural laboratory. Volcanism was the most intense during the period from 10 to 16 million years ago, but the last eruptions, happening some ten thousand years ago, indicate that the process might continue in the future.
Probably, the most spectacular eruptions were associated with the development of the basalt volcanic fields. The Bakony–Balaton Upland volcanic field comprises almost 50 eruption centres (shield volcanoes*, scoria cones*, tuff rings*, maars) developed from 8 to 2.5 million years ago. Similarly remarkable volcanic features provide the geoheritage basis for the cross-country Novohrad-Nógrád UNESCO Geopark (Hungary, Slovakia) and for the Steirische Vulkanland in Austria. There has also been a major effort to increase the visibility of the basalt volcanic heritage of the Persani Mts., Romania leading to a Geopark establishment.


20.

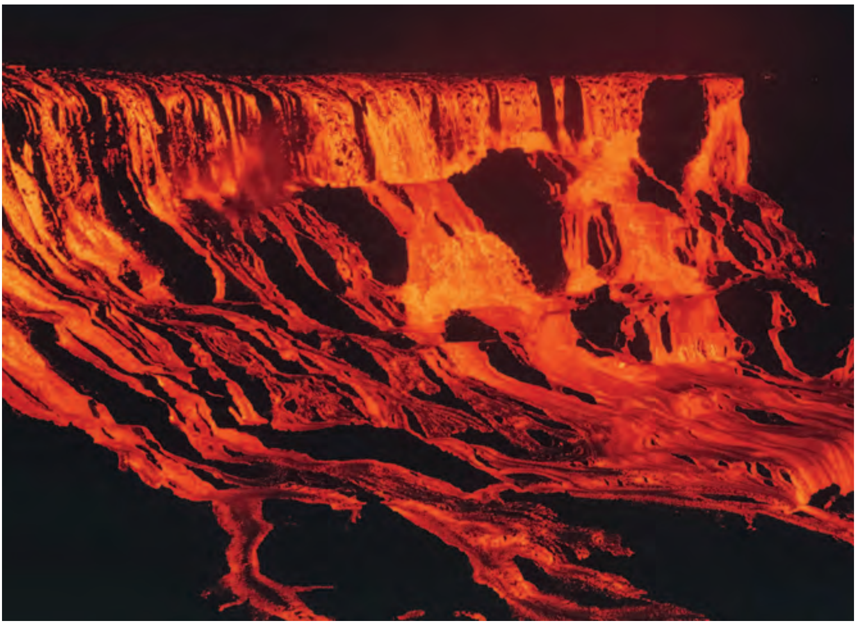

21.

Fig 22.



The receipt of magma generation:

When lithosphere becomes thinner (1), the underlying asthenosphere material (which is solid, but ductile and thus capable of moving) is getting to move upwards (2). As pressure drops, its melting point decreases (3) and at a certain depth, this could be lower than the mantle temperature: this is when melting starts (4)!



Volcanism from the source to the surface

The volcanic activity, the development of a volcano is not accidental. The only place where a volcano can grow is where there is a possibility for magma generation in the depth, i.e., at the upper mantle* and where the magma can break through the rigid crust. Although this sounds quite simple, it is rather a rare and particular situation. The point is that most magmas have physical properties that do not allow them to reach the surface. In order to understand the cause of volcanism, we have to descend into the Earth's interior through the vent of a volcano down to the site where magma is formed.

The Earth's interior is already fairly well known based on the results of experimental petrology and seismic velocity values. It is clear that except for the liquid outer core, the inner part of the Earth is composed entirely of solid material. The pressure and temperature conditions are also well constrained and the variation of the melting point with pressure is determined for various rocks thought to build up the interior of our planet. The melting point of the mantle rocks strongly increases with increasing pressure. Putting all of these together, we can state that a significant amount of melt is not present beneath the crust and magma could be generated only in a restricted depth range of the upper mantle*. Melting takes place when the ambient temperature exceeds the melting point of a solid material (**22**). It usually does not happen in the upper mantle, thus, the question is how this condition alters. For this, a dynamic process is required, i.e. the upward movement of the asthenospheric material. The asthenosphere* is part of the upper mantle beneath the lithosphere and it is made up of a highly viscous solid material, which is mechanically weak and has ductile deformation. This allows buoyancy-driven slow flow derived from temperature difference that affects density. As a result of upward movement, the pressure-dependant melting point of the mantle material decreases and at around 60-120 km depth it could become lower than the ambient temperature and melting starts. However, this could happen only if some water is dissolved in the mantle rock or other, more fusible rocks are also part of the upward moving asthenospheric material.

The question remains how upward asthenospheric flow could occur. This can be induced by the thinning of the overlying lithosphere or the quick depth change of the asthenosphere–lithosphere boundary. The partial melting of the mantle peridotite* results in basaltic magma. As its volume exceeds a certain level, the low-density magma could segregate from their source and move upward. But this is still not a simple process, since there is a vast amount


Stops of the nature trail:
1. Starting point
2. Volcanic heritage
3. Wash-house
4. Basalt lava plateau
5. Basalt
6. Scoria and spatter cone
7. Lakes on the lava plateau
8. Basalt lava
9. Firework eruption
10. The youngest basalt volcano
11. Pyroclastic flow
12. A rock fragment from the mantle
13. Monogenetic volcanic field
N
Hegyesd
Monostora
Szentbékkálla
Mindszentkálla
Kerék-rét
Falumúzeum
Hámori-domb
Szt. Péter-hegy
Péter-hegyi-dűlő
Kender-telek
Macska-domb
Herkentyű
234
Keresztfai-telek
Kis-Boncsos
Kis-Almádi
Sa-hegy
Alsó-rét
Sátormapuszta
Volt Vashámor malom
Eger-víz
Büdös-kút
Forgósi-dűlő
Kis-Hegyesd
Sátorma
Mécsár
Péter-hegy
354
Sátorma-hegy
356
Közép-hegyi-erdő
Nyír-meggy
303
302
10.
Füzes-tó
Kopácsi-hegy
301
295
Gyertyános
Karám
Felső-erdő
Sátormai-erdő
Hosszú-hegyi-dűlő
Kotyor
Hottó-kút
Hottó-kúti-völgy
Csókó-kút
Kút-fői-forrás
Bükk-szár-völgy
Mély-völgy
Régi sikló
Magyal
Farkas-tető
Mates-hegy
251
Téglaházi-dűlő
Veléte
Tűz útja tanösvény
Eresztvény
261
Öreg-hegy
Bocskor-kút
8.
Keleményes-kő
Hajagos
Hári-domb
Láz-tető
344
Köves-hegyi nyereg
Köves-hegy
344
Sanyarú-Kő-hegy
Kőtenger
Lovaspóló-pálya
Kő-h.
11.
12.
Veletei palotarom
Kis-hát
Bonta-tó
369
Homoki-dűlő
Szentimrepuszta (Sanyarúpuszta)
Kőtenger Panzió
Helytörténeti múzeum
Napraforgó Pajta
Öreghegy
Öreg-hegyi-kút
Régi strand
Kövesk...
Töttöskáli templomrom
Felső-rét
Viszkelén
Devecseri-hegy
Mátyás-domb
Kisfaludi templomrom
298
Garany-t.
283
Kopasz-hegy
302
13.
Tufabánya
Bács-hegyi-dűlő
Bácsi-kápolna
Fekete-Bács
Pipa-h.
260
Öreghegy
Parlag-rét
BALATON-FELVIDÉKI NP
Nyúlszalasztó
Kerekikáli templomrom
171
Kerekifarm
Kopár-rét
Honcsokos
Varga-verem
Alsó-rét
Sásdi-rét
Alsó-Sásdi rét
Sásdi-legelő
Theodora-Kékkő tanösvény
Idő Ösvénye
Mindszentkállai-árok
Sásdi-patak
Máté-forrás
Simon-f.
Kornyi-tó
Szoborcsoport
Káli-medence
Theodora Ásványvízüzem
Fekete-föld
Felső-
Alsó-
Tüskés
Theodora tanösvény
Urán-kút

Route of Fire Nature Trail, Hegyestű–Kopasz Hill

Trail mark: T

CARTOGRAPHIA
THE MAP EXPERT

Section of Balaton hiking map and Balaton Uplands, Keszthely Hills tourist guide and map, with the permission of Cartographia, Ltd.

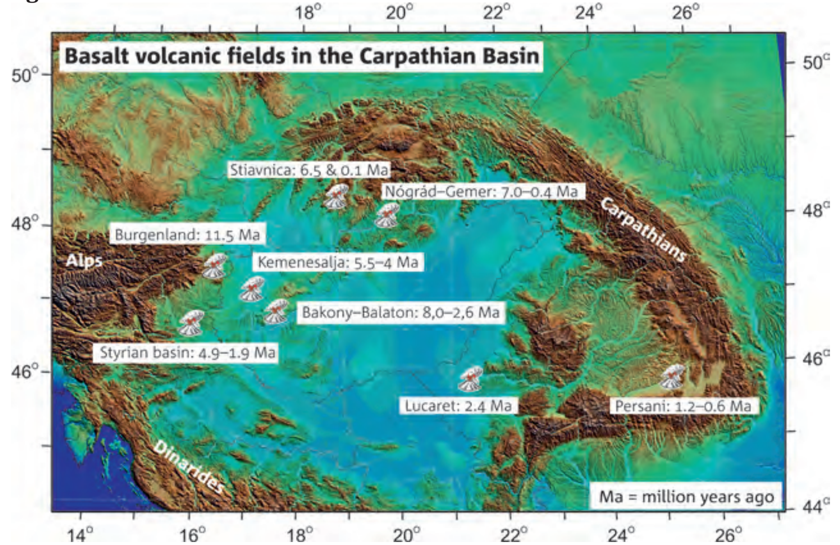
M = 1 : 40 000 — 1 km

of solid material, particularly the rigid lithosphere above it. The buoyancy force coming from the density-difference could drive the magma ascent until reaching the continental crust*. At this depth, the density-contrast disappears due to the major change in the lithology (the upper mantle consists of dense peridotite, whereas the lower crust is basaltic and the upper crust is granitic in bulk composition and they have less density). Therefore the majority of basaltic magma stalls beneath the crust. Nevertheless, we know that there is volcanism, so something is necessary to drive basaltic magma up to the surface.

The magma is not made up entirely of liquid material. It also contains solid crystals and additionally there are low amounts of volatile* phases dissolved in the melt. The volatile phases are water, carbon-dioxide, sulphur-dioxide, hydrogen sulfide and various halogens. At greater depth, they are dissolved in the melt, but as the magma ascends and pressure decreases (pressure is dependant on the thickness of the material above the magma) the volatiles tend to dissolve from the liquid phase. This also occurs during progressing crystallization in the magma chamber residing at shallow depth of the crust. The change in solubility means transformation into gas phases, i.e. appearance of gas bubbles in the melt. This is associated with volume increase, but in a closed system it causes a dramatic increase of internal pressure. A further consequence is the overall decrease of the magma density and therefore an increase of the buoyancy force. This could be enough to crash the solid rocks above it, allowing the further upward movement.

The ascent rates of the magma show great differences. A Hungarian research group determined how fast a basaltic magma could move and concluded that it could penetrate the entire crust within days! This is very-very fast; just imagine the eruption forecasting. How many days do the volcanologists have after detecting the first signs of magma movement? If there are no sensitive instruments, volcanism may start without any precursory indications. However, this is the worst-case scenario. Another option is that magma accumulates at the crust-mantle boundary. As the Hungarian scientists pointed out based on the careful studies of crystal assemblage in basaltic rocks, such a process is associated with numerous replenishments of new magma body for a prolonged period. The fundamental question is: when could a batch of magma leave this magma reservoir and reach the surface? The remaining question is how the magma will erupt, i.e. whether a lava flow or an explosive eruption will occur (**23**)? Interrogation the volcanic rocks along the Nature Trails could reveal the past volcanic stories.

Fig 24.



Basalt volcanic fields in the Carpathian Basin
Stiavnica: 6.5 & 0.1 Ma
Nógrád–Gemer: 7.0–0.4 Ma
Burgenland: 11.5 Ma
Kemenesalja: 5.5–4 Ma
Bakony–Balaton: 8,0–2,6 Ma
Styrian basin: 4.9–1.9 Ma
Lucaret: 2.4 Ma
Persani: 1.2–0.6 Ma
Alps
Carpathians
Dinarides
Ma = million years ago

Fig 25.

Szőlőhegy, Csékút
Kabhegy
Peres-hegy
Öcshegy
Kőhegy
Ollak
Gyertyánoshegy, Pula
Kistódomb
Tikhegy
Somhegy
Agártető
Bondoró
Gyertyánoshegy, Barnag
Királykő
Halom-hegy
Sarvaly
Kovácsi-hegy
Véndek
Haláp
Boncostető
Fenyveshegy
Prágahegy
Hegyesd
Füzes-tó
Balázstető
Szebike
Kopácsi-h.
Feketehegy
Tátika
Sátorma
Hegyestű
Hajagos
Eresztvény
Horoghegy
Tihany
Láztető
Csobánc
Kopasz-hegy
Várhegy
Fertős
Szent György-hegy
Kis-Hegyestű
Harasztos
Sabar
Gulács
Tóti-hegy
Lake Balaton
10 km
Szigliget
Badacsony
Kopaszhegy
Lava rocks
Pyroclastic rocks
Várhegy, Fonyód

What kind of volcano?

When most people think of a volcano, it's a high mountain with a perfect conical shape that comes into their mind. However, if we look around the Bakony–Balaton Upland area, we cannot see any remnants of a large volcano. Instead, there are many, almost 50 small volcanic edifices (**25, 26**) distributed at an area of about 3.500 km^2. Volcanologists did not count each of them as an individual volcano, but the whole area is considered a single volcanic item in the catalogue. It is called a *volcanic field* and many times, they described as '*monogenetic*' (**24**). What does a monogenetic volcanic field mean? Instead of a single central volcano having only one or closely packed vent structure where magma ascends and eruptions take place, there are many eruption centres in an area covering several hundred or thousand square kilometres. The size of the Bakony–Balaton Upland volcanic field is larger than that of the Eifel and comparable to many well-known volcanic fields worldwide (such as Springerville, Pancake, San Francisco in the USA). On the other hand, there are much fewer volcanic centres here compared with the Eifel, where more than 300 volcanoes were recognized or the Springerville, where there are more than 400. A similar volcanic field is the Pancake in Nevada, USA, where 75 volcanoes are located in an area of 2500 km^2.

What do these numbers mean and why are these volcanic centres distributed in such an area? In a volcanic field, basaltic magma always finds a different path through the crust to reach the surface. The single eruption events are often separated by long quiescence time which may last for tens of thousands or even hundreds of thousands of years. Thus, it is widely considered that each volcanic eruption can be connected to a single magma generation event in the upper mantle and the basaltic magma erupts within a short time. Indeed, we could find different chemical compositions and distinct petrological features of the basalts within the Bakony–Balaton Upland volcanic field. The Badacsony, Csobánc and Haláp are very close to each other, but their basalts are clearly different. This can be explained either by the distinct conditions of melt generation, such as different degree of melting or by the magma differentiation (crystallization

26.

Eruption chronology of the Bakony–Balaton Upland volcanic field

7.8–8.0 million years ago: Tihany, Hegyestű

4.5–4.7 million years ago: Szigliget, Tóti-hegy

4.1–4.2 million years ago: Halom-hegy, Hegyesd, Szent György-hegy, Szigliget, Sümegprága

3.8 million years ago: Hajagos, Halom-hegy, Fekete-hegy, Badacsony

2.5–3.6 million years ago: Kopácsi-hegy (Füzes-tó), Agár-tető, Bondoró, Szentbékkálla, Haláp

and mixing of magmas) in the magma stalling zone at the mantle-crust boundary (**27**). But how do we know when the eruptions took place?

The age of the volcanic events is determined by analyzing the radiogenic isotope* composition of the basalts. The isotopes of potassium and argon were used in this area. The potassium-40 (where 40 is the mass of the isotope) decays into argon-40 and calcium-40 isotopes and this radioactive* process lasts for a very long time. The half-life* is 1.251×10^{9} year, i.e. such a long time is required for a quantity to reduce to half its initial value. This is an advantage for the geochronologists, since this means that we could detect both the parent and the daughter isotopes in the rock. Measuring the potassium-40 and argon-40 isotopes and considering the half-life of the decay, it is possible to calculate how much time has elapsed since the formation of the given rock.

Now, we have a good picture of the eruption chronology in the Bakony–Balaton Upland volcanic field, thanks to the thorough geochronologic studies. The first eruptions formed the maar volcanoes at Tihany and the Hegyestű volcano at ca. 8 million years ago. Then, a long quiescence time occurred, at least according to our present knowledge. There was no volcanic eruption for more than 3 million years! Just think about it, 3 million years without volcanism, everything being quiet and peaceful, like presently!

Would anybody think in such a calm situation that further eruptions could take place in the future? In the historical time, such volcanic events have been quite rare. An example for this is in the area of the Lanzarote UNESCO Global Geopark (Canary Islands), where a major volcanic activity started in 1730, although no eruptions took place in the island for more than 10 thousand years. These unexpected natural processes, which could significantly affect both the environment and the society are called low-probability, high impact events. Timescale of volcanism differs from what people generally believe and therefore eruptions occasionally occur 'unexpectedly'. If we have no knowledge of or no experience about something throughout history, it is not sure that it could not occur in our lifetime. But let's go back to the eruption history of the Bakony–Balaton Upland volcanic field!

The renewal of the volcanism took place ca. 4.5-4.7 million years ago, when volcanoes of Szigliget and Tóti-hegy were active. Further eruptions occurred after a few hundred thousand years of quiescence time. Finally, the scoria cone of the Kopácsi-hegy and the complex basaltic volcano of Bondoró developed during the last volcanic period at ca. 2.5 million years ago. The long quiescence since that time indicates, even for the volcanologists, that no more volcanism could be expected here. Nevertheless, there has already been a 3-million-year long repose time… Who knows whether such a situation will not repeat itself?

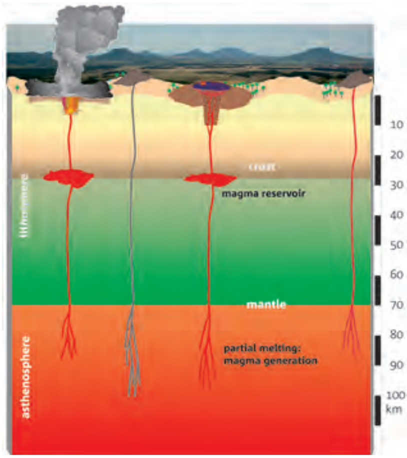


Fig 27.

The geochronological data suggest that this volcanic field was active or potentially active for more than 5 million years. In contrast, the lifetime of a high, conical central volcano is less than 1 million years. The relatively low number of volcanic centres in the Bakony–Balaton Upland volcanic field may suggest either limited potential for magma generation in the upper mantle, or the fact that the basaltic magmas remained in the mantle-crust accumulation zone. Probably they did not have enough buoyancy force to ascend to the surface. Further research is necessary to explain the reason for this. Finally, we have to explain what a monogenetic volcano means! The well-known volcanoes, such as the Etna or the Merapi erupt regularly with relatively short repose times. The volcanoes of a volcanic field behave differently. Volcanism lasts for days or maximum for a couple of years and then there are no further renewal eruptions. For instance, the Badacsony will never erupt again! Similarly, the Parícutin volcano in Mexico that formed in a cornfield in 1943 and was active for 9 years is already considered inactive and presumably will never erupt again! They work only once, therefore the name monogenetic.

This is the life of the volcanoes in a volcanic field: the next eruption will occur somewhere else, nobody knows where and when! This is the reason why eruption forecasting is very difficult in such areas. Presently, this is a major issue in Auckland, which is located right in a volcanic field in New Zealand. The last eruption there occurred more than 600 years ago and any time and at any place a new one could be expected. That is why, volcanological studies in monogenetic volcanic fields, like in our area anywhere in the world have a particular importance.

Volcanological detective work in the Nature Trails of the Bakony–Balaton UNESCO Global Geopark: lava lakes

There is a vast amount of gorgeous volcanic heritage in the area of the Bakony–Balaton UNESCO Global Geopark. They comprise almost all the phenomena characteristics of basaltic volcanic eruptions. The volcanological Nature Trails along more than 35 km and equipped with 31 interpretive panels help to get an insight into these spectacular processes. The volcanic rocks, being witnesses of the past eruption events, can tell us like an open book how the eruptions were taking place. Let us open this book and find a few interesting chapters about the volcanism of this area!

Lava lakes are one of the most exceptional, awesome features of the Earth (**31, 32**). Incandescent fluid lava with more than 1000 °C temperature is surging in a rounded crater*. Occasionally lava spatters occur when gas-rich ascending melt blobs reach the surface. During a calm period, its surface solidifies and a plastic lava skin or a thin rigid lava layer form on the top of the lava lake. However, convective circulation of the liquid magma body is ongoing beneath it. Where hot melt batches come up, the upper layer is breaking apart and the red liquid magma becomes visible. We can see here on a small-scale how plate tectonic* processes are taking place: there are divergent and convergent plates and even transform boundaries! A real natural laboratory, which is very rare on the Earth!

The oldest lava lake is in Erta Ale, Ethiopia, which was formed more than 100 years ago. There are only a few more examples, the one at Mount Erebus, Antarctica, located in the most unique environment, and the one at Mount Nyiragongo in Congo, which comprises the deepest (>600 m) lava lake. This latter one was discovered by Haroun Tazieff, the famous French volcanologist, who described the story in a book in 1979. Most lava lakes are ephemeral and disappear or solidify after a couple of years or decades, as it happened in the Kilauea volcanic field, Hawaii (**32**; e.g., Halema'uma'u, Pu'u 'Ō'ō, Kilauea Iki) in Ambrym (Vanuatu islands), in Masaya (Nicaragua) and in Villarica (Chile).

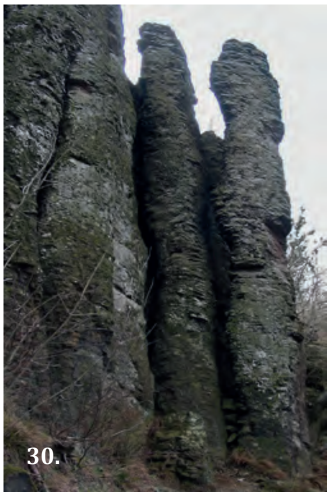
The lava lakes are formed in small pit craters and the surficial lava body is connected down to the magma chamber, which resides at a depth of a few kilometres. The continuous magma supply, the convective circulation in the magma column keeps the system alive.

In the area of the Bakony–Balaton Upland, lava lakes could develop within the wide craters of a few basalt volcanoes. How do we know that? Lava lakes either disappear or the melt remains in the crater and slowly solidifies. Slow cooling results in polygonal cracking (**28**) due to the contraction of the solid material. Cracking is always perpendicular to the cooling front. When the lava crops out due to subsequent erosion, the cracks slightly broaden (**29, 30**) as a result of precipitation, wind-erosion and temperature variation, i.e. freezing and thawing. Intermittent collapse of the tall and steep cliffs forms wide talus at the foot of the lava rock bodies. Meanwhile, the fracture pattern in the basalt is slowly getting to transform into columnar jointing. The columns have usually hexagonal and pentagonal shapes, since these geometric patterns relieve the maximum stress per unit crack. Observations, numerical calculations and experiments show that the column diameter is dependant on the cooling rate. If cooling is slow, as we could expect in a lava lake, thicker columns are formed. This is what we can see in the exposed steep basalt bodies in Badacsony and the Szent György Hill. In addition, we can often observe regular repetition of cracks perpendicular to the columns (**29, 30**). These are formed as the cooling front moves slowly down in the lava. They are called striae and their thickness also depends inversely on the cooling rate. As erosion is in progress, the basalt columns can be separated into large 'basalt coins' along the striae, as shown in the northeast part of the Szent György Hill. All in all, a viable interpretation is that these rocks could have been formed during slow cooling of lava lakes (**33, 34**). The spectacular basalt columns of Hegyestű (**28**) could represent either a smaller lava lake or cooling of vent-filling lava. In contrast, the gorgeous basalt columns in Haláp were formed during cooling of a thick lava flow.

Subsequently the basalt columns were often rounded and partially separated due to erosion. These tall 'organ pipes' are one of the most spectacular natural values of this area.


28.


29.


30.


31.


32.


33.


34.


35.


36.

When the basaltic magma explodes

Lava firework, lava curtain, lava fountains – these are various phenomena associated with explosive eruption of basaltic magma. These are indeed gorgeous events attracting millions of tourists each year. The low-viscosity magma gushes high in the sky during lava fountaining. The ejected glowing lava fragments fall back, accumulate and merge on the surface to form coherent lava flows, which spread and create extensive lava field around the fissure or the vent. The length of such an event may vary from days to months, whereas the lava firework eruptions occur with discrete bursts often separated with regular pauses. In Stromboli, the northern member of the Aeolian Islands, such events took place every 20-25 minutes for more than 2000 years. If we take a picture of it with long exposure time, the ballistic paths of the fiery clasts are spectacularly seen (**35**).

Such explosive events are controlled by the exsolution of volatile phases such as water, carbon dioxide and sulphur dioxide in the melt. The lava firework or in other words the Strombolian eruption is triggered by the surficial expansion of a large carbon dioxide bubble coming from crystallizing shallow magma chamber through the narrow feeder channel. When the carbon dioxide bubble expands, it disrupts the upper portion of the magma column which is rich in vapour bubbles. This is clearly reflected in the volcanic product of such eruptions. The scoria* clasts are full of rounded vesicles separated by thin walls of basaltic material. They look like a petrified sponge (**36**). The vesicles represent the vapour bubbles frozen in the basalt during the sudden cooling of the expanding magma foam. Such petrified sponge clasts are common at the Fekete Hill, mainly at the Boncsos scoria cone as well as in the northern quarries of Badacsony and on the top of Szent György Hill.

During explosive eruption of the basaltic magma, larger lava fragments could also be ejected. They often contain a dense rock clast, such as a mantle-derived peridotite in their interior. During the ballistic flights, these fluidal lava fragments rotate and finally get a fusiform shape with twisted ends, while others will have a rounded shape with breadcrusted, cracked surface (**37**). Such basalt bombs were frequently found in the Füzes-tó area, but presently they are pretty rare due to the uncontrolled sampling.

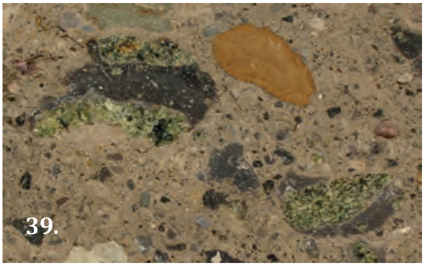

37.

The story of a unique pyroclastic flow

The columnar jointed rocks of lava lakes and thick lava flows, the spindle bombs and strongly vesiculated scoriae clasts formed during explosive eruptions are all the characteristic products of basaltic volcanism. However, there is also an atypical, interesting volcanic formation with a particular heritage value north of the village Szentbékkálla.

Three million years ago a few kilometres away from this location a violent explosion shook the environment. Suddenly, dense grey volcanic ash and white steam clouds billowed from the fractured surface to several kilometres high, while huge amount of ejected solid rock clasts and large blocks fall on the nearby area. The eruption cloud became so much saturated with these dense rock fragments that it could not rise further. Suddenly, it collapsed and a pyroclastic flow* driven by gravity crashed into a ravine (**38**). Debris of the fast-moving volcanic current filled the valley, where formerly a small river flowed quietly. Turbulent gas-rich pyroclastic surges* poured out of the rim of the valley and spread in the flat surroundings. When the eruption terminated, the former valley was entirely covered with grey volcanic ash and rock fragments. A number of superheated steam columns with skirl emerged from its surface...

38.



39.

This story is well represented in the wall of the abandoned quarry: having a closer look, you can see that the volcanic formation consists of variable rock clasts with abundant green fragments (**39**). They are peridotites transported by the ascending basaltic magma from the upper mantle. Furthermore, there are a number of additional rock types common in the Bakony and Balaton Upland areas: Silurian metamorphic rocks, Permian red sandstones, Mesozoic limestones and dolomites, Miocene marls and sandstones and even tiny fluvial quartz pebbles. On the other hand, there are not many basalts which represent the magma. The volcanic rocks in which lithic clasts are much more common than the juvenile clasts of the erupted magma, are formed by maar-volcanic explosive events (**40**). In this case, the mantle-derived magma ascends fast, crashing the nearby rocks and incorporate their pieces into the melt. In the upper part of the crust, at a depth of 100's of metres, the magma interacts with water in aquifer beds. The mixing of hot magma and cold water results in a violent explosion, which fragments the wall-rock as well as the magma and throws out this mixture of clastic material to the surface. Initially, so much rock fragments are in the eruption column that it is not able to rise, but gravitational collapse and results in a fast-moving gas and debris current, called pyroclastic flow. It moves particularly in the topographic lows, i.e. fluvial valleys. The buried water of the river turned into steam and the gases percolated through the thick deposit. They carried the fine material, while the larger fragments filled the void behind them. Thus, this gas segregation channels became visible in the solidified volcanic material (**41**). Pyroclastic flow deposits are very rare in basalt volcanic fields and such beautifully preserved gas escape pipes are even very rare, worldwide. Finally, an additional natural value of this volcanic product is the abundance of mantle-derived green peridotite rocks. They provide a unique opportunity for the scientists to study the nature and condition of building material of the upper mantle directly. Dear Visitor, please leave these fragments in the wall, leave them for the researchers, do not collect them! Just take a photo, and preserve this exceptional witness of a past volcanic eruption.

40.

41.

Geoparks: enhance visibility of geoheritage in a sustainable way

The Badacsony, Szent György Hill and the surroundings of the Fekete Hill represent a unique volcanic heritage, their formations reveal a long dynamic eruption history of this region. This heritage provided a strong basis for establishing a geopark in the Bakony–Balaton area, later awarded as a UNESCO Global Geopark status. The UNESCO Global Geoparks are unified geographical areas with a geological heritage of international significance and are managed with a holistic concept of protection, education and sustainable development. The geological heritage is used in connection with all other aspects of the area's natural and cultural heritage in order to enhance awareness and understanding of key issues facing society, such as using our Earth's resources sustainably. This heritage gives local people a sense of pride in their region and strengthens their identification with the area. High quality researches and training courses for local people help to find innovative ways to protect and exhibit the natural values through geotourism, while the geological resources of the area are preserved.

In June 2019, there are already 147 UNESCO Global Geoparks in 41 countries. In Hungary, the cross-border Novohrad–Nógrád Geopark was established in 2010-ben, while the Bakony–Balaton area was awarded a Geopark status in 2012.

The Bakony–Balaton UNESCO Global Geopark and other seven geoparks along the Danube region initiated a new project in 2017 with the following aim: the sustainable use of the exceptional wealth of natural resources and heritage in their areas. The main project result will be a joint Danube GeoTour designed to strengthen cooperation between the regions' geoparks and it acts as an innovative tourism product to increase visibility and tourist visits in them. Common strategy for sustainable management of geotourism pressures will form the basis for creating innovative geoproducts. The new interpretative approaches should increase local inhabitants' engagement and geopark management capacities and at the same time should lower the quality gap between the Danube and other EU geoparks.

Within the Danube GeoTour project two former Nature Trails have been renewed with a particular focus on revealing the volcanic histories, and a new volcanological Nature Trail has been established in the area of the Bakony–Balaton Geopark. Along the trails 31 interpretive panels help the visitors to get an insight into the volcanic and the associated cultural heritage. All these developments have been complemented with a new interactive exhibition at the Hegyestű Visitor Centre and with the present volcanological guide.

Glossary

Andesite: Volcanic rock, having silica (SiO_2) concentration intermediate between basalt and dacite. Plagioclase, pyroxene and amphibole are its main mineral components. The main volcanic rock type along subduction zones.

Asthenosphere: A part of the upper mantle between the lithosphere and 400 km depth, where the transition zone starts. It consists of solid material, although traces of melt might be present in their upper level. It is highly viscous, mechanically weak and ductilely deforming, thus its solid rocks could slowly flow. This is the principal region where basaltic magma could form.

Basalt: Volcanic rock, having relatively low silica (SiO_2) concentration. It contains high-magnesium minerals such as olivine and pyroxenes. It is the most abundant volcanic rock of the Earth.

Crater: It is a usually rounded, variably deep depression in a volcano above the vent.

Dacite: Volcanic rock, having silica (SiO_2) concentration intermediate between andesite and rhyolite. Feldspars, biotite, amphibole and rare quartz are its main mineral components. It usually occurs in subduction zones.

Earth's crust: The outermost solid layer of the Earth. Compared to the underlying mantle, it is less dense and has a significantly different composition. It is formed and grows primarily by magmatic processes, but later sedimentary (formed by surficial weathering, transportation and deposition) and metamorphic rocks (formed by solid phase transformation at high pressure and/or temperature) become integrated parts of the crust.

Earth's mantle: It is by far the most voluminous part of the Earth's interior between the crust and the outer core. It consists of solid material, primarily high density magnesian and ferroan silicates and oxides. It is a highly viscous material that could slowly flow due to the ductile physical properties.

Half-life: During the radioactive decay, the time required for a quantity of the parent isotope to reduce to half its initial value.

Isotope: Variants of an element which differ in their mass number. This means that isotopes of an element have the same proton number, but different neutron number.

Juvenile component: Those particles in a pyroclastic rock that represent the erupted and disrupted magma.

Lithosphere: The outermost rigid shell of the Earth that is subdivided into tectonic plates. It contains the crust and the upper part of the mantle, which has rigid mechanical properties. It is underlain by the asthenosphere, which consists of weak, plastically deforming solid material.

Maar: A volcano type which is formed by phreatomagmatic or phreatic eruptions and its volcanic material contains almost only disrupted bedrock fragments and no juvenile clasts. Maar volcanoes have very deep craters filled subsequently with water and appear as rounded lakes.

Magma chamber: A zone in the crust, where eruptible, melt-dominated magma is residing.

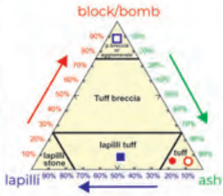
Magma reservoir: A zone in the crust, where magma in various form is residing: it comprises often long-lived, mostly crystal-rich, melt-poor bodies (crystal mush) and ephemeral melt-dominated magma lenses (magma chambers).

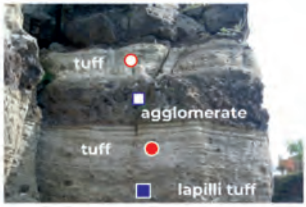
Magma: A molten or semi-molten multiphase natural material beneath the surface. In addition to the liquid melt phase, it contains solid crystals and exsolved gas bubbles. The basaltic magma generated in the upper mantle by partial melting of peridotite.

Miocene: A geological epoch started 23.03 million years ago and lasted until 5.33 million years ago.

Peridotite: A group of rocks which build up the upper mantle (the lower part of the lithosphere and the asthenosphere). These rocks have abundant olivine and two types of pyroxenes. Small peridotite pieces from the brittle upper mantle could be incorporated into the ascending basaltic magma and are found in pyroclastic rocks and lava flows as xenoliths.

Phreatic eruption: An explosive volcanic eruption caused by the interaction between hot magma and cold groundwater that causes steam explosion. In the erution product no magmatic component exists, but it con-





tains only the fragments of the disrupted bedrocks.

Phreatomagmatic eruption: An explosive volcanic eruption caused by mixing of hot magma and cold water or water-saturated sediment. It results in violent explosions when tiny particles of both the magma and the surrounding rocks are incorporated into the eruption cloud.

Pyroclastic flow: Gravity-driven, fast-moving current of hot gases and volcanic fragments and particles. It spreads laterally, mostly in depressions and has a great devastating force. It is formed either by collapse of overweighted eruption cloud or collapse of growing lava domes.

Pyroclastic rock: A clastic rock formed by explosive volcanic eruption.

Pyroclastic surge: A low-density pyroclastic current, consisting mostly of hot gases and much less solid fragments moving horizontally, turbulently on the surface.

Quiescence period: Shorter or longer calm period or repose time between active volcanic phases.

Radioactive decay: Natural decay of unstable atomic nucleus into another one by emitting high-energy radiation.

Rhyolite: Volcanic rock, having high silica (SiO_2) concentration. Quartz, feldspars and biotite are its main mineral components. It usually occurs in subduction zones where the continental crust is thick.

Scoria cone: A type of volcano made up of scoria clasts and has a conical shape. It forms by Strombolian-type lava firework eruptions.

Scoria: A pyroclast with abundant rounded vesicles formed usually by explosive volcanic eruption (Strombolian lava firework eruptions), but it could also form the upper part of a viscous lava flow (aa lavas).

Shield volcano: A type of volcano formed by fluid, far-reaching basaltic lava flows. It has a low profile resembling a warrior's shield.

Tuff ring: A type of volcano formed by phreatomagmatic explosive eruptions. It has a wide crater and contains mostly volcanic ash.

Vent: A vertical channel within the volcano, where the magma comes up to the surface.

Volatiles: Those materials, which are in gas or fluid state on the surface. They are dissolved in the magma at high pressure, but as pressure drops or crystallization is in progress, volatiles exsolve and form gas bubbles in the melt. The most abundant volatiles are water, carbon dioxide, sulfur dioxide and hydrogen sulfide.

Volcanic ash: Particles with less than 2 mm size and formed by explosive volcanic eruptions. They could be either rock fragments, crystals or glass shards.

Bazalt Organs Nature Trail, Szent György Hill

Trail mark: T

Stops of the nature trail:

1. Starting point
2. Basalt organ
3. Lava lake
4. Monogenetic volcanic field
5. Panoramic view of volcanoes
6. Life on a basalt volcano
7. From volcano to remnant hill
8. Volcano fairy tale

CARTOGRAPHIA
THE MAP EXPERT

Section of Balaton hiking map and Balaton Uplands, Keszthely Hills tourist guide and map, with the permission of Cartographia, Ltd.

M = 1 : 40000 — 1 km

Interreg
Danube Transnational Programme
Danube GeoTour

Project funded under the Danube Transnational Programme supported by the European Regional Development Fund and co-financed by the Hungarian State.

Project co-funded by European Union funds (ERDF, IPA)

http://www.interreg-danube.eu/danube-geotour