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Geothermal Potential Map

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Introduction

The present investigations have been carried out in the framework of the DANREG programme established by Austria, Hungary and Slovakia. The DANREG programme made possible the investigation of the thermal water conditions of areas along the River Danube in the light of recent research. The objective of the programme was to study thermal systems across country borders using uniform methods resulting in the joint publication of a geothermal potential map.

The legend shows very simply the expectable water temperatures by drilling to impermeable rocks (mainly crystalline schists) in maximum depth of the basin bottom by different colors (cold = blue; mixing moderate Temp. = variations of violet; Hot = red).

Hydrogeothermal setting

Danube Basin

In the Danube Basin following four areas or structures, have a potential for the exploitation of geothermal water: the central depression, the Komárno block, the Dubník Depression and the Levice block. Within these the geothermal waters are bound to Neogene sands, sandstones and conglomerates, as well as to Triassic carbonates. The temperature field at a depth of 1500 m is characterized by temperatures ranging roughly from 45 to 85 °C. Characteristically, the highest temperatures occur in the eastern part of the area (ˇahy), while westwards, near the Malé Karpaty Mts, the temperature decreases to about 65 °C. The lowest temperatures (45 °C and even less) were observed in the Komárno block.

Central depression

Off dish-like shape and brachysynclinal structure, this depression, located between the towns of Bratislava and Komárno/Komárom, is filled with Quaternary, Rumanian, Dacian, Pontian and Pannonian sediments. Quaternary and Rumanian sediments are represented by gravels and sands, while the other stages by alternations of clays and sandy clays with sands and sandstones.

The geothermal water reservoir is limited at the top by a plane at a depth of 1000 m and at the bottom by a relatively impermeable basement — an aquiclude (clay), which dips periclinally from its periphery to its centre and reaches a depth of 3400 m (Franko *et al.* 1984). Hydrogeologically, the structure has probably an interstratified overflow, pore permeability and confined water level regimen. Geothermal waters, bound mainly to sands and sandstones (aquifers) of Dacian, Pontian and Pannonian age, are heated to 42–92 °C. The clays stand for an aquiclude. The presence of aquifers decreases from the periphery towards centre of the basin, which is due to the fact that aquifers diminish downwards. Based on lithology six (6) hydrogeological units have been established in the reservoir and its cover, each representing a complex with different ratio of aquifers and aquicludes (*e.g.* a complex with approximately balanced aquifers and aquicludes; a complex of aquicludes, a complex with aquicludes predominating over the aquifers etc.). The hydrogeological units do not equivalent the stratigraphic units of the Neogene, because the beds of aquifers and aquicludes alternate vertically and wedge out horizontally.

The aquifers with the highest absolute transmissivity coefficient (Tp > 1011 m^3) occur characteristically in the central part of the depression, while towards its margins these values decrease. The most extensive aquifers are the Pontian ones, whereas the Pannonian aquifers, and in the surroundings of Èalovo (È–2) also the Dacian aquifers occur at their periphery. The temperature field is characterized by temperatures of around 65 °C (FGÈ–1) to 75 °C (GNZ–1) and by heat flow ranging from 68 to 87 mW/m^2. The yield of springs (free weir) is between 4–23 l/s, the water temperature between 45–74 °C, and the mineralization between 1.1–8.3 g/l. Thermal output of wells ranges from 0.5 to 4.6 MW.

As a rule, the changes of the chemical composition of waters with depth reflect an increase in both the mineralization value and the Na-Cl [component S1(Cl)] and a decrease in Na-HCO_3 (component A1) and in HCO_3/Cl ratio. The geothermal waters belong to a distinct Na-Cl type, with mineralization exceeding 10 g/l (typical for Badenian and Pannonian aquifers), or ranging between 5 and 10 g/l (Pannonian and Pontian aquifers), as well as to Na-HCO_3 type with mineralization between 1–5 g/l (Pontian, Dacian and well "washed" Pannonian aquifers), or up to 1 g/l (Pontian and Dacian aquifers). A transition between the distinct Na-Cl type and the Na-HCO_3 type of water represents the Na-Cl type with the A1 component exceeding 30 meq/l, or the Na-HCO_3 type with S1(Cl) component exceeding 30 meq/l (typical for Pontian aquifers). Genetically, the Na-HCO_3 type with mineralization up to 1 g/l , or ranging from 1 to 5 g/l, belongs to petrogenic water, while the others to marinogenic water (infiltration degraded). The waters contain CH_4, N_2 and CO_2.

To assess the potential resources of geothermal waters the Wang 2200 T desk computer programme, MODEL (M. Fendek) was applied. The Jacob's transformation of the Theis equation was used to calculate the relation of pressure depression and of well yields. The calculation was made for the depth level 1500 m, for well spacing 6 km, for an average water temperature above 60 °C and for a seasonal exploitation (185 days per annum) using free weir. Provided the water is so used as to reach the reference temperature (15 °C) the potential resources amount to 1027 l/s, which would correspond to a gross thermoenergetic potential (total exploitable thermal output) of 193 MW.

Komárno block

Located in the SE part of the Danube Basin, roughly between the towns of Komárno and ˇtúrovo, the Komárno block is a morphologically dissected structure of the Transdanubian Range. The geothermal waters are known to occur in natural springs (Patince, Virt, Obid) and wells.

In structural–hydrogeothermal terms (Remπík *et al.* 1979; Remπík *et al.* 1992) it was divided into the Komárno high block and the Komárno marginal block. In both structures the thermal waters are bound to Triassic limestones and dolomites of the pre-Tertiary, or pre-Cretaceous basement. The Komárno high block is limited by the isobath 700–800 m of the pre-Cretaceous carbonate basement, or by tectonic lines, respectively, running next to these isobaths. It is a structure with an intense exchange of water, which is strongly cooled to reach at depth between 600–800 m the temperatures of 20–22 °C, at depths 1100–1300 m 24.5 to 26.5 °C and at 3500 m 40 °C (Remπík *et al.* 1992). The water is of Ca-Mg-HCO_3 type with mineralization reaching some 0.7 g/l (in the area of ˇtúrovo the Ca-SO_4 — component is increased due to contact with gypsum) and are genetically classified as petrogenic (carbonatogenic) waters.

The Komárno marginal block surrounds the high block from the western, northern and eastern sides. It accumulates thermal waters heated to over 40 °C (the highest temperature observed to date is 68 °C). Its water is of the Na-Ca-HCO_3-Cl type with mineralization of some 0.8 g/l (Modrany area) and a mixed type of water with predominance of Ca-SO_4 component and elevated content of Na-Cl component, with mineralization between 2.8–3.9 g/l (Komárno area). All these types represent waters of mixed genesis. The mixture is composed of carbonate-sulfatogenic waters proper and from distinctly infiltrationally degraded waters from the overlying Miocene, which soaked into the carbonate complexes mainly during the incipient stage of the Miocene transgression. Also the waters of Na-Cl type (Marcelová) with mineralization of 90 g/l (brines) occur here.

To calculate potential resources of geothermal water for the Komárno high block a natural dynamic discharge through a structure, amounting to 133 l/s of water heated to 20–40 °C, was considered. Their technically exploitable thermo-energetic potential amounts to 9.7 MW (used as a whole). The results of hydrodynamic balancing proved to be in agreement with the results of geothermal balancing. The geothermal water regimen is affected by the pumping of karstic waters on the Hungarian side (Tatabánya, Dorog). The Komárno marginal block accumulates static reserves of geothermal waters.

Dubník Depression

This structure, located in the eastern part of Danube Basin, is filled mainly with the Miocene sediments underlain by crystalline schists and granitoids of the Veporicum Unit (Proterozoic–Palaeozoic). As observed in the wells HG-3 and VTB–1 the geothermal waters are bound to basal Badenian clastics (conglomerates, sandstones) at a depth between 1000 and 2000 m. At the 1500 m depth level the temperatures range between 65 and 85 °C. The yields of wells vary between 1.5 and 15.0 l/s, and the temperatures between 52 and 75 °C. The water is of Na-Cl type and its mineralization ranges from 10 to 30 g/l. These geothermal waters can be exploited by means of reinjection. The thermo-energetic potential of local geothermal energy reserves, obtainable by means of reinjection, represents 808 MW (Remπík & Fendek 1995).

Levice block

Located in the north-eastern part of Danube Basin, this block, composed of Mesozoic rocks of the higher nappes, is locally underlain by the remnants of the Mesozoic envelope of the crystalline complex (Fusán *et al.* 1979). To the east the structure is limited by a north–south striking fault running west of Levice. The nappe Mesozoic smoothly dips from a depth of some 700 m at Santovka–Túrovce ridge, or at Levice, respectively, down to 1300–1500 m at Pozba (wells P–1, 2, Po–1). As a plateau it dips first smoothly and then more steeply westwards. The Mesozoic envelope of crystalline complex which merges to a depth of about 2500 m, is its only westward continuation. Neogene sediments overlie the Mesozoic rocks. Most geothermal waters in the Mesozoic rocks (mainly Triassic dolomites, subordinately quartzites), as well as in the basal Badenian clastics, are heated to 70–80 °C (Remπík & Franko 1983). The main aquifers (Triassic dolomites) are 232 to 375 m thick. The temperature field at the depth level of 1500 m is characterized by a temperature around 80 °C. Geothermal waters intersected by the wells Po–1 and GRP–1 in Podhájska, have yields of 53 and 28 l/s, the temperatures of 80 and 69 °C, respectively, and the mineralization reaches around 19 g/l in both of them.

In the Levice block only distinct Na-Cl types of geothermal water occur, with mineralization ranging between 12 and 20 g/l. Mineralization decreases from 19.8 g/l (Podhájska–1) in the west to 12–14 g/l (Pozba–4) in the east. Genetically, the waters are of degraded marinogenic type, which percolated during Neogene (probably during Badenian time) into the bottom of the sedimentary basin (made up of Triassic dolomites) and metamorphosed at the water-rock interface.

The prognostic thermo-energetic potential of geothermal energy resources in the Levice block has been assessed by means of modeling which implied exploitation through a reinjection system (exploited and reinjected amount <50 l/s, network of wells 2 km apart), represents 126 MW [Franko *et al.* (eds) 1995]. Exsurgences of geothermal waters are known in the eastern part of Danube Basin beyond the mentioned area, or structure, respectively. These were intersected by shallow wells and represent geothermal water potential. At Santovka (B–3) and Dudince (S–3) these waters are heated to some 26–27 °C.

Vienna Basin

A southern offshoot of the Slovak part of Vienna Basin (Kröll & Wesselly, 1993) represents the westernmost part of the Danube region. The basement of the Neogene is composed mainly of Mesozoic limestones and dolomites of the continuation of the Alps to the Malé Karpaty Mts envelope unit, located at depths between 500 and 1000 m. These carbonates, as well as the basal clastics (conglomerates, sandstones) of Neogene age, presumably contain geothermal waters with temperatures ranging between 20–50 °C, in the central parts till >100 °C and mineralization of up to 190 g/l (Aspern 1, Hauptdolomit 3106–3296 m, 108 °C).

In Austria former and general applications came especially from exploration wells for hydrocarbons, like in Hungary and Slovakia. The realization for spas (*salus per aquam*) in former times (energy crisis during the late seventies) especially for heating purposes took place at carbonate *i.e.* dolomite reservoirs, further from Neogene sandstones (esp. Upper Pannonian), which have been proved to be important.

The region best known by drilling and geophysics is the Vienna Basin, where the Neogene sandstones and carbonates of the Calc-Alpine substratum, the Lower Pannonian Basin, the Transdanubian Range, Bakony — Balaton region in Hungary and the southern Slovakian Danube region are important.

Below the Alps autochthonous Malm carbonates have been proved to contain extended aquifers. Thick Dogger deltaic sandstones could be targets in some cases.

An extended area containing a considerable large reservoir volume is the NCA Zone with its thick platform carbonates and joint porosity but unfortunately out of the evaluated Danubeb region. We will animate a follow-up project for the northern and especially southern following part bordering to Slovenia, which is well-equipped in geothermal research by the Lubljana Geothermics Institute. In Austria areas with a relatively high geothermal gradient can be distinguished from those with a lower gradient. The southeastern parts of Austria (Styrian Basin, Burgenland) adjacent to the Pannonian region have a high gradient according to the low thickness of the lithosphere there. In the Vienna Basin and the Molasse the gradient is normal and in the Alps it is low. High temperatures would require deeper drilling, but thicker reservoirs are available.

North Vienna Basin

The northernmost nappe unit in the North Vienna Basin is the continuation of the Flysch Zone and the Klippen Zone. Beneath the Neogene sediments these rocks are generally impermeable local — regional layers. These consist of an alternation of schists and marls with intercalated sandstone layers of Neocomien till Eocene age. In the North Vienna Basin being the wide spread basis of the pre-Neogene sediments the Flysch Zone is not the absolute impermeable baserock. As the tectonically basis nappe of the overlaying NCA (Northern Calcareous Alps) nappes the Flysch sediments continue far out of the project-area to SE. Because of their pelitic grain-size they act as an impermeable basis for karstic aquifers.

The northern NCA nappe units consist in the project area basically of the Göller nappes, belonging to the Ötscher nappe system and therefore to the Tyrolicum. In the northern part, which is covered by Neogene, the tectonically disturbed substratum (anhydrite, schists, dolomite of Permoskythian age, further Middle and Upper Triassic: shales and sandstones, on top thick Hauptdolomit) has been investigated by oil-drilling. In the bordering zones to the Upper Alpine nappes (Juvavicum) the Cretaceous Gosau as a continuation of the Grünbacher Mulde could be detected in the underground.

The Upper Alpine nappes (Juvavicum) also begin with a Permoskythian basis, consisting of shales, dolomites and anhydrites. They are overlain by thick Ladinian dolomite and limestone, further on the clastic Lunzer beds of the Carnian. On top of it there are dominant thick Hauptdolomit and Dachsteinkalk as important karstic aquifers. Openhole-tests from Triassic dolomite in 1800–2950 m in Baumgarten/March brought out formation-saltwater with 15–81 g Cl/l, like in Gänserndorf, where the joint-permeability seems to be better. The temperatures might be higher, because of greater depth (3100–3500 m) of test intervals. The Hauptdolomit in depths of 2500–3300 m beneath Vienna (Kaisermühlen, Kagran, Hirschstetten) contains hydrogen sulfide salt water with 25–31 g Cl/l.

The Neogene strata (conglomerates, sandstones) have been tested in Breitenlee (Helvetian–Badenian), Essling (Karpat) and Strasshof (Helvetian–Badenian). Whereas the clastic sediments show moderate chloride concentrations (6–16 g Cl/l) in depth of 1450–2630 m some mixing processes with deeper Cretaceous or Triassic dolomite aquifers seem to be responsible for chloride enrichment up to 103 g Cl/l. This can be determined by the results of discharge tests at the mentioned unsuccessful oil-drilling Aspern 1, which was evaluated for geothermal heating purposes in 1976 (Hauptdolomit 3106–3296 m, 108 °C in 3100 m, Q = artesian, pumping 11.6 l/s at draw-down s = 300 m, Total mineralization is 190 g/l with 92 g Cl/l).

From other sites unfortunately no temperature measurements or continuous discharge measurements (pumping tests) are available. Geothermal research led to calculations of up to maximum 190 °C temperature exploitable fluid (Ronner 1974).

South Vienna Basin

The pre-Neogene structures and continuations of the Alpine nappe systems are comparable to the mentioned units in the northern Vienna Basin (Wessely 1983). Additionally beneath the NCA nappes there is the prolongation of the Grauwacke Zone to NE. Near Orth/Danube dark shale-clay-schists, quartz arenites and quartzites, further shaly limestones and marls have been drilled. Generally these rocks are nearly impermeable aquitards — aquicludes.

The Grauwacke Zone together with the overlying NCA units have been moved tectonically over the Central Alpine and Tatridic basement rocks.

The Central Alpine Unit lies beneath the Grauwacke Zone and the Neogene basin-filling from the Hundsheimer Berg via Leitha Hills and Rosalien Mts far on to SE. These small mountains in Austria mark the continuation of the Alps to the Carpathians.

At the base there are older Precambrian schists and gneisses. They are overlain by rocks of the Semmering-Mesozoic (Verrucano, quartzites, Middle Triassic limestones and dolomites, Keuper shale, Kössener schists and Liassic limy marls. These rocks are mainly impermeable, except the Middle Triassic dolomites, which might be aquifers by joint-porosity and karstification. But their catchment area on the surface seems to be to small for recharge and storage capacity.

Similar conditions characterize the Tatrides, a further deeper geologic-tectonic unit. Their Permian–Mesozoic covering rocks act hydrogeologically like the Semmering Mesozoic, mentioned above.

The Neogene sediment filling of the South Vienna Basin is very heterogeneous. By several SW–NE and some SSW–NNE striking faults numerous vertical high and low structures have been set up during the Alpine orogeny. The faults are mainly synsedimentary, so that the thickness varies sharply.

Important for hydro-geothermics are the deep zones. The so-called "Schwechater hole" goes down to –5200 m B.s.l., where as the "Mitterndorfer Senke" reaches –3000 m B.s.l. and is still tectonically active by sinking tendency. It has been filled in its uppermost part with 170 m of quaternary gravels with great drinking-water management importance.

The sedimentation started in the Karpatian age with terrestric-limnic boulders, conglomerates, weathered gneisses and pelitic matrix between the components. The permeability of these mudflow sediments is relatively low.

After those primary terrestical deposits, marking the first uplift of the Alps and the Carpathians in the hinterland a tectonic stable phase followed. That was the reason for the transgression. The main synsedimentary subsidence took place from Badenian till Dacian time. At the borders of the South Vienna Basin especially surrounding the Leitha Mts platforms with lithothamnia reefs, like a ring-shaped atoll enclosing sandy intercalations. Beneath the younger terrestrial Pannonian sediments, drillings at Frauenkirchen and Halbturn tested in 1600–1850 m saltwater (19 g Cl/l) with 70 °C already at 1500 m depth. Sarmatian regressive conglomerates and sandstones have been explored at Pamhagen with 71 °C in 1778 m and 4.6 g Cl/l, whereas the lower Pannonian in 404 m yielded a small inflow with 30 °C and 5.4 g Cl/l.

Pannonian Basin

Research on the geothermal conditions of the Pannonian Basin has been in the forefront of interest for over a century. As a result of the increasing deep-drilling activity it has been recognized that there is a significant thermal water reserve in the Mesozoic carbonate formations of the Transdanubian Range (TR) and in the clastic sediments of the basin regions. Research started in the 50s has revealed that not only the geothermal gradient is significantly higher throughout the country than the world average but also the Earth heat flux density. *I.e.,* the heat of the Pannonian Basin is not simply a result of local effects of uprising thermal water but it reflects the elevated temperature of the lithosphere below the whole tectonic unit.

Thermal springs of the TR and the subsurface continuation of the Mesozoic formations have been known and used for centuries. Thermal water wells installed in Budapest on Margit-sziget (Margaret Island, 1867) and in Városliget (Municipal Park, 1868–78) in the end of the last century were among the firsts in Europe followed by many other drillings in the begin-ning of the century. Thermal water exploitation in the Little Hungarian Plain (LHP) began in Gyõr in 1962 and the number of drillings was multiplied in the decades after. Numerous studies investigated the thermal water conditions of the region, the most important being those by Korim (1973, 1981), Lorberer (1977, 1982, 1986, 1996) Liebe & Lorberer (1982) and Liebe (1983).

The Hungarian study areas fall in various geological units: the northern part of the Kisalföld Basin, north-eastern part of the TR (Gerecse, Pilis Mts and its subsurface continuation to the Rába Line) and the Northern Hungarian Palaeogene Basin.

Kisalföld Basin

The Little Hungarian Plain (Kisalföld) is the surface of the southern part of a deep basin which is shared also by Slovakia. The subsidence of the basin in different rates began probably in the late Early Miocene. The thickness of the Tertiary sediments reaches its maximum (7000 m) near Szigetköz. The formation of the depression started in the Miocene. Sinking was highest at Lipót and Lébénymiklós where a sharp tectonic line is found (Rába Line). The tectonic line, however, is present only up to the upper parts of the Miocene formations. Thick Tertiary sediments were deposited concomitantly with the intensive sinking. The basement is made up of two units of different age and type. In the area west of the Rába Line Palaeozoic metamorphic rocks form the basement covered unconformably by Neogene formations. The only exception is borehole Msz–1 in which Permian–Lower Triassic sandstone has been described. The basement of the area located to the east of the tectonic line consists of Mesozoic rocks of Transdanubian Range-type which rise to the surface at the eastern margins along a series of listric faults.

The basement composed of metamorphic rocks subcrops at the western margins of the basin. Metamorphic rocks form blocks on the surface (Sopron Mts). The presence of Eocene formations in the basin margins is uncertain but Oligocene clayey marl beds overlying Triassic rocks have been hit by drilling at Komárom.

Miocene formations can be found almost everywhere at the basin margins and are present in great thickness in the middle region of the basin. The Miocene strata are thinning on the highs of the Palaeozoic basement and may be absent in places. Their average thickness is 3000 m. They consist predominantly of pelitic rocks with thin interbedded sandstones, conglomerates and occasionally tuffs and tuffites. Shallow marine sediments consisting of limestone, conglomerates and sandstone can also be found at the basin margins (*e.g.* Hegykõ region).

In the whole region of the Kisalföld Basin the Miocene rocks are overlain by Pannonian formations. Their thickness exceeds 3000 m in the Gyõr Basin. There, the predominantly pelitic rocks of Early Pannonian age could not be penetrated by drilling because of the great thickness. Thin Lower Pannonian formations were also found at the basin margins and highs. The Upper Pannonian formations are characterized by alternating sand, sandstone and clayey marl. Their thickness is 500 m at basin margins and their maximum thickness is 2100 m. The sequence terminates with a widely distributed coarse-grained Pleistocene fluvial clastic formation of spatially changing thickness.

The north-eastern region of the Transdanubian Range (TR)

East of the Rába Line the Mesozoic TR-type formations of the basement of the Kisalföld Basin are rising gradually to higher elevations along the eastward listric fault series. Further away they outcrop as the north-eastern part of the TR in the Gerecse and in the Pilis Mts. These formations outcrop until the Esztergom–Pilis tectonic line and then continue further in the depth. They outcrop only in the Danube left bank blocks (Nagyszál, Nézsa). The Gerecse Mountain is a fractured rock body situated between the Tata and Esztegom tectonic lines where, besides the SW–NE and NW–SE striking fractures, N–S lineaments active in the Palaeogene occur also.

The very thick Upper Triassic carbonate basement formations are covered by a thin Jurassic sequence. The Cretaceous sediments are made up of flyschoid, clastic series which differ from those of the TR. In the marginal areas (Tatabánya, Dorog basins) there are Palaeogene formations of significant thickness.

The TR unit continues towards north-east in the Buda Hills and Pilis Mts which is indicated by the continuation of oblique faults, such as the Ördögárok and Vörösvár faults, are easily discernible in the Pest Plain. Besides the thick Triassic formations of great extent, the Jurassic and Cretaceous formations are entirely missing. The entire Palaeogene and Oligocene series can be found. The Miocene is present in reduced thickness.

The Northern Hungarian Palaeogene Basin

The mid- to early Alpine structure sinking to the NE along the Pilis fault is replaced by the Palaeogene Basin and Miocene volcanic mountains. The basement covered by Tertiary sediments can be separated into two parts which are connected along a tectonic line. The Mesozoic basement rocks are succeeded by Veporic metamorphic crystalline schists along the tectonic line.

In the cover of the Mesozoic basement at some places there are Cretaceous and Palaeogene sediments. Due to the subsidence started in the Eocene, a mighty sequence of Tertiary sediments was deposited. The Eocene is represented by biogenic limestone and marl. The Oligocene is made up of sandstone and pelitic rocks (clay, clay-marl) the clastic counterparts of which are found in the basin margins.

The thickness of the Miocene does not reach the thickness of the Palaeogene. The beginning of Miocene sedimentation is represented by sandy and gravely sediments, which are replaced by schlie formations both vertically and horizontally. One of the most typical Miocene formations are the volcanic rocks: andesites and andesite tuffs.

The Pannonian rocks (mainly Upper Pannonian) are gradually thickening to S–SE direction in the northern part of the Pest Plain.

Thermal water hydrogeology

The geological units of the study area form two separate but directly connected thermal water aquifer systems. These are the thermal water aquifer of the Kisalföld Basin made up of porous sediments and the karstic formations of the TR together with the thermal water aquifer system of the carbonate basement formation faulted bellow the thick loose sediments of the basin. The aquitard sediments in the Hungarian Palaeogene Basin are not important from this point of view.

Geology of the thermal water reservoir

Clastic thermal water reservoir. The thermal water aquifer system is primarily made up of Upper Pannonian formations, however, at the margin of the basin the Miocene complex might be also an important thermal water reservoir.

The Upper Pannonian reservoir can be well delineated from all sides. In Hungary, conventionally, groundwater having a temperature higher than 35 °C at discharge is qualified as thermal water. Accordingly, the upper boundary of the reservoir is provided by the 35–40 °C isotherm surface which is situated between 700–900 m depths. The lower boundary of the aquifer is defined by the impermeable Lower Pannonian formations. Thus the reservoir has a bowl shape in which significant thermal water reserves are located between 800 and 2500 m depth.

The thermal water reservoir is of a multi-layer system where the formation and hydraulic parameters of each layer change within wide ranges. The lower part of the Upper Pannonian unit contains thicker and more discontinuous layers. The thickness of each of the individual sand-sandstone aquifer layers varies between 2 to 20 m. Towards the interior part of the basin the number of sandstone aquifer layers is increasing but simultaneously thickness, porosity and permeability are decreasing as a consequence of sediment compaction within the young sedimentary basin. Commonly, the sand bodies are lens-shaped which cannot be followed for long distances laterally. Often, sandstone and clay–claymarl layers are interlaced and form multi-component thermal water units of large dimensions. Beside the frequent alternation of sand, sandstone and claymarl layers, sandy-clay and clayey-sand beds are also common. At the depth of 1800 m the degree of compaction increases sharply and results in the sharp decrease of porosity and discharge. The Pannonian formations are thinner and are lifted up higher at the margins of the basin. The fine-grained, pelitic sediments of the Lower Pannonian act as aquitards. These sediments form the lower boundary of the porous thermal water reservoir in the centre of the basin. The locally occurring sand layers are thin and are isolated from each other and the Upper Pannonian sand aquifers, thus they have no hydrogeological significance.

The base Miocene sediments of the Pannonian series are mainly claymarls but locally contain also porous limestone, sand and conglomerate layers of smaller thickness. The Miocene formations are located in the inner part of the basin below the Pannonian series of several thousand metres thickness, where due to the high temperature and compaction thermal water does not occur. However, at appropriate depths along the margin of the basin these layers might contain thermal water. These formations are of less significance from the viewpoint of thermal water exploitation and are utilized in most cases together with some other reservoirs. Two outcrops of these formations are known in the study area, at Hegykõ in the western margin and in the Ács–Bábolna region at the eastern margin of the basin.

Fractured carbonate reservoirs. The Mesozoic basement formation is situated at an increasingly higher elevation at the eastern margin of the Kisalföld Basin (*e.g.* in the Komárom region it is situated at a depth of around 1100–1200 m) thus becoming perspective for thermal water development. The Mesozoic aquifer system is the deeply buried continuation of the main karstic aquifer of the Transdanubian Range extending until the Rába Line. The main thermal water aquifers are Middle to Upper Triassic limestones and dolomites, the thickness of which can locally exceed over 3000 m.

The basement is strongly related to the surface formations also hydraulically. The Triassic thermal water reservoir complex is recharged by the infiltrating precipitation through the outcropping carbonate formations of the TR. The infiltrating precipitation is transported to the deep along hydraulic flowpaths and is heated up gradually. The main karst aquifer is covered by aquitards of Upper Cretaceous and Palaeogene formations situated above the karst water level at the margins. In this way, precipitation infiltrating into the main karst can reach discharge locations only flowing deep in the basement and can rise to the surface along tectonic lines at the mountain margins.

The flowpaths of groundwater transport are determined basically by the karstic basement surface and the base of sediments in the covering aquitard. Based on field experience in the TR karstification of limestone occurs mainly along tectonic lines and extends to only 100–200 m depth from the upper surface of the limestone.

Along greater tectonic zones exceptionally good aquifer zones might develop. Due to overthrusting the continuity of carbonate aquifer bodies is interrupted by Lower Triassic aquitards or marl beds clipped and dragged away in the tectonic zones. Thus the hydraulic conductance along certain faults might be limited. The bulk of groundwater can only move along the strikes of thrust zones in the reservoir towards the natural discharge sites. The average porosity of the reservoir is 2.3–2.5%. The transmissibility of the carbonate rocks varies within 5 orders of magnitude ($0.3 < T < 7000$ m^3/d). In cases of large water level fluctuation of certain tectonic zones this value can be even higher than 10 000 m^3/d. Such high-conductivity zones are the NW–SE striking transverse faults while the longitudinal faults are of aquitard character.

Because of their great significance thermal springs and thermal water wells in Budapest and in its surroundings which belong also to the main karst aquifer of the TR are important to mention. The tectonic zone developed along the River Danube provides discharge opportunity for groundwater recharging in the outcropping karstic area and heated up along deep flowpaths. However, along the structural zones cold water is recharging in nearby areas and is being transported towards the discharge zones. According to the mixing ratio of warm and cold water, the springs and frequently spring-groups have different water temperatures.

Thermal water hydrogeological characters of the Palaeogene. There is no notable thermal water aquifer system in the Palaeogene sediments of the basin. Aquifers having groundwater temperature higher than 30 °C are rare and have no appropriate recharge. To gain greater thermal water yields only the Mesozoic main karst aquifer provides suitable areas where the basement is situated deeper than 1000 m. The notable thermal water occurrences are bound to the tectonic lines.

Geothermal conditions

The numerous groundwater and discharge water temperature data of thermal water wells made possible the investigation of geothermal conditions of the studied region. The reliability of data produced by different measurement methods need to be assessed individually due to the differences in precision and measurement conditions.

In order to assess the reliability of groundwater temperature data in thermal water wells and hydrocarbon exploration drillings DÖVÉNYI *et al.* (1983) proposed a number of categories in which he accounted for the measuring conditions, groundwater temperature and temperature at different times after leaching. The highest expected temperature of the study area is between 50–60 °C at depth 1000 m below sea level in the Kisalföld Basin and is between 63–88 °C at depth 1500 m. In the central part of the basin it can be higher than 90 °C at the depth of 2000 m.

The groundwater flowpaths in the carbonate aquifer are determined primarily by faults and tectonic lineaments. Groundwater and bedrock temperatures change spatially significantly. The deeply circulating groundwater of elevated temperature is discharging at the structural zones of marginal areas of mountain ranges. The thermal karst springs and the main thermal water wells lining along the River Danube are situated in such a zone. The exact determination of temperature distribution is rather complicated due to the mixing of karstic thermal water with locally infiltrating cold water in the discharge zones. There are no direct measured data from the mountainous recharge area but the temperature of the karst water does not exceed 20 °C even at 1000 m depth. The geothermal gradient varies between wide limits in the study area. The gradient is between 32–47 °C/km in the Kisalföld Basin. In the TR the geothermal gradient cannot be determined.

Measurements were carried out at the Geophysics Department of L. Eötvös University (Budapest) in order to determine the thermal conductivity of the various sediments. Since the measurements were carried out to determine the heat flux for the whole country only few measurements were located in the study area which do not permit detailed evaluation.

Potentiometric conditions

In the Upper Pannonian thermal water aquifer system of the Kisalföld Basin hydrostatic conditions prevail. This means that the initial groundwater levels in the thermal water wells are around the groundwater table. The additional effect of "thermal lift" results in increased groundwater level. In the case of 60–70 °C discharge water temperature groundwater level increase is about 20 m and it is about 30 m in case of 70–80 °C discharge water temperature. Due to this, static water level at well installation is above ground surface almost everywhere. There has been a decrease in the static pressure as a result of groundwater extraction in the past decades. The decrease of pressure is characteristic for the entire region and coincides with the decrease of static groundwater level which is more than a few metres today. The pumping of the numerous originally artesian thermal water wells is carried out by submersible pumps. External effects are important mainly in the carbonate thermal water reservoirs at the mountain margins. In the TR beside drinking water extractions groundwater extraction in connection with mining was also present and had significant effect on the reservoir. The greatest pressure drop occurred in the confined thermal water aquifer. Recently, mining-related groundwater extractions have decreased to the fraction of the original volumes. This is manifested also in minor increase in the karst water levels. The restoration of the natural pressure conditions can be expected in a few years.

In the Kisalföld Basin pumping extraction of thermal water reserves —recharging from above or laterally in the drinking water aquifers— has water resources management constraints. This is because regional extraction would affect extractions recharged from the upper, cold water aquifers and would cause unacceptable decrease in the groundwater level. The excessive pressure drop in the upper drinking water aquifers would also increase the danger of contamination from the surface.

In wells located in the Miocene formations pumping has no water resources management constraints although uneconomic pressure drop caused by pumping may impose constraints due to the confined nature of the reservoir. The significant karst water extractions of different purposes do not allow the installation of new thermal water wells. The decrease of mining-related groundwater extraction in the last years is observable only in the slow restoration of the groundwater resources.

Due to groundwater extraction exceeding the recharge volumes the installation of new thermal water wells is possible only with the recycling of the extracted water. From a technical viewpoint, however, recycling of water is unproblematic only in fractured reservoirs. In case of porous thermal water reservoirs the problem of recycling is technically unsolved yet.

Chemical characteristics of thermal waters

The chemical composition of thermal waters found in the northern part of the LHP is largely variable both horizontally and vertically. The dominant chemical character and total dissolved solid content is different in the formations of various age. Waters of the Upper Pannonian aquifer are dominantly alkaline–bicarbonate with medium TDS (Total Disolved Solids) content which has extremely high values in the area of the Csorna–Kapuvár–Mihályi boreholes. These waters are also characterized by Cl, Na, TDS contents increasing with depth. Locally groundwater has high Br, I, Cl contents (*e.g.* Mosonmagyaróvár, Lébénymiklós, Gyõr). In the region of Mosonszentjános and Mihályi a very high SO_4 anomaly is found.

The Miocene thermal waters are varied with respect to their chemical character: alkaline–bicarbonatic waters can be found in addition to alkaline–chloridic waters. The TDS is very high regardless of the chemical character. Br and I contents are locally notable.

In the Kisalföld Basin the dissolved gas content is much variable, between 0.01–4.98 cm^3/m^3. The lowest value is found in the deepest aquifers while the highest one is observable in the marginal regions of the basin. The most important gaseous components are CO_2, CH_4 and N_2.

The groundwaters in the karstic thermal water aquifers are of alkaline–bicarbonatic or calcium–bicarbonatic character with low TDS. TDS and SO_4 is high only in thermal waters ori-ginating from greater depth in the region of Pér and Gyõrszemere. The large water extraction has resulted not only in the cooling of groundwater in the mixing zone of lukewarm to warm karst water but also in the decrease of concentrations compared to the original composition.

Many thermal water wells have been claimed to yield mineral water and have been used for medical purposes (baths and drinking therapies) for decades. The spas in Budapest and in the LHP are known world-wide.

Summary

The area studied by the DANREG programme can be divided into two large units in terms of thermal water hydrogeology: the clastic aquifer system consisting primarily of Upper Pannonian and Miocene aquifers and the carbonate aquifers.

The clastic reservoir made up mainly of Upper Pannonian sediments in Hungary, from Miocene aquifers in Austria is a multilevel reservoir in which formations and the hydraulic parameters of the rocks vary within wide ranges. Along the basin margins the Miocene thermal water aquifer of less importance occurs too. In the thermal aquifer system near-hydrostatic conditions prevail to which contributes the groundwater level increase caused by heating. The 40 °C isotherm surface is between 800–1000 m depths and the 10 °C isotherm surface is between 2000–2200 m. The chemical properties of thermal water in the Upper Pannonian aquifer is alkaline–bicarbonatic while in the Miocene aquifer it is alkaline–chloridic, locally mineral waters with high iodide and bromide contents are found.The Mesozoic carbonate thermal water reservoir situated to the east of the Rába Line can be considered as part of the karst system of the TR. As a result of tectonic processes the bed-rocks have been faulted and fractured making possible the storage of hundreds of cubic km of karst water.

Recharging karst water at outcrops withdraws heat from the host rock while heating up gradually. Groundwater flow turns to springs at the boundary of Mesozoic karstic formations where it mixes with cold water from unconfined karst aquifer and discharges to the surface. The two thermal water aquifers are discharged by a number of thermal water wells and springs which are utilized for various (balneological, agricultural and industrial) purposes.

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