Volcanic terroirs in Hungary

Compiled by

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1. Epilogue *vs*. prologue

Sometimes the epilogue precedes the prologue. So is the case in this study. Some important terms need to be clarified and interpreted right at the beginning, in order to ensure a better understanding.

1.1. Volcanic wine?

In general, the fundamental question of the study is whether volcanic wine exists and, if so, what it really means. The influence of volcanoes on vineyards is one of the oldest and most fascinating aspects of winemaking, providing unique and inimitable wines. A wine with unique flavours and complexity is the gift of volcanic soils that are rich in nutrients (minerals).

It is not the wine that is volcanic, but the bedrock and the soil that forms on it, and the grapevine grows in this soil of volcanic origin.

The volcanic bedrock and soil are distinctive features of the terroir and important parts of the geoterroir.

We therefore recommend using the term volcanic terroir instead of volcanic wine (also on the label of the wine bottle).

1.2. Some thoughts on terroir

Explaining the huge diversity of quality, flavors, and aromas is no easy task. What fascinates us is geology and its relative role in determining which vineyards are winners and which are losers. There are a number of factors that influence the character of a wine and are usually summarized under the French term "terroir". What is terroir? A terroir refers to the overall environment or "sense of place" in which a vine is grown. The term has an almost mystical connotation, but it encompasses all the factors that together determine the uniqueness of a wine from a wine region or, within that region, from a particular area (a producer or vineyard). These factors range from geological conditions (bedrock and the resulting soil, geological time, etc.), climate and viticultural practices to the expertise of the winemaker and the wine consumers, including cultural background and traditions. To better understand the uniqueness of a wine from a particular wine region, these factors need to be identified and studied. This is, of course, a basic principle, but in most cases the opportunities offered by science and scientific interpretation are not used. The bedrock, minerals, chemical elements (cations and anions), and soil are important elements of a terroir in a given geographical and climatic area. These elements make up the geoterroir. It is obvious that a large area (a wine region) is influenced by largely similar climatic conditions, so the differences in quality between wines from neighbouring vineyards, which are often at the same altitude and on the same slope, cannot be explained by climatic differences alone. The emphasis is therefore on geology as one of the key factors influencing the character of the grapes. Our study focuses on the volcanological aspects of a geoterroir (igneous rocks, minerals, elements, and volcanic soils).

However, it would be a big mistake to try to impose the geoterroir per se on a wine region and then fetishize it. One must not forget the cultural assets of a wine region, its traditions or even the art of the winemaker.

1.3. What are the "volcanological" characteristics of the different wine regions in Hungary?

Before we answer this question, which at first glance may not seem so complicated, it should be clarified what is meant by the terms volcano and volcanic activity. Contrary to popular belief, a volcano is not just a cone-shaped mountain (Figure 1) that occasionally spews out lava flows or explodes magma like fireworks. The question requires a more complex answer.

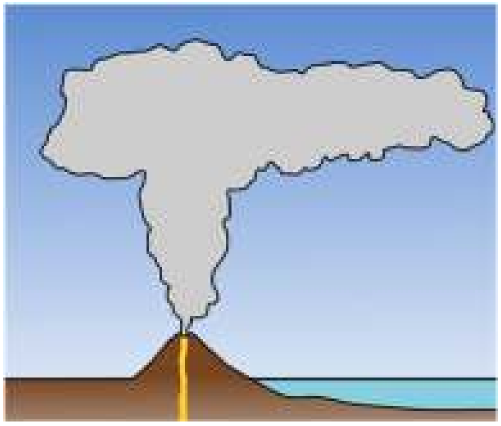

Figure 1. *Conventional representation of a volcano*

The volcanic cone (if there is one) is only a very small (though undoubtedly important) part of a larger structure, the volcanic-plutonic system. The volcanic-plutonic system (structure) can be divided into four levels or processes depending on depth: partial melting of the mantle (asthenosphere), detachment and movement of melt/magma towards the surface (lithosphere), melt/magma stagnation and differentiation (crust), and volcanic eruption (surface) (Figure 2). Contrary to popular belief, magma does not originate from the liquid convection zone beneath the Earth's crust, but is typically formed by the partial melting of various pre-existing rocks consisting of silicate minerals in the so-called root zone, the lower part of the lithosphere (lithosphere = crust + upper part of the mantle) and the upper part of the mantle (the asthenosphere beneath the lithosphere). The evolution and composition of the parent rocks in the root zone are different.

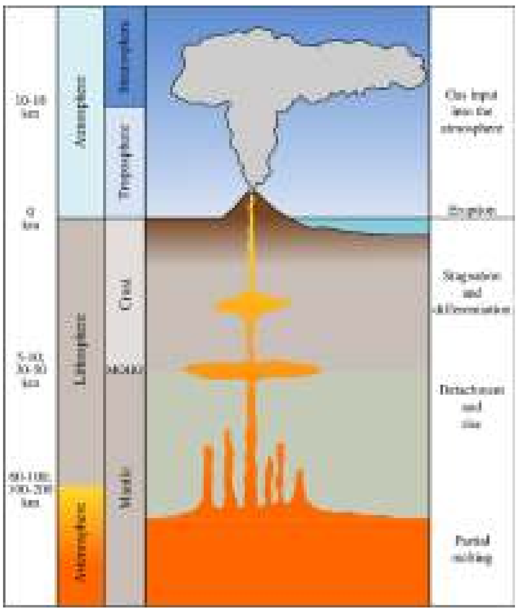

Figure 2. *The volcanic-plutonic system*

The differences between the source rocks and between the processes that lead to magma generation can only be understood in the context of the global (plate) tectonic framework. The study of processes in the root zone plays an important role in understanding why volcanoes form in particular places on Earth, what influences the composition of the magma or what type of eruption (effusive or explosive) the volcanoes produce. The composition of the magma, its viscosity, rate of ascent, its interaction with water and its saturation with volatiles all have an influence on whether the eruption is effusive and the magma reaches the surface in the form of "quiet" lava flows or whether the eruption is accompanied by violent explosions. All active volcanoes emit gases into the atmosphere, sometimes tens of thousands of tonnes per day, even without violent explosions. Degassing of the bubbling magma can take place at depths of up to several kilometres from the surface and does not necessarily have to be accompanied by explosive eruptions. The high ascent rate of the magma is particularly suitable for triggering explosive volcanic activity. During high-energy explosive eruptions, volcanic ash and gases can rise up to 40 km into the atmosphere, but the gases can reach even higher regions of the atmosphere. However, not all magma reaches the surface. Figure 2 clearly shows that only a small portion of the magma produced at greater depths reaches the surface, most of it is trapped and crystallized at various depths in the lithosphere. In other words, there are magma reservoirs ("magma chambers") of different shapes and sizes beneath the volcanoes. Volcanic rocks are solidified representatives of the magma that has reached the surface. The composition of the ascending magma is shaped by subsurface processes and the type of the eruption is determined by the composition of the magma. The composition of magma or lava at the surface may differ only slightly, i.e., the chemical and mineralogical composition of a particular igneous rock is essentially the same at depth as at the surface. Figure 3 illustrates that, for example, rhyolite "adds" the same chemical elements (minerals) to the volcanic soil as granite and gabbro is the same as basalt, while andesite is mineralogically and chemically the same as diorite. Plutonic and volcanic rocks that form in the volcanic-plutonic system can be displaced to a new depth, i.e. to a new pressure (P) and temperature (T), mainly due to tectonic processes, by intense vertical and horizontal movements (in geological time) of the lithosphere. Their chemical composition is then incompatible with the new conditions and the minerals are therefore transformed (to attain the minimum energy state). This process is called metamorphism. The types of minerals and therefore the type of metamorphic rocks that can form under a given P-T condition are essentially determined by the chemical and mineralogical composition of the original rock (protolith). Protoliths, which are dominated by quartz and feldspar, include granite and rhyolite of igneous origin. These are chemically very simple systems in which K^+, Al^{3+} and Si^{4+} are the most important cations. Since quartz, feldspar, and mica (biotite and muscovite) are the stable minerals in this system over a wide P-T range, metagranite, metariolite, and gneiss (orthogneiss in the case of igneous protoliths), which were formed by metamorphism of the above-mentioned parent rocks, also contain these minerals. The composition of the rocks resulting from the metamorphism of andesite (diorite) and basalt (gabbro) is characterized by the predominance of Fe-, Mg-, and Ca-silicates. As the original igneous rocks are essentially H_2O-free and formed at very high temperatures, low-temperature metamorphism makes their minerals unstable and, in the case of metabasalt, for example, transform into OH-bearing phases (zeolites, chlorite, and amphibole). Metagranite, metarhyolite, orthogneiss, and metabasalt are also part of the volcanic terroir.

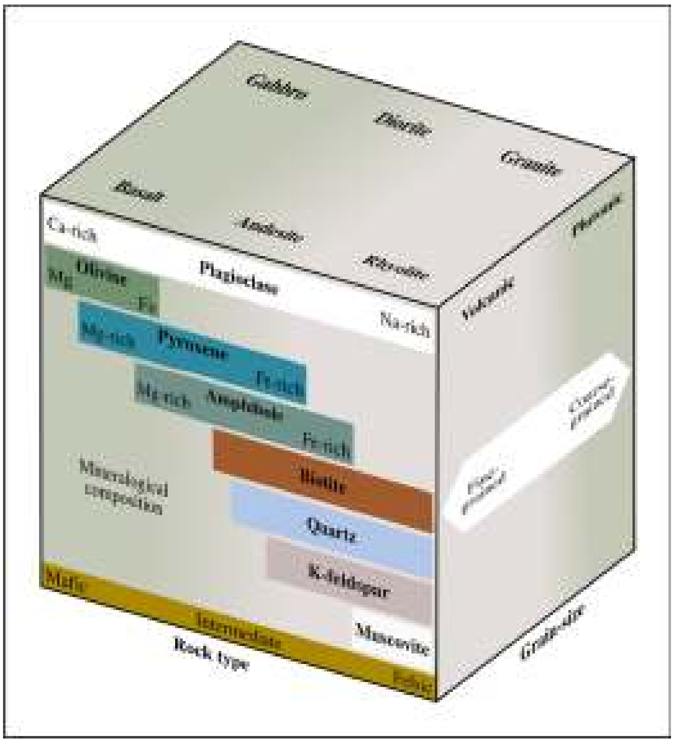

Figure 3. *The nomenclature, color (felsic, intermediate, and mafic), mineralogical composition, and grain size of the most important plutonic and volcanic rocks in the volcanic-plutonic system*

According to our interpretation, the volcanic (geo)terroir includes not only strictly volcanic (effusive) rocks, but also plutonic rocks and metamorphic rocks of igneous protolith.

In Table 1, three Hungarian wine regions are shown as examples, with three different volcanic terroir rocks (rhyolite lapilli tuff – volcanic rock, granite – plutonic rock, orthogneiss – metamorphic rock) and the same or very similar major element geochemical composition (of course the mineralogical composition is the same) (see the wine regions for more details).

Table 1. *Major element geochemical compositions of volcanic, plutonic, and metamorphic terroir rocks*

Chemical composition (weight percent)	**Tokaj Wine Region**	**Etyek-Buda Wine Region**	**Sopron Wine Region**
	Rhyolite lapilli tuff (volcanic rock)	**Granite (plutonic rock)**	**Orthogneiss (metamorphic rock)**
SiO_2	72.89	71.66	72.80
Al_2O_3	12.47	14.19	15.03
Fe_2O_3	1.84	1.99	1.45
MnO	0.05	0.05	0.04
MgO	0.16	0.57	0.33
CaO	1.02	0.76	0.49
Na_2O	2.53	3.58	2.83
K_2O	5.18	4.48	5.60
P_2O_5	0.05	0.08	0.30

Considering the mineralogical composition and, implicitly the chemical composition, it is not surprising that similar soil-forming materials (the formation of similar inorganic soil components) are the function of similar weathering processes (physical and chemical weathering) and geological time. At the end of a multi-phase weathering sequence, the minerals or volcanic glass typical of volcanic rocks are transformed into secondary minerals with lower specific mass and higher volatile content. The (mineralogical and granulometric) composition of the soil-forming sediment is also responsible for the formation of different genetic soil types (including volcanic soils).

The volcanic soils in the Hungarian wine regions are not young (recent) volcanic soils (as in Sicily or the Canary Islands). There has been no active volcanism in Hungary for more than 2 million years. It is very important to emphasize the role of geological time in soil formation, as these volcanic soils were not formed on newly deposited volcanic material (pyroclasts, lava, etc.), but on volcanic and plutonic rocks that are up to 10 million years old.

One must also consider which chemical elements (ions) ("minerals") the grapes need for their growth, what the vines "eat" from the soil (or from the fertilizer). Of the 94 chemical elements that occur in nature, grapes only need 17, namely the following: primary nitrogen (N), phosphorus (P), potassium (K) and secondary sulphur (S), magnesium (Mg) and calcium (Ca) from the major elements (> 0.1 wt%). Of the trace elements (< 0.1 wt%), grapes need zinc (Zn), boron (B), iron (Fe), manganese (Mn), copper (Cu), molybdenum (Mo), nickel (Ni) and chlorine (Cl). They also require carbon (C), hydrogen (H), and oxygen (O) from water and air. These chemical elements are also present in the most important rock-forming minerals of volcanic/plutonic/metamorphic rocks (Table 2).

The characteristics of the volcanic terroirs in the Hungarian wine regions are outstanding in terms of the volcanic, plutonic, and metamorphic (with magmatic protoliths) bedrocks and the resulting volcanic soils.

Table 2. *The most important rock-forming and accessory minerals of the rocks of volcanic terroirs and their chemical composition (the chemical elements essential for grapes are in bold)*

Mineral	Chemical composition
Olivine	$(\mathbf{Mg,Fe})_2SiO_4$
Orthopyroxene	$\mathbf{Mg}_2Si_2O_6$ – $\mathbf{Fe}_2Si_2O_6$
Potassium feldspar (orthoclase, microcline)	$\mathbf{K}AlSi_3O_8$
Plagioclase feldspar	$\mathbf{Na}AlSi_3O_8$ – $\mathbf{Ca}Al_2Si_2O_8$
Amphibole	$(\mathbf{Na,K})_{0\text{-}1}\mathbf{Ca}_2(\mathbf{Mg,Fe^{2+},Fe^{3+}},Al)_5Si_{6\text{-}7,5}Al_{2\text{-}0,5}O_{22}(OH)_2$
Biotite	$\mathbf{K}(\mathbf{Fe,Mg})_3(AlSi_3O_{10})(OH)_2$
Muscovite	$\mathbf{K}Al_3Si_3O_{10}(OH)_2$
Chlorite	$(\mathbf{Mg,Fe})_3(Si,Al)_4O_{10}(OH)_2\cdot(Mg,Fe)_3(OH)_6$
Quartz	SiO_2
Zeolites	$\mathbf{Na}_2Al_2Si_3O_{10}\bullet 2H_2O$ – $\mathbf{Ca}_2Al_2Si_4O_{12}\bullet 6H_2O$
Kaolinite	$Al_4Si_4O_{10}(OH)_8$
Serpentine	$\mathbf{Mg}_6Si_4O_{10}(OH)_8$
Montmorillonite	$(\mathbf{Ca}_{0,5},\mathbf{Na})_{0,7}(Al_{3,3}\mathbf{Mg}_{0,7})[Si_8O_{20}(OH)_4]\bullet nH_2O$
Apatite	$\mathbf{Ca}_5(\mathbf{PO}_4)_3$
Sanidine	$(\mathbf{K,Na})AlSi_3O_8$

Ilmenite	**Fe**TiO_3
Epidote	**Ca_2(Al_2,Fe)**$(SiO_4)(Si_2O_7)O(OH)$
Magnetite	**Fe_3**O_4
Zircon	$ZrSiO_4$
Nepheline	**Na_3K**$Al_4Si_4O_{16}$
Leucite	**K**$AlSi_2O_6$

1.4. What are the characteristics of wines from volcanic terroirs?

A simple way to put the question is as follows: what does the volcanic soil on which the grapes grow actually consist of? There are two possible answers to this question: a metaphorical and a professional geological answer. Both are important (especially for marketing), but not both are scientific. Let us look at the first answer. There is a lot of romance in the world of wine. Talking about wine can be taken to mean that wine is always either good or bad, beautiful or ugly..., it is fine but very boring. The more nuanced talk about wine should not be banished (at all costs, or even if we do), but one should always be aware of the absolute professional meaning of one's words. When it comes to talking about wine, a gibberish of over-sophisticated jargon with no professional content is often used. This not only shows a lack of credibility, but also a great disdain for one's own wine-drinking community, the audience. What exactly is meant by this?

The origin of the inorganic solid particles in volcanic soils is only one aspect of a soil. In addition, there is the very diverse (geological) mineralogical composition, closely related to this, the mineral content, the concentration of decomposed organic matter and the water retention capacity. Volcanic soils also exhibit great diversity. As these differences are associated with different climatic conditions, topography, slope gradients, grape varieties and other aspects, there is no standard sensory criterion for wines from volcanic soils.

However, there are also characteristics that unite wines from different volcanic terroirs and make them special. What are these features? Minerality, a taste and scent of silica, a scent of flint or gunflint, an earthy or warm, wet stone scent, a metallic scent, and, above all, acidity. And then elegance and complexity. In addition to all these, an excellent tendency to a long shelf life.

Let us look at minerality as one of the most important characteristics of a volcanic terroir. Two of the most renowned Hungarian volcanic terroirs are the Tokaj and Badacsony Wine Regions, where the characteristic rocks are rhyolite and basalt. Are these both volcanic terroirs? Yes. Do their wines have a similar mineral flavor and aroma profile? Sensory observation suggests that they do. The rock-forming minerals in rhyolite are quartz, potassium feldspar and biotite, whereas, basalt is made up of clinopyroxene and plagioclase feldspar (± olivine and orthopyroxene). One is enriched in Si, K, (Na) and depleted in Mg, Ca, and Fe, however, the other has a low Si, K, (Na) content and a high Mg, Ca, and Fe concentration. They have a similar taste and scent profile, but a different mineralogical composition. How is this possible?

Minerality is a flavor profile, a geological metaphor.

Rocks and minerals are tasteless, they have no flavor.

Although there are some minerals such as halite (NaCl) (salty taste) or sylvite (KCl) (bitter-salty taste) that have a certain flavor, they are not rock-forming minerals (silicates) and do not occur in igneous rocks. The minerals that make up the Earth's solid crust and, to a certain depth, the Earth's mantle, are characterized by a certain, but not necessarily constant chemical composition, crystalline structure, and shape. Apart from water, grapes are not made up of soil but of oxygen, hydrogen, and carbon from the air, and it is powered by sunlight. In order for photosynthetic and other organic processes that use these elements to function, relatively small amounts of other elements, i.e. nutrients, are also needed. Most of these come from the soil (and are released into the soil through the weathering of geological minerals), therefore, they are usually referred to as mineral nutrients or often simply minerals, mostly ions that are necessary for the vine plant. And here lies the source of all the confusion. Although most of these mineral nutrients are derived from minerals in the geological sense, they are not the same thing. The chemical elements that make up geological minerals form a crystalline structure, they are crystalline compounds, and a whole series of processes must take place before they can be separated, dissolved and transported to the roots of the vine so that they can be absorbed into the vine's system. So, although they are ultimately related, there is a significant difference between these two types of minerals, even within a single vineyard, let alone the wine. The actual concentration of mineral nutrients in the wine is usually negligible. The total inorganic content of a wine usually ranges between 0.15% and 0.4% (most of which is potassium, calcium, and magnesium).

What about the scent of flint or gunflint?

The scent of flint or gunflint is also metaphorical. In some types of quartz, the crystalline character can only be recognised under a microscope, as the crystals are extremely small. This is also the case with the variety known as flint. Flint is the old mineralogical term for quartz and is rarely used in scientific literature. In everyday language, it is the collective name for the microcrystalline, cryptocrystalline and hyaline varieties of silicon dioxide (SiO_2). Like other silicates, however, flint has neither taste nor smell. The scent that one smells when one makes a spark comes from the tiny particles of burning iron: flint remains inert.

A taste or scent of silica?

Silicon dioxide (SiO_2) has no taste or smell. Because of these properties, silicon dioxide is used in the manufacture of glass, including wine bottles and glasses.

The roots of grapevines cannot absorb the inert, insoluble silicon dioxide compound. Therefore, if the sharpness or metaphorical siliceous quality is considered a characteristic of very dry, acidic wines, it cannot be due to the presence of flint or related substances in the grapes.

The earthy smell is also not due to the inorganic components of the rocks and soils.

The earthy scent comes from organic compounds, such as 2-methyl-isoborneol from algae and a terpene called geosmin [from the Greek geō (earth) + osmḗ (smell)], which is produced by bacteria and moulds. Both compounds have an aroma that is released into the air when the soil is cultivated. They also have a surprisingly low detection limit (up to a few trillion particles). Higher concentrations in wine can even lead to it being considered as tainted.

The scent of warm/wet stones is not related to the geological material.

The scent of warm and/or wet stones can be related to the release of organic oils, the scent is called petrichor. Petrichor is an acronym of the ancient Greek words pétra/pétros (rock/stone) and ikhṓr (blood of the gods).

The minerality of a wine from a volcanic terroir, irrespective of the sensation, cannot be a literal, direct taste of the minerals and/or mineral components of the rocks, minerals or the soil. However, this does not mean that this anecdotal belief is made-up, but that any possible nexus must be indirect.

A more complex scientific explanation of minerality is not part of this study. Nevertheless, it has to be noted that it is neither basalt nor olivine that one tastes in wine. Even if it is otherwise true that the bedrock is expressed in the soil, just as the sediment (e.g. loess) deposited on a solid rock of volcanic origin determines the properties of the soil above it. Soil is a polydisperse system in which billions of microorganisms (microbes) "work" in a single gram in a biotope-specific composition. It is the interactions between roots and microbes that make the grape what it is, and thus the wine that is made from the grapes. Every wine is therefore identifiable with the terroir, including the volcanic terroir. So it is life that has a taste. The grapes are not nourished by rhyolite or granite, but by the fungi and bacteria that live in the soil.

Minerality is just one excellent way of associating wines with a volcanic terroir. However, it is worth asking how the use of the terms “volcanic terroir” or “minerality” influences consumers when buying wine. In our opinion, the information on the wine bottle (even if it is hidden behind a QR code) and the price of the wine are two important factors that help consumers to choose a particular wine style and variety. We are convinced that developing the image of a product, namely a wine from a volcanic terroir, is only possible through an effective combination of marketing, sensory concepts, and scientific background. In addition, it is essential to involve the winemakers and to share and discuss the necessary general geological information (about volcanology, igneous and metamorphic petrology, mineralogy, etc.) specific to the wine region and the winery.

The largest and most important volcanic areas in Hungary are the Tokaj, Bükk, Eger, Mátra, Badacsony, Balaton Highlands and Somló Wine Regions.

2. Tokaj Wine Region

The Tokaj Wine Region was the first closed wine region in the world, which offered special protection for the area by banning wine imports from abroad. The landscape structure, which has developed over the centuries and is the basis for constantly evolving vineyard and viticulture, was inscribed on the UNESCO World Heritage List in 2002 as the Tokaj-Hegyalja Historic Wine Region Cultural Landscape. The area is characterized by a very heterogeneous geological structure dominated by Miocene volcanic rocks (ca. 10–15 million years old). The importance of geology was recognized by József Szabó – the founder of Hungarian geology – in the second half of the 19th century. He applied a holistic approach to study the geological, pedological, and wine geochemical features of the wine region. In the 150 years that have passed since then, the petrographic foundation he laid has led to significant volcanological, geochronological, and geochemical findings that have given us a better understanding of the evolution and complexity of the volcanic landscape in the Tokaj-Hegyalja region.

The description of the igneous rocks of the wine region is based on the (formation-based) stratigraphic classification of the Hungarian Stratigraphic Committee. The main units are the lava rocks and pyroclastics (products of explosive eruptions) of the Tokaj Volcanic Complex. In addition to the long-established fossil records, the schematic timeline of volcanism has been refined by K–Ar geochronology that became widespread in the 1980s and the ongoing zircon U–Pb geochronology. The oldest volcanic rocks were formed in the Badenian, whereas, subsequent periods were characterized by the alternation of explosive and effusive volcanic activity. Rocks classified in the Sátoraljaújhely, Szerencs and Vizsoly Rhyolite Lapilli Tuff Formations are the products of eruption centers. Owing to its special geodynamic environment, all members of the calc-alkaline rock series from basalt to rhyolite are present in the Tokaj Mountains. A large volume of rhyolitic rocks were produced by the initial, siliceous explosive eruptions. Subsequent phases are represented by andesitic and dacitic effusive volcanic rocks. Caldera structures, such as the Sátoraljaújhely and Szerencs Calderas, were formed by the explosive eruptions.

Volcanic rocks are represented by calc-alkaline andesite, dacite, and rhyolite. Magmatic differentiation and crystallization led to their diverse mineralogical composition. Ortho- and clinopyroxenes, amphibole, and plagioclase dominate in andesite. The most important rock-forming minerals of rhyolite are biotite, sanidine, and quartz. The crystal content of lava rocks is the function of cooling rate and the phenocryst content of lava rocks is generally lower than that of subvolcanic rocks. Pyroclastics are characterized by a various grain size due to the fragmentation of volcanic material during explosive eruptions. Their subsequent alteration, such as silicification, zeolitization, and hematitic discoloration, is of great importance. The geochemical composition of the rocks is also informative, based on their SiO_2-content the rocks cover the basaltic andesite and rhyolite categories. Differences in the major element composition reflect the igneous processes.

3. Bükk and Eger Wine Regions

Most of the rocks of the Bükk and Eger Wine Regions are associated with large volume siliceous explosive volcanic eruptions. The southern foreland of the Bükk Mountains (i.e. the Bükkalja Volcanic Area) consist of rocks with a various texture that were formed at 18.1–14.4 Ma by explosive and caldera-forming eruptions that brought huge amounts of magma to the surface. Once the vast amount of magma was ejected from the Earth's upper crust, the resulting void caused the surface to collapse. One should, therefore, not imagine a typical central volcanic structure here, but fissures from which magma was ejected.

A general feature of explosive volcanic eruptions is that the magma is blown into pieces of varying size (fragmentation) and the deposition of volcanic debris is mainly determined by its interaction with the air (or water). During the explosion, the initial energy and buoyancy force the volcanic debris into the higher regions of the atmosphere, which then falls out of the eruption cloud depending on its density and size. Pyroclastic flows (volcanic debris flows) can form huge sheets on the surface or channel into depressions to fill valleys. These high temperature gas and debris flows propagate rapidly and can travel up to 100 km. In pyroclastic flow sediments, debris of different sizes (pyroclasts) are deposited all at once, i.e. they are very poorly classified. Debris ranges from ash (< 2 mm) through lapilli (2-64 mm) to blocks and bombs (> 64 mm).

Lapilli tuff is the most abundtant rock type in the Bükkalja Volcanic Area. The ash and lapilli-sized debris was deposited from pyroclastic flows. Finer-grained tuff and slightly coarser-grained lapilli stone may also occur. Vesicular, porous pumice [solidified magma (melt) foam] can often be found in the rocks.

Studies in the Bükkalja Volcanic Area have shown that the rocks formed well-defined horizons over time. The oldest stratigraphic unit is the Tihamér Rhyolite Lapilli Tuff Formation. The age of the rocks ranges from 18.1 to 17.1 Ma and they are mostly massive (unstratified), siliceous, pumiceous lapilli tuffs of rhyolitic composition. Distinguishing the eruption events is usually only possible by geochemical and absolute dating methods as the rocks usually do not exhibit significant petrological differences (e.g. in their mineralogical composition and texture).

The Bogács Dacite Lapilli Tuff Formation overlies the rocks of the Tihamér Rhyolite Lapilli Tuff Formation. These rocks are characterized by a lower silica concentration. They are reddish due to their higher and oxidised iron content. Most of the rocks are lapilli tuffs from pyroclastic flows, which are often welded.

The rocks of the Tar Dacite Lapilli Tuff Formation are typical in the western part of the Bükkkalja Volcanic Area. The rocks are mostly dacitic pumiceous lapilli tuffs and they formed at 15.1–14.8 Ma. The thickness of the formation can reach 200 m. The volcanic eruption centre was probably located around Demjén.

The Harsány Rhyolite Lapilli Tuff Formation represents the products of the youngest volcanic eruptions in the region, with ages between 14.7 and 14.4 Ma. The rocks are highly siliceous rhyolitic pumiceous lapilli tuffs of pyroclastic flow origin. In some places, the size of pumice can reach 30–40 cm.

4. Mátra Wine Region

The Mátra Wine Region is the second largest wine region in Hungary. It is located in two well-defined areas, in the region of Gyöngyös and Veresegyház. The Gyöngyös Area lies in the southern and western foreland of the Mátra Mountains. The Veresegyház Area is scattered in the Gödöllő Hills. These two regions are geologically very different, the details of which are described below.

Most of the surface of the hilly regions of the Veresegyház Area is covered by Pleistocene loess that overlies Oligocene and Miocene sandy-clayey sediments; nevertheless, volcanic rocks can also be found. To the west of Szendehely, for example, small patches of dacitic tuffs from the explosive eruptions of the early volcanic phase of the Börzsöny Mountains (16–15 Ma) occur.

The Gyöngyös area is geologically very diverse, owing to the Miocene volcanism of the Mátra and Cserhát Mountains. Volcanism of the Mátra Mountains can be divided into three main phases. During the first phase, explosive eruptions produced pyroclastics (lapilli tuffs) referred to as the Hasznos Volcanoclastic Unit. Lava rocks were also described from the Zagyva Valley (Gömörhegy Andesite Unit). The volcanic activity of the first phase was interrupted by a series of caldera-forming explosive eruptions that produced the Tar Dacite Lapilli Tuff Formation. The dacitic lapilli tuffs thickly covered the southern foreland of the Mátra Mountains. During the second phase, major volcanic structures formed in the southern and southwestern part of the Mátra Mountains. The Nagyhársas Andesite Unit consists of pyroclastics and lava rocks with various texture. The latter is represented by vesicular, scoriaceous or amygdaloidal varieties. Dioritic intrusions penetrated the andesite and formed a hydrothermal system. Zinc and lead ore deposits of economic importance were formed in the area of Gyöngyösoroszi. Hydrothermal alteration resulted in chloritization and clay mineralization. With the decline of andesitic volcanism, clayey-sandy limestone sediments were deposited on the southern and southwestern side of the Mátra Mountains. They are often accompanied by diatomite ("diatomaceous earth"), formed in a warm aqueous environment as a result of post-volcanic activity that are classified in the Szurdokpüspök Formation. This may also contain rhyolite tuff layers. The third volcanic phase took place in a terrestrial environment. The Kékes Andesite Unit consists of lava rocks, coarse-grained pyroclastics and dykes. The Kékes Andesite is more basic, has a higher magnesium content and a basaltic andesite character. It may contain minor olivine in some lava flows and dykes.

Volcanic soils formed by the weathering of andesitic and dacitic rocks predominate the Gyöngyös Area. These soils are rich in minerals, which provide a special character for the wines from this region. The Veresegyház Area is characterized by loess, sand, clay, and terrace gravel, thus, volcanic soils are negligible.

5. Balaton Highlands and Badacsony Wine Regions

The Balaton Highlands is one of the monogenetic basaltic volcanic fields of the Carpathian–Pannonian region. Such volcanic fields can have a lifespan of millions of years, with active eruptive phases separated by stages up to hundreds of thousand years without any volcanic activity. The timing of volcanic eruptions can be determined by the K–Ar isotopic analysis of basalts.

The available age data indicate that the basaltic volcanic activity occurred between 8 and 2.5 Ma. The basalts of Tihany and Hegyestű were the first to form at 7.8–8 Ma. This was followed by a very long (3 Ma) dormant period. The basalts of Szigliget and Tóti Hill, and probably also the shield volcano of Kab Hill formed, followed by a few hundred thousand years of dormancy, and then came the volcanic eruptions of Halom Hill, Hegyesd, Szent György Hill, and Sümegprága (at 4.1–4.2 Ma). After another pause, the volcanic eruptions of Badacsony, Fekete Hill, and Hajagos followed (at 3.8 Ma). The most recent phase of volcanism was at 2.5–3.6 Ma, when the volcanoes of Agár Hill and Haláp were formed. Several volcanoes were active around Szentbékkálla and Kopácsi Hill, and the most recent volcanoes were Bondoró and the volcanoes of Lake Füzes.

The volcanic activity took place within a continental plate. Scientific studies suggest that neither a hot mantle plume nor lithospheric thinning played a direct role in the basaltic volcanism. The cause of magma generation and ascent to the surface is therefore still being investigated.

Basaltic magma can come to the surface in different ways. The crystal and volatile content determine the mobility of the magma, i.e. its viscosity. When a significant amount of gas bubbles accumulate near the surface of the magma, an overpressure is created, that makes the magma burst to the surface with an explosion. If the gas phase has a smaller volume, the basaltic magma rises to the surface as a lava flow. Most of the volcanoes in the Balaton Highlands produced lava flows, although explosive eruptions have also occurred to a lesser extent. However, the basalts of lava flows do not cover large, continuous areas, but rather appear as small centres in the Balaton Highlands. The exceptions are the Kab and Agár Hills.

The slow cooling of basaltic lava leads to contraction that forms a columnar structure as can be seen in the the characteristic landscape of Badacsony and Szent György Hill. The structure of the columns (i.e. a pentagonal to hexagonal cross-section and a various diameter) is the function of the cooling rate and the thickness of the lava mass. The basaltic lava rock is more resistant to erosion than the volcaniclastic sediments formed by explosive eruptions. This is the reason for the characteristic landscape of the Tapolca Basin, where an inverse morphology can be observed: the surface is heavily eroded and only the basaltic lava rocks that previously filled the depressions (craters and valleys) have resisted erosion and are exposed as buttes.

Basaltic scoria and volcaniclastic sediments (pyroclastics) formed by explosive eruptions can also be found in the region. They are porous and more prone to weathering, thus promoting soil formation. Hydrovolcanic explosive eruptions (when the magma interacts with groundwater or aqueous sediments) produced fine-grained pyroclasts (compact basaltic debris and fragmented volcanic glass that represents the melt and easily alters to clay minerals). These sediments were dispersed and fell out of the eruption cloud from a greater distance and formed the so-called tuff rings or tuff cones.

The volcanic heritage of the Balaton Highlands is not only geologically significant but also outstanding for defining the landscape. The columnar basalts, such as the morphology of Hegyestű and Badacsony are unique sights. The structures formed by the erosion of volcanic rocks, as well as the remntants of cinder cones and lava spatter cones provide insights into the volcanic activity and its impact on the landscape.

The present-day geological structure and geomorphology of the Balaton Highlands, the natural asset of the region, is the result of basaltic volcanism and erosion.

6. Somló Wine Region

The Somló Wine Region lies on the slopes of the extinct volcanoes of a young (3–5 Ma) monogenetic volcanic field on the southeastern edge of the Little Hungarian Plain. The Little Hungarian Plain Volcanic Area is located on the western edge of the Pannonian Basin, i.e. a group of small volcanoes with a maximum diameter of a few hundred metres, which were active only for a short geological time (<1 year) and consist mainly of basalt and basaltic tuff.

The volcanic activity occurred in several phases. The volcanoes were fed by mantle-derived magmas that initially intruded into the water-rich sediments causing massive phreatomagmatic eruptions. Tuff rings were created by the accumulation of fine-grained volcanic debris. Subsequently, when there was almost no water left in the area, the intensity of the eruptions decreased and Stromboli-type eruptions became dominant that formed cinder cones. Hawaiian-type eruptions followed, characterized by gas-driven lava fountains that created lava spatter cones. In the final stage, when the magma had been outgassed, lava lakes were formed. An exception is Kissomlyó, where the volcanic activity took place in two stages. A small lake formed in the crater in-between and the basalt that intruded into the crater formed pillow-like structures (pillow basalt).

The volcanoes in the wine region exhibit a variety of morphologies due to erosion and mining. While Somló is a perfect, untouched butte, mining at Ság and Kissomlyó has removed the hard lava rocks, leaving a hollow space in their place. The changes in the morphology of former volcanoes have contributed to the understanding of the geological evolution of the region.

Volcanic rocks are represened by dark, porphyritic or aphanitic basalts. The most important primary minerals are olivine, pyroxene, plagioclase, and magnetite. Geochemical studies revelead that the basalts originate from the asthenosphere with a similar geochemical character to that of the source region of oceanic island basalts. The basalts were dated to 3.4 Ma on Somló, 4.63 Ma on Kissomlyó and 5.48 Ma on Ság Hill.

During the weathering of the rocks in the area, various minerals (e.g. olivine, pyroxene, and plagioclase) break down, releasing elements such as calcium, magnesium, and sodium. Common weathering products and secondary minerals are clay minerals, calcite, chlorite and Fe-oxides. The most common soil types formed by the weathering of basalts and surrounding rocks are Cambisol (brown soil), Luvisol (clayey brown forest soil), Lithosol (skeletal soil), and Erubase (black calcareous soil).

Rocks of the Somló Wine Region not only play a role in understanding the geological past, but also contribute to the formation of soils and the development of local wine culture. Formations revealed by erosion and mining provide important insights into the processes of volcanic activity.

7. The "proper" epilogue

This study shows that the criteria for classification as a wine region were not determined by geological conditions and data, but by other factors. Of the 22 wine regions of Hungary, 16 have a well-defined volcanic terroir. According to our data, about 18% of the total area of the 16 wine regions is covered by volcanic and plutonic rocks and igneous talus derived from them. Statistical data cannot always be clearly linked to wine regions, wineries, vineyards or outcrops of igneous rocks, just as the individual volcanic terroirs do not belong to a single wine region. In our experience, most of the Hungarian winemakers are terroir-oriented, use the (natural) concept of terroir and consider it important to emphasize that the wine also reflects the geo-heritage of the area.

A terroir wine is associated with a specific area. The question is: what is the unit of area that accurately represents the volcanic terroir. In this study, volcanic terroir was defined at the level of wine regions, but due to the characteristics of volcanic-plutonic systems (especially the irregular surface distribution) a precise classification is only possible after very thorough geological, petrological, and pedological studies at the vineyard or even parcel level. This also means that within a vineyard with an excellent volcanic terroir, it is possible to produce a selected wine at parcel level based on the diversity and surface distribution of the plutonic and volcanic rocks.

This is by no means an easy task. Is it possible? Yes, indeed. Is it a lot of work? Yes, of course. Do Hungarians have the necessary expertise? Yes, indeed. Is there the will to do it? Yes, of course.

Let us make sure that the terroir wines take their rightful place.