Hydrogeological setting of Balaton Highland

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Balaton Highland is a geological band extending between Bakony Range and Lake Balaton to the west from Balatonfűzfő.

Lake Balaton

Lake Balaton famous for its several hundred year's tradition of bath culture is a natural lake having the largest surface in Central- and Western Europe. Its surface amounts to 594 km^2 at average level with a water volume of 2 billion m^3, and average depth of 3.6 m. According to recent studies it was formed between 7000 – 5000 years ago being thus a very young feature.

The lake's popularity is due to its silky, soft water. The oxygen-rich, calcium-magnesium-hydrogen-carbonate water quickly takes over air temperature. Its chemical composition qualifies it as *mineral water*. It is warmest in July with 20-25^oC and pH of 7.8-8.8, being slightly alkaline. Its water quality is affected by phosphorous promoting the proliferation of algae. Its water level is regulated by the lock in its southern shore, in Siófok. Its investigation started in 1891, the collection of hydrological data was initiated in 1921.

Quite a number of renowned scientists were involved in the investigation of the lake and its environment. Undoubtedly *Lajos Lóczy Sen.* (1849-1920) was the most outstanding of them. He compiled and wrote the Balaton monograph including 10 volumes in the turn of the 19th and 20th centuries.

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Hydrogeological impact of the geological formations

The northern shore of Lake Balaton is especially rich in one-time and recent springs and small creeks that provided excellent sites for the formation of roman settlements almost 2000 years ago. The *Lower Palaeozoic* (Ordovician-Silurian) phyllite prominent in the geological makeup of the region is practically impervious whereas the overlying Permian Red Sandstone can be characterised as an intermediary fissure-water aquifer featuring relevant secondary porosity only in the fractured zones and loosened segments. This horizon gives rise to the sparkling springs in *Balatonfüred*.

Triassic carbonate rocks (limestone, dolomite and marl) fail to compose a uniform karst system as a result of lithological variations and secondary tectonic effects. These formations can be classified in four hydrogeological units. The Lower- and Upper Triassic marls feature the lowest water yield, the Lower Anisian shallow marine carbonates provide intermediate discharge, whereas the continuous sequence made up by the Anisian dolomite and limestone, the Ladinian Buchenstein Formation and the Lower Karnian Füred Limestone Formation (with its largest karst passage, the Lóczy Cave) is of high water yield. The Upper Triassic platform carbonates (limestone and dolomite) are the hydrogeologically most important geological formations of the area with the Great Dolomite Formation featuring the highest water retention capacity giving rise to a number of high-capacity springs, like Siske Spring in Balatonfüred, Nosztor Spring in Csopak and Király Well in Lovas.

Triassic formations are covered by Pannonian basalt and basalt tuff over large areas. Some smaller lakes were formed in the upwelling zones of the local flow zone in the regions blocked by one-time lava flows (Bika Lake, Barkás Lake, Sátorma and Füzes Lake on the summit of Fekete Hill). The main part of the infiltrating water flows upward in the fissures of the basalt sequence breaking surface as springs on the boundary of the Somló Formation, approximately some 100-150 metres above the karstwater level in the Triassic assemblage. The coldest springs emerge from the fractured, fissured basalt. It turned out that water drifts in joints result in uneven temperature distribution and the coldest point of the system can be observed in the vicinity of the spring's gushes. It is called the *chimney-effect*, where the temperature of the springs is 8-10^{o}C. The Mesozoic main karstwater aquifer and the fissure water aquifers in the Permian formations are drained by the wide-ranging Tihany Formation. Cyprian spring gushes in the boundary of the Somló and Tihany Formations.

The Nagyvázsony limestone extends over quite a large area as overlying Triassic and older Neogene sequences. It has been widely subjected to karren impact, it occurs in porous blocks as well as in compact, hard versions. The *freshwater limestone* in which local

suspended karstwater level can be formed is hydrogeologically completely isolated from the Triassic karst.

Quaternary formations regulate infiltration characteristics, they slow down precipitation to reach deeper, older aquifers. Given that they do not have considerable thickness in the area they do not have significant impact on deep infiltration of precipitation.

Tectonic impact

Geological units extend in NE-SW belts but perpendicular transverse strike-slip faults play also an important role determining the flow characteristics of the water. Horizontal faults feature very high transmissibility along their strike like Kékkút Fault along the boundary of Permian and Triassic assemblages where strong water flow can be presumed towards SE. The majority of spring gushes can be associated with such sites, the faults are pressure equalizers and deep faults have a certain role in the upwelling of carbonic acid.

The imbricated structure formed as a result of space reduction processes is a determining factor in the communication between different hydrogeological units (Hidegkút, Nemesvámos, Szentkirályszabadja, and Pécsely Basin).

The flow and nature of groundwater

Free surface high karstwater is typical of Balaton Highland. Precipitation has a large impact on its regime. The discharge of springs follows the precipitation peak with a delay of 1-2 months and it is affected by a number of factors. Natural flow directions are regulated by differences between the altitude of the sites of infiltration and discharge.

Springs gush commonly along the faults crossing the strike of the sequences. Balaton Highland can be characterised by the formation of local flow systems (Kál Basin in the region between Balatonfüred and Balatonalmádi, Pécsely Basin). A local pressure depression was created in Fűzfőgyár Site as a result of industrial karstwater exploitation, whereas an inferior pressure depression effect of the bauxite mines in Nyírád was observable in the environs of Hegyesd and Monostorapáti.

Given that local systems are in hydraulic communication with each other, considerable pressure changes can occur within short distances. It is typical for the intermediary flow system that karstwater in the north flows towards north, whereas in the south towards Lake Balaton. Local gushes were detected in the bottom of Lake Balaton detected already by *Lóczy* in 1913.

Of the two spring groups those in Kékkút and in its vicinity gush in the boundary of the Permian and Lower Triassic formations feature a rather high mineral content due to their high carbonic acid content. Ammonia content is very high with a considerable amount of the trace elements Li, B, Sr, Co, and Ni with quite much iron dissolved and precipitated of the Permian Red Sandstone. Hydrogen-carbonate, chloride and sulphate are also more than in usual karstwater.

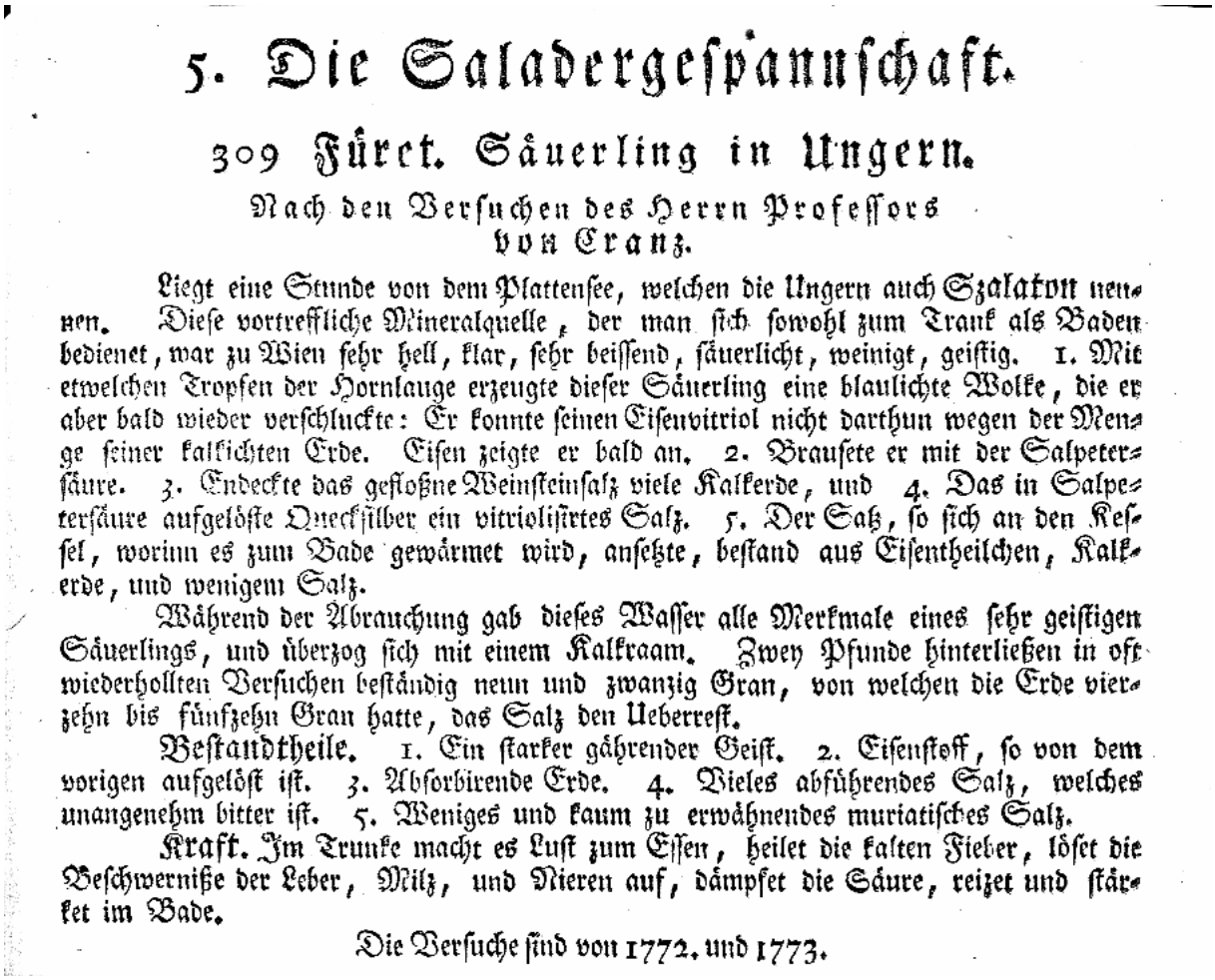
The other group includes karstwaters gushing of Triassic limestone and dolomite aquifers. They feature calcium-magnesium-hydrogen-carbonate water of the average temperature of 12°C with considerably diluted, low chloride and intermediate sulphate content.

In *Balatonfüred* and in its environs medicinal springs have been known since Roman times, their water has been used for centuries. The today heart hospital was built between 1866 and 67 where cardiovascular diseases are treated.

Figure 1 **Balatonfüred,** Kossuth Spring, Rabindranath Tagore (1861-1941) bust

The cave formed in the Upper Triassic limestone was named after *Lóczy*. It was brought about by carbonic acid water upwelling during postvolcanic processes. Sparkling springs still active today evolved presumably then, like the one-time Franz Josef-, today Kossuth-, as well as Berzseny Spring and Polány Well (*Figure 1*). Travellers, natural scientists and famous persons were keen on coming to Balatonfüred. The components and the effect of the acidic water were described by Heinrich Johann Crantz (1722-1797), professor of medicine and

chemistry in his monograph (1777) (*Figure 2*). Another, favourable opinion of the medicinal water was stressed by the English physician, Richard Bright (1789-1858). The Indian poet, Rabindranath Tagore (1861-1941) was treated also here. He commemorated his convalescence with planting a lime tree and his bust stands in the lakeshore promenade.



5. Die Saladergeſpannſchaft.

309 Füret. Säuerling in Ungern.

Nach den Verſuchen des Herrn Profeſſors von Crantz.

Liegt eine Stunde von dem Plattenſee, welchen die Ungern auch Szalakon nennen. Dieſe vortreffliche Mineralquelle, der man ſich ſowohl zum Trank als Baden bedienet, war zu Wien ſehr hell, klar, ſehr beiſſend, ſäuerlicht, weinigt, geiſtig. 1. Mit etwelchen Tropfen der Hornlauge erzeugte dieſer Säuerling eine blaulichte Wolke, die er aber bald wieder verſchluckte: Er konnte ſeinen Eiſenvitriol nicht darthun wegen der Menge ſeiner kalkichten Erde. Eiſen zeigte er bald an. 2. Brauſete er mit der Salpeterſäure. 3. Endeckte das gefloßne Weinſteinſalz viele Kalkerde, und 4. Das in Salpeterſäure aufgelöſte Queckſilber ein vitrioliſirtes Salz. 5. Der Satz, ſo ſich an den Keſſel, worinn es zum Bade gewärmet wird, anſetzte, beſtand aus Eiſentheilchen, Kalkerde, und wenigem Salz.

Während der Abrauchung gab dieſes Waſſer alle Merkmale eines ſehr geiſtigen Säuerlings, und überzog ſich mit einem Kalkraam. Zwey Pfunde hinterließen in oft wiederhollten Verſuchen beſtändig neun und zwanzig Gran, von welchen die Erde vierzehn bis fünfzehn Gran hatte, das Salz den Ueberreſt.

Beſtandtheile. 1. Ein ſtarker gährender Geiſt. 2. Eiſenſtoff, ſo von dem vorigen aufgelöſt iſt. 3. Abſorbirende Erde. 4. Vieles abführendes Salz, welches unangenehm bitter iſt. 5. Weniges und kaum zu erwähnendes muriatiſches Salz.

Kraft. Im Trunke macht es Luſt zum Eſſen, heilet die kalten Fieber, löſet die Beſchwernüße der Leber, Milz, und Nieren auf, dämpfet die Säure, reizet und ſtärket im Bade.

Die Verſuche ſind von 1772. und 1773.

Figure 2 H.J. Crantz's article about the springs of **Balatonfüred** (a part)

Apart from the 34 springs a number of boreholes were drilled in the city. Four, 20-45-m deep groundwater observation wells were established in 2009.

According to the investigations performed till today medicinal water evolves of the upwelling groundwater, whereas carbonic acid may originate of the Earth's mantle. While in 1959 the mineral water was recorded as of typical carbonic acid nature with more than 1000 mg/l carbon dioxide, this value was substantially lower in 1968 (600 mg/l) and again higher in 1977 (950 mg/l). Simultaneously, the amount of cations and anions vary as well qualifying accordingly the mineral water as alternating between calcium-magnesium-, magnesium-calcium-hydrogen-carbonate- and sulphate types. Its total dissolved solids contents varies essentially between 2000 and 3000 mg/l. Starting from the second half of the 19th century the mineral water had been bottled for almost 100 years.

In **Tihany Peninsula**, apart from the traces of the Late Miocene basalt volcanism having acted some 8 million years ago, cones of calcareous tuff formed during postvolcanic processes. They can be observed as constituting geyserites. It was the period of the evolution of the so-called maar lakes, whereas in the periphery of the volcanic region hot springs emerged. Eruptions occurred in aqueous environment in the one-time Pannonian lake and in the karstwater positioned higher. It is the site of the occurrence of Congeria fragments washed out by Lake Balaton. From 1995 mild medicinal water of 20°C has been produced of a 200-m deep well. It is exploited of Triassic limestone presumably underlying Pannonian and Miocene sequences. A study trail and a street were named here after Lajos Lóczy.

The majority of rapid creeks flowing from the highland towards Lake Balaton were utilised by a series of ***water mills*** essentially for cereal grinding. The water mill of **Örvényes** established on Séd Creek on the ancient land of the Tihany Abbey was in function already in the 11th century operating continuously still under Turkish occupation (*Figure 3*). As a result of the introduction of modern mill equipment after 1885 the small water mills ceased to operate. Together with the other ones this mill was taken in state property in 1951 and it was put under protection. Due to lack of water it does not operate now. It acquired its present form following a main reconstruction in the 19th century. To date the village became a holiday resort.

Figure 3 The water mill of **Örvényes**

The most spectacular sites of **Kál Basin** are the areas covered by stone sea. The basement of the basin is made up of Middle Triassic dolomite subjected to karst processes underlain by the aquiclude Lower Triassic marl. Groundwater flows towards Korny Lake which was formed on the boundary of the two sequences. The lake's level follows the changes in karstwater level.

The Campilian limestone is the oldest Triassic formation detected first in Kékkút in 1921 in a depth of 12 m. It is overlain by clay then by gravel near the surface. The recovered water emerged 0.6 m above the surface and the related yield was 19.4 l/m. It has been qualified as calcium-magnesium-hydrogen-carbonate carbonic acid mineral water. It was the chemist, Kálmán Emszt who first called the spring Theodora, originally denoted Anna Spring and the new well was also named Theodora. The name's origin is still unclear. It has long been misleading that the producer related it to the Byzantine empress Theodora. 4 exploitation and 4 observation wells have been established in Kékkút so far. The Theodora mineral water of Kékkút leads the market of bottled mineral water production in Hungary (*Figure 4*).

Figure 4 The Theodora mineral water spring of **Kékkút**

During the hydrogeological research it turned out that the karstwater system of Kál Basin is independent of the Bakony main karst. The mineral water of Kékkút does not originate directly of the karst but it emerges along the crossing of two significant structural lines. Apart from a major water flow along the faults, the fissure water of the Permian sandstone as well as the Lower Triassic karstwater can also be detected mixing in.

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