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Thermal mineral water springs in Karlovy Vary

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Abstract In the western part of the Czech Republic about 130–180 km west of the capital of Prague, in an area of about 300 sq km, several dozen mineral springs occur from various origins, with water of different chemical characteristics, temperatures, and levels of carbonation and radioactive intensity. Mineral waters are widely utilized, in particular for spa treatment of a broad range of ailments as well as for bottling (curative and table waters), industrial uses of carbon dioxide, evaporation for the salts dissolved in them and, in regard to thermal waters, for local heating.

Key words Thermal mineral water springs · Spas · Czech Republic

Mineral waters in western Bohemia

The best-known spa resorts in western Bohemia include Marianske Lazne, Frantiskovy Lazne, Jachymov, and Karlovy Vary. Thermal (40–73°C), carbonated ($75\,\mathrm{l\,s^{-1}}$ of gaseous CO_2 and $400–1000\,\mathrm{mg\,l^{-1}}$ of free CO_2 dissolved in water) mineral waters rich in dissolved solids (TDS $6400\,\mathrm{mg\,l^{-1}}$) with a total discharge of $30\,\mathrm{l\,s^{-1}}$ help cure diseases of the stomach and the digestive tract. About 85,000 patients are treated every year in Karlovy Vary for three- to four-week stays. Additional thousands of visitors use the spas' sport and recreational facilities and for short relaxation stays.

Historical background

Discharging from the Tepla riverbed (tepla means warm in Czech), the Karlovy Vary thermal springs were known by the Slavonic tribes that settled in that region in the 6th century AD. Artifacts of Stone Age settlements have also been found near Karlovy Vary. The never-freezing mineral springs issuing from the Tepla River were known as "vary" (boiling, in Czech). The town was founded by the Czech King and Roman Emperor Charles IV in 1348, who conferred on it special privileges to use the thermal waters. There is a beautiful romantic legend associated with the foundation of the town:

King Charles set out from the Loket Castle (about 12 km from Karlovy Vary) to hunt in the surrounding deep forests. However, the hunt was not successful. At dusk, upon returning back to the castle, the royal entourage beheld a stately deer. They started to chase it. The deer tried to flee from the hunters and their dogs; it was pursued to the top of a steep rocky cliff and jumped into an abyss below. When the hunters climbed down into the deep valley they saw geysers of hot springs. "These are boiling waters" said the Royal Burgrave, "I wanted to show them to your Royal Highness for a long time but the deer came first." The king, enchanted by the beauty of the natural sight, said: "I will found a city on this place, and a castle to bear my name. They will enjoy all the royal privileges and will return health to those who ail. Let the rock from which jumped the deer that has led us to the hot springs be called the Deer's Jump for eternal memory." The statue of a deer on the rocky outcrop over the town, and the name of Karlovy Vary (Charles's Hot Springs) shall always remind us of their history.

The first written reports on physicians' recommendations to use the Karlovy Vary mineral waters for curative purposes date back to the early 16th century, and sound amazingly modern. Doctor Vaclav Payer recommends alternating drinking thermal water and bathing in it, and going on a diet. Fifty years later, and then throughout the Baroque period, the medical community's views of mineral water cures were quite controversial. Physicians prescribed drastic dosages: drink 60 cups of water a day and spend 12 hours a day in thermal water baths until "the skin cracks and the disease is allowed to leave the body."

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Fig. 1 Unknown artist of the Dresden School: View of Karlovy Vary from the east (colored engraving, 1815)

Treatment of patients similar to the way we know it today was introduced by Dr. Becher as late as around 1750.

The spa's importance began to grow from the mid-17th century. In the early 18th century, Karlovy Vary was already a social center popular with European rulers, nobility, and aristocracy (Fig. 1). New bath houses, hotels, a theater, and a colonnade were built there. Historical documents list 247 patients in 1756, 5000 patients in 1848, and 70,000 patients in 1912. Books kept by spa houses register repeated calls and stays of geniuses of the world's music, literature, and arts: Bach, Beethoven, Goethe, Schiller, Chopin, Wagner, Dvorak, Brahms, Paganini, Tchaikovski, etc. After 1945, a tradition was started in Karlovy Vary. International music and film festivals and scientific congresses were held there.

The first reports on the chemical composition of the Karlovy Vary springs date back to 1522. The analysis, which was performed on a par with current methods, was made by Dr. Becher in 1749. The first credible measurements of the mineral waters' discharge (yield $>2200\ \mathrm{l\ min^{-1}}$) are known also from the same period.

The capture of mineral springs has undergone considerable development. It was complicated by the carbonated mineral water frequently bursting through both inside and outside the Tepla riverbed. Initially (1570), thermal springs were accumulated in shallow collection holes in the river bed and water passed through open troughs to the bath houses. To achieve the required head, the water was allowed to expand and was collected in shallow boreholes, 3–5 m deep, situated on the Tepla banks. However, the boreholes quickly filled with incrustations—sediments from the mineral water—and had to be drilled again. In spite of that, thermal water kept breaking out around the boreholes as well as in the Tepla riverbed. This happened very frequently in the 18th and 19th centuries and caused damage to buildings and roads as well as causing a temporary decline in the yields from boreholes and springs. The break in 1809 was described by laymen as an earthquake.

A new technique of capturing carbonated thermal water was introduced in 1912 when R. Kampe installed flow-over towers for the water. At the head of a borehole, free carbon dioxide is separated from the water and fanned away. The thermal water is then piped to spa houses, containing only the dissolved CO_2. The high level of the Karlovy Vary thermal water's vulnerability, caused by its shallow captation, prompted extensive hydrogeological investigations, which resulted in a totally novel concept of collection. In 1981 and 1982, three inclined collection wells were drilled, thereby intercepting thermal water at a depth of more than 8 m for the first time in history. Thermal water accumulates at a depth of 44–88 m, which is the level of CO_2 evasion, thereby bringing to an end—after 500 years—the era of shallow development of the Karlovy Vary thermal springs, which had been fraught with numerous technical problems and placed constraints on the spa resort's development. In 1984–1986, deep boreholes also intercepted the so-called small springs.

Geologic and hydrologic setting

The Karlovy Vary region lies in the western part of the Bohemian Massif, which forms the easternmost part of the European Hercynian folding (Meso-Europe) and covers Bohemia and the western part of Moravia. The development of the Bohemian Massif has been affected by all major geotectonic cycles—Cadomian orogeny (which consolidated the base of the Bohemian Massif), Caledonian, Hercynian (characterized by disintegrating the Bohemian Massif into blocks of different development), and Alpine (neoid tectogenesis manifested in rejuvenation of the Epihercynian platform and vulcanism associated with Saxonian tectonics).

Of decisive importance for the genesis of mineral waters (cold, hot, carbonated) was the Ohersky Rift, which came into being by the resumption of neoid tectogenesis in an ancient mobile zone. The rift separates two important geological units of the Bohemian Massif: the Ore Mountains block (an area of intensive Hercynian tectogenesis) and the Tepla-Barrandien block (a stable Varisan intermontane block). The Ohersky Rift is delineated by two rift faults of a northeast–southwest direction and a distinct central fault along the longitudinal axis of the rift (Kopecky 1971).

The Ohersky Rift is part of the European–African system and has all the characteristics typical of an intercontinental rift (Kopecky 1971). In terms of hydrogeology and genesis of mineral water, the important features are an asymmetric terraced trough with a markedly alkaline magmatism, the existence of a gravimetric minimum, an intensive thermal flow, migration of neoid tectonic and volcanic activity in the direction of the structural axis (from northeast to southwest); and allied occurrence of CO_2 in the aftermath of active volcanism. Since the early 20th century, various authors have been pointing out the relation between the occurrence of CO_2 and neoid volcanism. The genesis of the regional distribution of mineral waters in the Bohemian Massif in relation to old neoid-rejuvenated structural–tectonic lines was first noted by Vrba (1964) (Fig. 2).

The Karlovy Vary thermal mineral waters are genetically linked to the Karlovy Vary Pluton as part of a complex of Hercynian intrusive rocks (Carbon-Perm) of granitoid composition. The Karlovy Vary Pluton is oriented crosswise to the Ohersky Rift and is composed of porphyric, biotitic, two-mica, and muscovitic granite to granodiorite, in some places heavily weathered to kaolin (to a depth of 50 m) and hydrothermally transformed (along the fracture systems). Pluton emerged in two intrusions separated in time—the older "montane granite" some 300 million years ago, and the younger "Ore Mountains granite" 250 million years ago. Thermal waters are associated with the latter. The Karlovy Vary Pluton surfaces include a large outcrop covering about 1000 sq km.

The occurrence of Karlovy Vary springs, concentrated in a short stretch of the Tepla valley thermal zone, is predisposed tectonically and associated with the intersections of faults of two directions. The west–east to WSW–ENE direction, which corresponds to the Ohersky Rift, is of transregional importance. Of local importance is a system of faults in the NNW–SSE direction (azimuth 330°, inclined 70–80° towards the southwest), which is referred to as the Karlovy Vary Thermal Spring Line. Geophysical investigations identified the depth of the Mohorovicic discontinuity as 30–32 km, the thickness of the granite pluton at about 10 km, a high geothermal activity of 80–90 mW m^{-2} (Cermak 1979), and the highest negative values of Bouguer anomalies in the Bohemian Massif.

Fossil and recent carbonated mineral waters have been identified in the thermal zone. The tectonically predisposed shatter belts are as much as 6 m thick, the rocks in them are disturbed by strong cataclastic to mylonitic deformations. They were subsequently silicified and filled

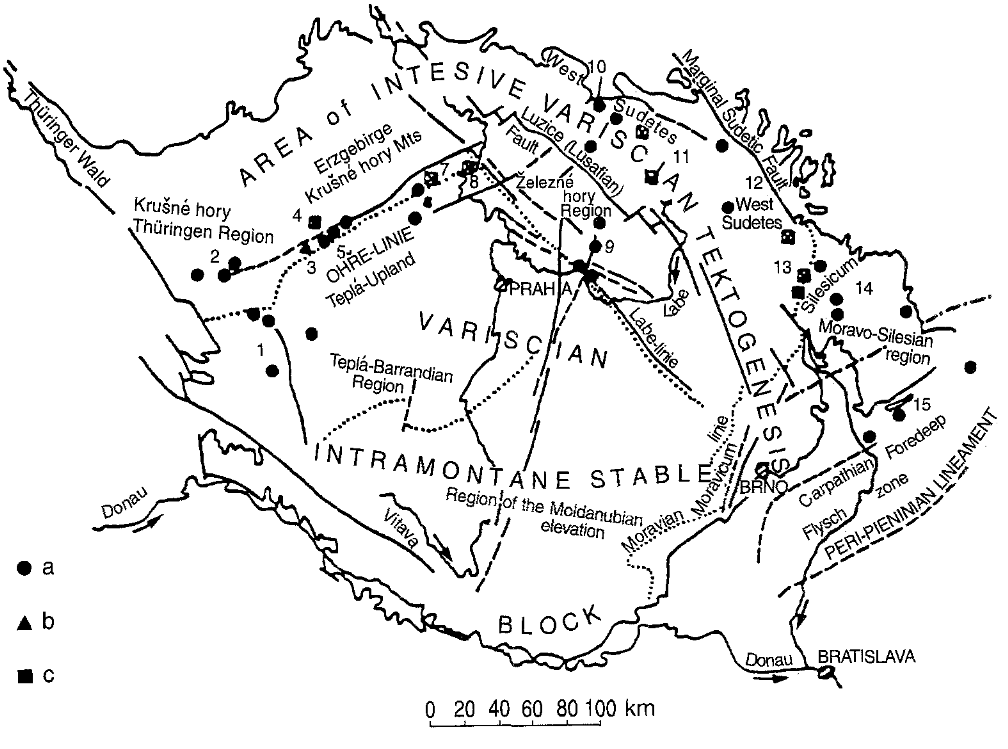

Fig. 2 Distribution of cold and thermal mineral waters in relation to the geotectonic structure of the Bohemian Massif: (a) cold carbonated mineral water; (b) thermal carbonated mineral water; (c) thermal nongaseous mineral water thermal springs of Karlovy Vary No. 3

with chert veins containing small crystals of barite, which is evidence of their hydrothermal origin. On the surface of the thermal zone there are layers of different types of sinters, as much as 8 m thick, including aragonite, a chemically almost pure calcium bicarbonate that crystallizes rhombically over 50°C and, characteristic of Karlovy Vary, pisolite (colloquially called pea-stone in Czech).

The fractures with active inflows of thermal water are open; an instance of this is an inclined investigation borehole, terminated at a depth of 133 m due to a massive influx of thermal water. A log sound (length 1050 mm, width 36 mm), which was sunk in the borehole passed through the footwall of the borehole into an open fracture to a depth of 370 m. The direction of the open fracture corresponded with the Karlovy Vary Thermal Spring Line.

The discharge of the so-called Large Springs is controlled, according to Vylita and Pecek (1981), by a fault system of the Karlovy Vary Thermal Springs Line (NNW–SSE) at the points where it crosses deep faults genetically associated with the Ohersky Rift (NE–SW). Investigations have identified outflow of the springs over an open, steeply inclined fault having a NNW–SSE direction. The surfacing of the thermal water is mobilized by carbon dioxide (the gas-lift effect). Due to high pressures, gaseous CO_2 that rises from the depths completely dissolves upon contact with water. It escapes from water only in the last stage of the thermal water rise when a change in pressure and temperature triggers its escape at a depth of 60–80 m. The process of evasion accelerates as it nears the surface, whereby the mass of the water–gas mixture (1 : 3) decreases, which positively affects the discharge level and yield from interceptor wells. The springs' high overpressure had ruled out the possibility of thermal water mixing with a cold water aquifer. Nevertheless, its effects were eliminated with development of a collection system for the thermal water installed in 1981–1982.

Isotope analysis of sinter deposits and studies of the morphological development and terraces of the Tepla river show that the emergence of the Karlovy Vary springs can be estimated between 40,000 and 250,000 years ago.

Since the first half of the last century, the group of so-called small thermal spring attracted geologists' attention because of its linear arrangement. The springs form a kind of peripheral area of the large spring field. Discharges of thermal water are concentrated in a tectonically disturbed zone up to 150 m broad, which runs through the Karlovy Vary granite in the Tepla valley under an azimuth of 326°. According to the latest investigations, the central part of the disturbed zone constitutes a tectonic trough (Vylita and Pecek 1981). In the tectonic zone, the granite is extremely disturbed tectonically, is silicified, and contains numerous chert veins. The differences in the temperature and yield of the small springs is attributed to the different outflow paths of mineral water in the tectonically disturbed subsurface zone and the extent to which thermal water mixes with a shallow groundwater system drained by the Tepla river. In tectonically fractured granite, a two-layer aquifer with fracture permeability had formed. The upper aquifer is composed of cold water with shallow circulation, which overlays the bottom aquifer with deep-circulating thermal waters. There is a close relationship between the two aquifers. In the course of increased recharge of the upper aquifer during periods of precipitation, the thermal aquifer is contaminated and subsequently so also are the shallow collecting holes that collect water from the small springs utilized for drinking cures. For this reason, in 1984–1986, the small springs were intercepted in boreholes at different depths, thereby eliminating the possibility of their contamination from the upper shallow cold aquifer.

Methods of development and use

Development of the so-called large springs, known as the Karlovy Vary Thermal Spring Field, was started nearly 500 years ago (about 1500 AD). At that time the springs discharged to two shallow holes on the right bank of the Tepla. Gradually, the number of holes increased to ten but their depth had never exceeded 8 m under the river bed. Thermal water was captured near the surface, in the caverns of the aragonite layer. The elevation of discharges of these springs gradually rose by 4 m. To prevent uncontrolled discharges in the Tepla riverbed, it was frequently and repeatedly sealed using various methods. However, with the growth of the spa resort and, in particular, erection of a new colonnade over the springs in 1975, shallow collection of springs was fraught with many technical problems. It was only the deep capture of the large springs in 1981–1982 that enabled the sealing off of uncontrolled discharges of thermal water in the riverbed, by means of injecting under pressure a mixture of clay and cement. These injections could not be used for the shallow capture because the mixture penetrated into the shallow wells through caverns. Into the layer of injected aragonite were drilled so-called regulating boreholes to relieve the thermal water and gas pressure upon the aragonite layer and the colonnade's foundations sunk under the level of the river's bottom. Relieving the aragonite plate was essential because very accurate measurements had demonstrated its rise by 25 mm over three years.

The deep captation of thermal springs had been preceded by several years of comprehensive geotectonic, petrological, hydrogeological, atmochemical, hydrochemical and geophysical investigations, and the drilling of several investigation boreholes.

On the basis of this investigation, four inclined (14.5–20.5°) capture wells were constructed that intersected at different depths (48–88 m) the tectonic fault zone through which carbonated thermal water rises to the surface (Fig. 3). The spring, with an overflowing fountain of thermal water and gas, was intercepted in an inclined well at 14.5°, azimuth 314°, depth 71 m, discharge level 12 m over the terrain. The discharge from the four wells of the large springs is 1700 l min^{-1} and 4795 l min^{-1} of carbon dioxide.

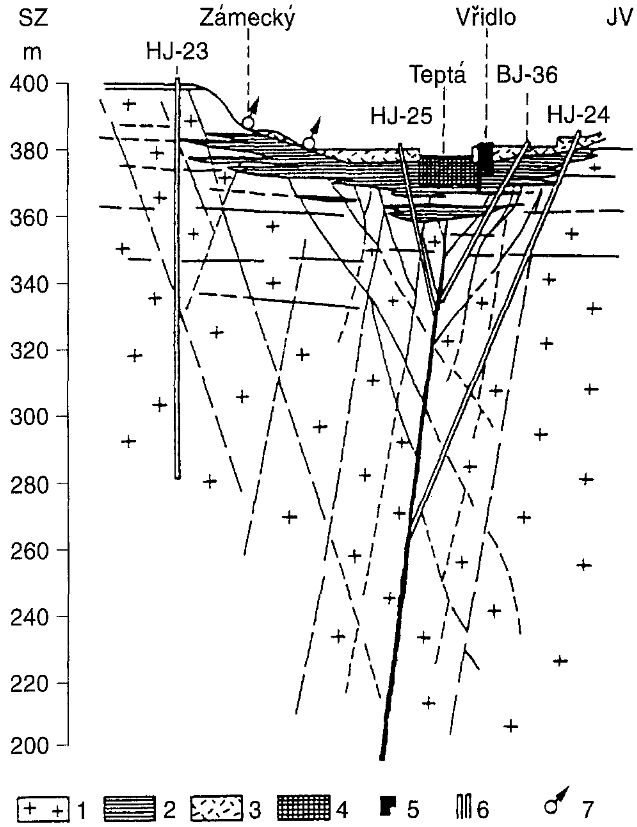

Fig. 3 Scheme of the discharge path of Karlovy Vary thermal mineral water (after Vylita and Pecek 1981): (1) granite; (2) aragonite; (3) Quaternary deposits and stockpiles; (4) old sealing of the river bed; (5) old shallow captation boreholes; (6) new inclined investigation and captation wells; (7) thermal springs

The wells were designed with anticorrosion screens and cement on their outer perimeter to a depth of about 16 m. When drilling penetrated a fracture with thermal water, a strong jet of water always spurted out, carrying clastic rocks up to 150 mm in diameter (in the 1–2 h until closing the borehole, several cubic meters of this material were ejected). The drilling required special equipment to keep discharges of thermal water and gas fully under control.

Capture of the large springs in deep wells and injections into the Tepla riverbed have resulted in an increase in and stabilization of the yield of thermal water and gas and a profound reduction in their vulnerability. The ratio of water and gas improved from 1 : 1.24 to 1 : 1.33. Formerly it had been 1 : 3 because thermal water is captured at approximately the depth of CO_2 evasion (Vylita and Pecek 1981).

Since the 15th century, the large springs have traditionally been used for baths and drinking for various cures. Later, evaporation for salts was introduced and carbon dioxide started to be used in industry. Souvenirs are made of polished aragonite, and the famous "petrified" Karlovy Vary roses are created by immersing them in the wells.

Capture and therapeutic application of the group of small springs began in the late 1770s when a local physician, Dr. Becher, introduced them in drinking cures. The small springs' yield is substantially lower. Depending on the complexity of their rise to the surface, they have varying temperatures, TDS, and CO_2 levels. The discharges from the springs were taken from shallow wells. The latest modifications of the wells were made before 1912. Shallow captation resulted in an increase in contamination of the mineral waters, and closing down of the springs for several days was normal. For this reason, in the case of small springs, comprehensive investigations resulted in a new concept of captation in wells of different depths (the original shallow wells have been preserved). The new wells have helped stabilize mineral water yields and temperatures, as well as volumes of gas. Only natural overflow from the boreholes is utilized, and the effects of the shallow cold aquifer have been completely eliminated. Small springs, and recently also mineral water from the wells that have replaced them, are used only for drinking cures. Some of the small springs have traditional Czech names.

Table 1 indicates that the yield and, particularly, the temperature of the mineral water from boreholes have increased in comparison with the earlier shallow captation.

Chemical character and temperature

The Karlovy Vary siliceous carbonated thermal waters are the hottest mineral waters of the Bohemian Massif.

Table 1 Comparison of average values of yield, temperature, and CO_2 level of some small springs from shallow captation holes and wells[a]

	Temperature (°C)		Yield (l min^{-1})		Free dissolved CO_2 (mg l^{-1})		Depth of well
Name	A	B	A	B	A	B	B
Karel	42.6	61.4	2	20.0	692	660	70.0
Vaclav	59.4	64.5	13.4	2.5	539	579	9.6
Libuse	41.2	62.9	5.1	3.8	610	814	17.6
Skalni	52.9	58.4	3.6	4.2	687	821	20.0
Rusalka	49.1	61.0	2.4	5.1	624	618	7.8
Mylnsky	52.9	54.8	2.6	3.4	704	682	24.0
Trzni	49.6	64.0	7.2	9.6	763	836	38.0
Sadovy	47.4	45.0	9.0	10.0	1020	1400	37.0
Svobody	61.4	64.6	8.5	9.5	566	755	38.6

[a] A: captation holes; B: wells

Table 2 Principal ions in Karlovy Vary thermal water[a]

Cations	mg l^{-1}	m val^{-1}	mval %	Anions	mg l^{-1}	m val^{-1}	mval %
Na	1701.00	73.985	85.52	Cl	612.34	17.270	19.56
K	78.90	2.018	2.33	NO_2	0.00	0.000	0.00
NH_4	0.11	0.006	0.00	NO_3	0.50	0.008	0.00
Mg	47.42	3.900	4.51	HCO_3	2127.13	34.860	39.49
Ca	124.25	6.200	7.17	CO_4	0.00	0.000	0.00
Mn	0.09	0.003	0.00	SO_4	1722.46	17.932	40.62
Fe	1.34	0.048	0.06	PO_4	0.32	0.003	0.00
Li	2.47	0.356	0.41	F	5.20	0.274	0.31
H	0.00	0.000	0.00	OH	0.00	0.000	0.00

[a] SiO_2: 76.20 mg l^{-1}; TDS: 6499.73 mg l^{-1}; pH: 7.45; BOD: 1.54 mg l^{-1}; conductivity: 8100; $^{222}R_n$: 5–50 Bq l^{-1}
mval: total amount of substance in miligrams per liter which corresponds to 1 gramatom of hydrogen
mval%: percentage proportion of total cation/anion content in 1 l volume

Their chemical type is uniformly Na–SO_4–Cl–HCO_3, their TDS more than 6 g l^{-1}, temperatures range from 40 to 73°C, free carbon dioxide dissolved in water ranges from 400 to 1000 mg l^{-1}. Major cations and anions are listed in Table 2.

Carbon dioxide dominates in gas content (95–99% vol). Among the remaining gases, nitrogen occurs at a level of tenths to units of percentage volume and oxygen at thousandths to units of percentage volume. Argon and helium are at very low levels.

Thermal water protection

Thermal water protection should be understood in terms of internal and external protection. Internal protection of thermal water against construction activities (laying of foundations) and local pollution sources was addressed successfully by introducing a deeper captation of the water in boreholes. External protection is of principal importance, as kaolin and lignite are mined from open-pit mines near the spa resort. Protective measures are defined in terms of area and implemented in three degrees of protection zones, as well as in terms of depth (extraction of kaolin and lignite is restricted to a certain depth derived from the discharge level of the thermal water). This restriction on mining is important, as formerly hot and carbonated groundwater broke out several times in the kaolin and lignite mines.

The regulation that defines the extent of the protective zones, and the Mining Act specifically list the activities that may be undertaken in protection zones, including the recharge areas.

References

Cermak V (1979) Thermal flow in Czechoslovakia. Prague: Geological Survey Institute

Kopecky L (1971) The Ore Mountains—Charecka Zone and Rynsky Fault and their importance for deep structures. In: Investigation of deep geological structures of Czechoslovakia. Brno: pp 157–185 (in Czech)

Vrba J (1964) Origin and occurrence of carbon dioxide and carbonated mineral waters, Varisan Platform, Central Europe. Econ Geol 59:874–882

Vylita B and Pecek J (1981) Investigation of the Karlovy Vary Springs structure. Geol Surv J 161–614 (in Czech)