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DEEP GROUNDWATER CIRCULATION IN THE TECTONICALLY ACTIVE AREA OF BURSA, NORTHWEST ANATOLIA, TURKEY

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Abstract—Faults related to the neotectonic stress regime of northwest Turkey permit the rise and outflow of thermal waters in two different districts in Bursa city. Based on their geographical, physical and chemical characterization, two different circulation systems with maximal spring temperatures of 82°C (TDS = 1207 mg/L) and 46°C (TDS = 504 mg/L) can be distinguished. Isotopic data indicate different local recharge areas and residence times of at least 50 years. Water temperatures at depth are about 110 and 50°C. Calcite dissolution and silicate hydrolysis are the dominant water–rock interactions. The dominant processes that affect both deep groundwater circulation systems are: mixing with shallow groundwater, loss of energy by heat conduction, and interaction with gases from mantle, crust and atmosphere.

Key words: hydrogeology, thermal waters, isotopes, Anatolia, Turkey.

INTRODUCTION

This study is part of the interdisciplinary project MARMARA realized by the Swiss Federal Institute of Technology (ETH) in Zurich (Schindler, 1993). MARMARA involves the study of tectonics, geology, hydrogeology, seismology, geodesy and geothermal prospects in the Marmara Sea region. This paper focuses on deep groundwater circulation of thermal waters within a tectonically active area of high seismicity in and around Bursa. Every step of thermal water evolution from infiltration to outflow has been reconstructed, taking into account water–rock–gas interaction, gas exchange, heating, and mixing. Based on the resulting model, we discuss the protection of the Bursa thermal waters and improvement of their use.

The city of Bursa is situated to the south of the Marmara Sea at the northern slope of the highest mountain in western Turkey (Mount Uludag, 2543 m a.s.l.) on a large travertine

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complex. Thermal waters with temperatures up to 46 and 82°C discharge within the two districts of Çekirge and Kükürtlü at the western end of Bursa city, just above the plain (100 m a.s.l.) (Fig. 1). As with many other geothermal systems in western Turkey, the circulation of the Bursa thermal waters is also closely related to a major fracture zone (Eisenlohr, 1995; Greber, 1994; Mützenberg, 1991).

Bursa was the first Ottoman capital (1326–1451), and has grown into one of the largest cities in Turkey, with a population of over 800,000. Once famous for the natural beauty of its environment, Bursa is today faced with environmental pollution caused by the expanding textile and automobile industry and the problem of its rapidly increasing population.

The semi-arid climate of Bursa is characterized by warm dry summers and cold wet winters. The mean annual temperature at Bursa is 14.4°C, and the mean annual precipitation amounts to 710 mm with little snow during wintertime. The climate of Bursa is strongly influenced by the high elevation of Mount Uludag, with precipitation of about 1000–1600 mm per year and a mean annual temperature of about 4.6°C at 1877 m a.s.l. (Gürer, 1991). On Mount Uludag the Mediterranean vegetation on the plain changes to deciduous forest characteristic of semi-humid regions with increasing altitude. In the higher, more humid regions of Mount Uludag, it is followed by mixed forest, humid coniferous forest, and Alpine vegetation at an altitude of more than 2000 m a.s.l. (Rathjens, 1952).

GEOLOGICAL SETTING

Turkey forms part of the Alpine–Himalayan orogenic belt and is a region of great tectonic complexity (Ketin, 1966). Its geological and tectonic evolution has been dominated by the repeated opening and closing of the Paleozoic and Mesozoic oceans (Dewey and Sengör, 1979; Jackson and McKenzie, 1988). Neotectonic activity and the lack of large-scale tectonic units make it very difficult to distinguish the effects of different orogenies within the Bursa–Uludag area (Sengör, 1985; Imbach, 1992). Recent studies involving Global Positioning Systems (GPS) and measurements of seismicity show that the strike-slip movements of the North Anatolian Fault System and its more extensional regime in the westernmost part still affect the Bursa area (Straub, 1996; Schindler, 1993; Eyidogan *et al.*, 1991).

Stratigraphic units

Mount Uludag consists mainly of metamorphic rocks of Paleozoic age (Ketin, 1947). Rocks of high-grade regional metamorphism, which crop out in the central part of Mount Uludag, are separated from rocks of low-grade metamorphism by tectonic contacts. A leucogranite of Oligocene age outcrops within the high-grade metamorphic unit in the region of the Uludag plateau (Bingöl *et al.*, 1982). The Paleozoic sedimentary cover of the crystalline basement can only be observed in the eastern part of the Bursa plain. There, strongly brittle-deformed basalts, marls, sandstones and arkoses crop out below brittle-deformed fusulinid-bearing limestones of Early Permian age. These are the oldest sediments that can be found. There are no unmetamorphic sediments of Late Paleozoic or Mesozoic age on Mount Uludag. In its western part, close to the hot springs, relics of Neogene sediments and volcanic rocks of Middle or Late Miocene age lie directly on low-grade metamorphic rocks.

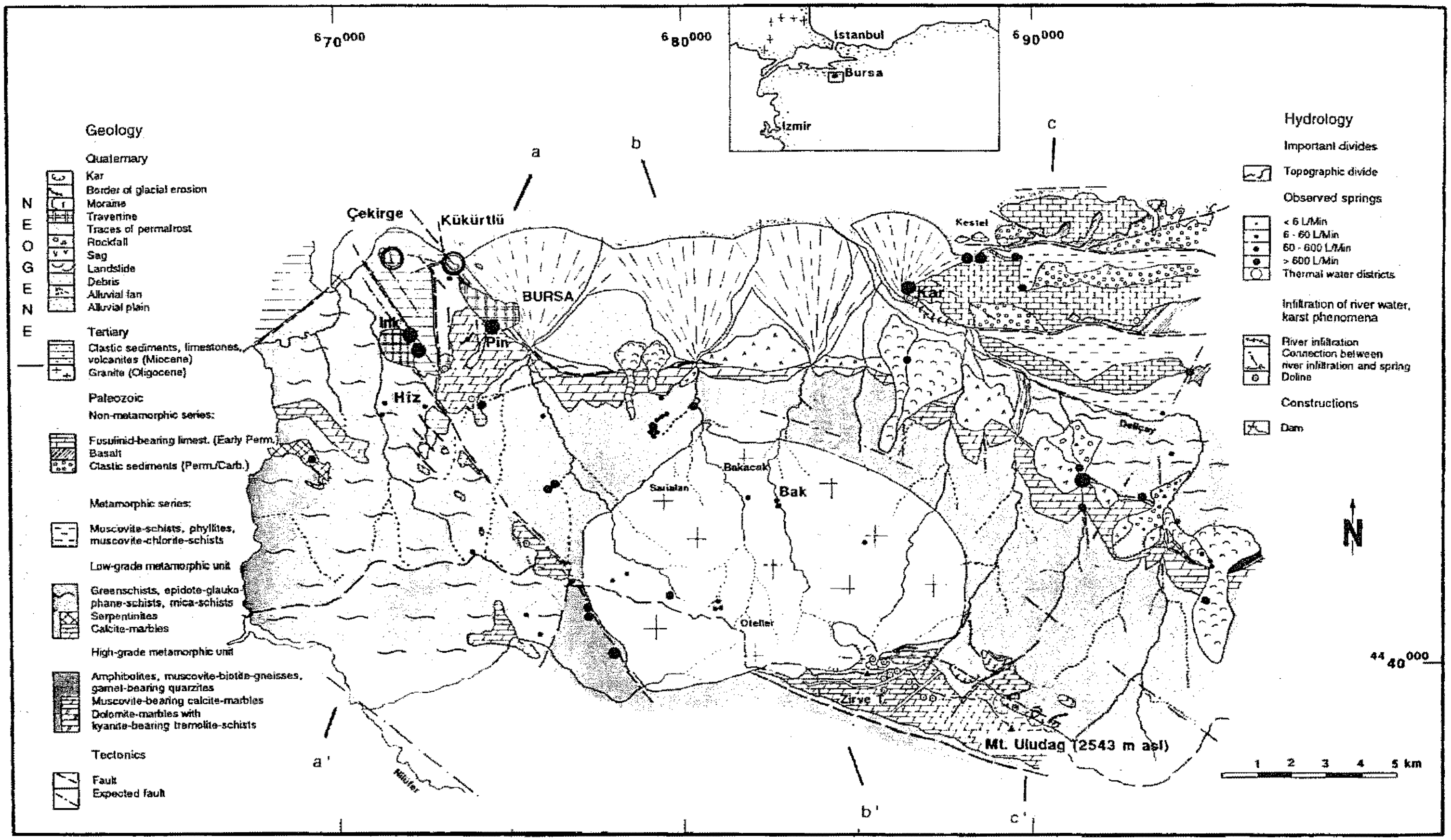

Fig. 1. Geological map of Mount Uludag, Turkey, with location of springs.

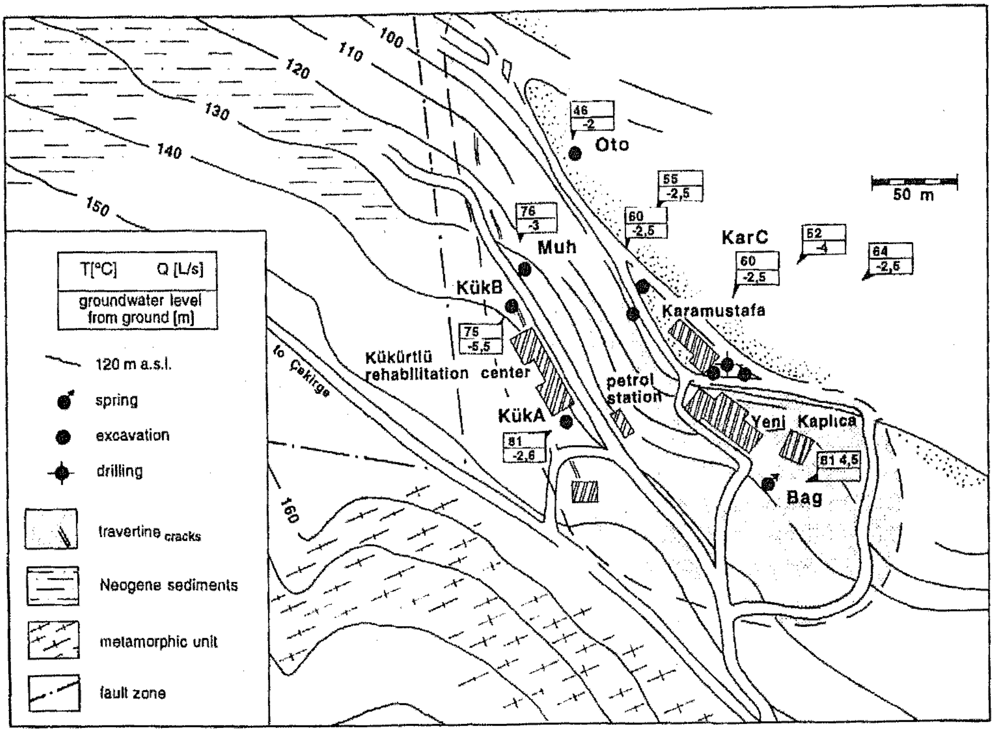

Fig. 4. Kükürtlü thermal water district.

restricted to the travertine complex, and the freshwater limestone of the Neogene unit acts as main aquifer close to the surface.

The "bathing" tradition in Çekirge can be traced back to the Roman–Byzantine period (Tchihatchef, 1887; Fritsch, 1882; Smith, 1851). The ancient name of the *Eski Kaplica* ("old public bath") was *Pythia* (the priestess of the temple of Apollo at Delphi). It was built around 500 A.D. The early development of a water distribution system in Çekirge made it possible to control and regulate the use of thermal water over many centuries. A well-organized health resort has been established, which nowadays impedes any additional use of thermal water by drilling [e.g. it is forbidden to use the thermal water from the *Ipeker* drilling (name of the owner), which was drilled illegally]. A common water distribution system shared by various private and state rehabilitation centres guarantees the controlled use of thermal water in this district. There are two main natural outflows: *Vakifbahçe* (Vak) and *Zeyni'nene* (Zey). The amount of water flowing from these, the hottest springs (Vak $T = 46$°C; Zey $T = 44$°C), cannot be measured precisely, but ranges between 700 and 1700 m^3 per day (for distribution network see Imbach, 1992). The additional use of legally drilled artesian thermal waters with temperatures of about 35°C at present amounts to 600 m^3 per day.

In Kükürtlü, which is situated two kilometers east of Çekirge towards the city-center of Bursa, thermal water flows out within a small travertine complex, which covers a tectonic contact (Fig. 4). Temperature and mineralization of the Kükürtlü thermal water vary within the location. The hottest and most mineralized thermal water discharges at the highest elevation of the travertine complex [e.g. the spring *Bagdemlibahçe* (Bag); T = 82°C, TDS = 1210 mg/L]. In shallow excavations and boreholes close to the plain, water temperatures of about 50°C (TDS ~1088 mg/L) are measured. Open cracks with vertical precipitation layers running parallel to the Neogene contact indicate that the thermal water rises along this important fault zone.

The use of thermal water in Kükürtlü developed later, under the Ottoman rulers (Hammer, 1818). The *Yeni Kaplica* ("new public bath"), was built in the 16th century and is still in use today. The hottest water within this district discharges at *Bagdemlibahçe* and is used for bathing purposes at the *Yeni Kaplica*. The amount of water flowing from this spring is not precisely known, but ranges between 150 and 400 m^3 per day. At all other localities a total of 200 m^3 per day is pumped from shallow excavations or boreholes for bathing and heating, but also for car-washing. There is no arrangement between the different private and state users in this district.

As the following quotations from Sandison show, the strong seismicity in this area affects the hot water systems:

> (Sandison, 1851, p. 19): "On the night of the 19th April, 1850, a shock of considerable violence occurred at Brussa ("Bursa"), lasting from eight to ten seconds ... It was noticed that at Zehekerghé ("Çekirge") a momentary stoppage of the mineral springs accompanied the earthquake."
> (Sandison, 1855, p. 543): "By its resistless force, computed of about thirty seconds' duration (earthquake from 11th April, 1855), almost every stone-building left standing was overturned, or irreparably shattered ... New streams of boiling water have burst out from the ground at the sites of the hot mineral baths, whilst the former currents there have been greatly increased in volume."

However, although strong seismicity affects the hot water systems, a long-term change in water temperature is not observed, as old reports from Grisebach (1841), Smith (1851) and Fritsch (1882) prove.

Cold water

The Bursa area is rich in cold groundwater. The most important springwaters on Mount Uludag are of Ca-HCO_3 type (TDS < 600 mg/L). They flow from strongly deformed marble layers at the northern foot of Mount Uludag just above the plain [e.g. the karstic spring *Pinarbasi* (Pin); Q_{max} = 600 L/s, TDS = 321 mg/L] and close to the post-Miocene main fault near the village of Inkaya [e.g. the karstic spring *Inkaya* (Ink); Q > 100 L/s, TDS = 438 mg/L]; for their location see Fig. 1. Both springs have built large travertine complexes. The lower part of the large Pinarbasi travertine complex is mainly covered by alluvial fans and acts as an important aquifer within the Bursa plain.

Karstic marble layers at the topographic divide between Mount Uludag and large dolines up to 100 m in diameter are considered to be significant infiltration areas. Karstic springs are also related to river water infiltration [e.g. the karstic spring *Karapinar* (Kar); Q_{max} = 1000 L/s, TDS = 314 mg/L]. In addition to these huge springs, which mainly discharge just above the plain, low salinity spring waters also emerge at a few liters per minute from within the gneiss unit at higher altitudes on Mount Uludag (TDS < 50 mg/L). The central high plateau of Mount Uludag above the timber line, where the granitic intrusion crops out, must be considered the likely recharge area of these springs. In addition to deep-seated groundwater circulation on Mount Uludag, shallow groundwater circulation takes place as a result of onion weathering and granular disintegration of

Table 3. Physical, chemical and isotopic data of selected springs. The Vak and Bag samples represent the hottest waters of the thermal water districts. The Ink, Pin, His, and Bak samples represent different cold groundwater types on Mount Uludag

	Bursa thermal waters		Cold groundwaters			
	Kükürtlü	Çekirge	Mount Uludag			
Sample name	Bag	Vak	Ink	Pin	His	Bak
Sampling date	89-Sept-05	89-Sept-06	89-Sept-08	89-Sept-08	89-Sept-12	89-Sept-11
Sampling altitude [m a.s.l.]	130	220	450	250	810	1650
Field analyses						
T [°C]	81.1	45.7	14.8	15.0	11.2	7.3
$EC_{25°C}$ [μS/cm]	1456	541	484	502	392	30
Q [L/min]	270	960	6000	36000	30	0.5
pH	6.5	6.7	7.4	6.8	7.2	6.7
Alc [mmol/L]	8.2	4.8	5.7	4.0	4.3	0.2
Aci [mmol/L]	2.2	0.8	0.6	0.5	0.3	0.3
O_2 [mg/L]	0.4	1.3	9.1	7.2	7.1	8.1
Cations [mg/L]						
Li^+	0.68	<0.1	<0.1	<0.1	<0.1	<0.1
Na^+	220	35	5	7	2	3
K^+	22.8	5.6	1.2	1.9	0.8	0.5
Mg^{++}	8	21	20	15	8	0
Ca^{++}	90	65	76	53	78	2
Sr^{++}	0.55	0.46	0.24	0.11	0.05	0.03
Ba^{++}	0.07	0.10	0.02	0.02	0.02	0.01
Mn^{++}	0.06	0.04	0.04	0.06	0.03	0.04
Fe^{++}	0.52	0.23	0.20	0.07	0.11	0.11

Anions [mg/L]						
F^-	5.8	0.9	0.1	0.1	0.1	0.0
Cl^-	11.6	5.4	5.8	7.6	4.4	3.5
I^-	0.080	0.050	0.040	0.040	0.040	0.045
Br^-	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
HCO_3^-	531	296	284	215	275	9
NO_3^-	<0.08	0.2	5.0	2.2	1.9	0.2
PO_4^{---}	0.50	0.38	0.25	0.27	0.21	0.14
SO_4^{--}	268	58	35	15	7	5
Balance						
Cations [meq/L]	15.45	6.63	5.65	4.23	4.59	0.29
Anions [meq/L]	14.93	6.28	5.64	4.11	4.82	0.36
Non dissociat. [mg/L]						
As	0.13	0.04	0.05	0.03	0.02	0.02
B	1.70	0.07	<0.004	0.02	<0.004	<0.004
Si	45.37	15.35	5.35	3.76	2.97	7.84
TDS [mg/L]	1207	504	438	321	381	31
Environm. isotopes						
^3H [TU]	0.9 ± 0.7	1.2 ± 0.7	12.1 ± 0.9	18.1 ± 1.4	25.6 ± 1.8	15.4 ± 1.3
δ^2H [‰SMOW]	-72.3 ± 1	-68.8 ± 1	-68.3 ± 1	-64.5 ± 1	-64.5 ± 1	-70.6 ± 1
$\delta^{18}O$ [‰SMOW]	-10.62 ± 0.15	-10.75 ± 0.15	-10.79 ± 0.15	-9.27 ± 0.15	-10.31 ± 0.15	-11.00 ± 0.15
$\delta^{34}S$ [‰CD] in SO_4	13.9	6.0				
$\delta^{18}O$ [‰SMOW] in SO_4	1.6	6.8				
Noble gases						
^3He [cm^3/g]	1.19×10^{-13}	8.35×10^{-13}	0.71×10^{-13}			
^4He [cm^3/g]	17.9×10^{-8}	118.2×10^{-8}	$(5.18 \pm 0.001) \times 10^{-8}$			
^{20}Ne [cm^3/g]	4.89×10^{-8}	24.75×10^{-8}	$(18.94 \pm 0.08) \times 10^{-8}$			
$^{20}Ne/^{22}Ne$	9.86	9.72	9.81 ± 0.05			

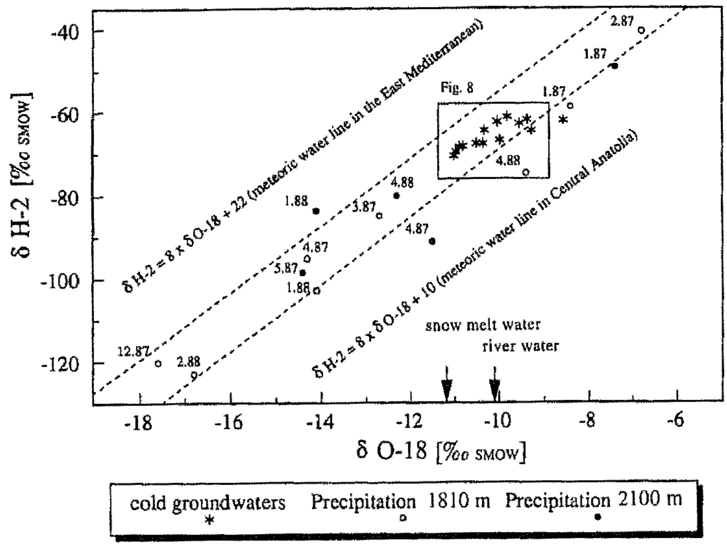

Fig. 6. Isotopic data of cold groundwaters, precipitation, melt-water and river water sampled on Mount Uludag at altitudes between 140 and 2310 m a.s.l.

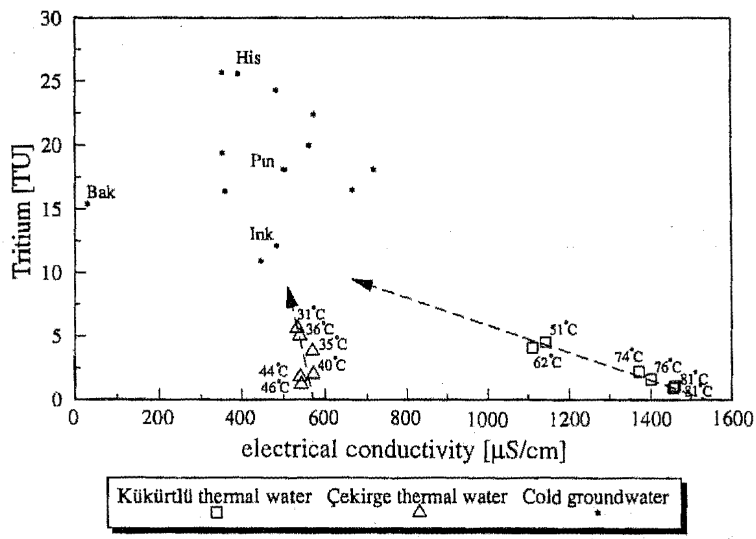

Fig. 7. Electrical conductivity and tritium data of hot and cold waters, indicative of water mixing within the outflow zone of thermal water.

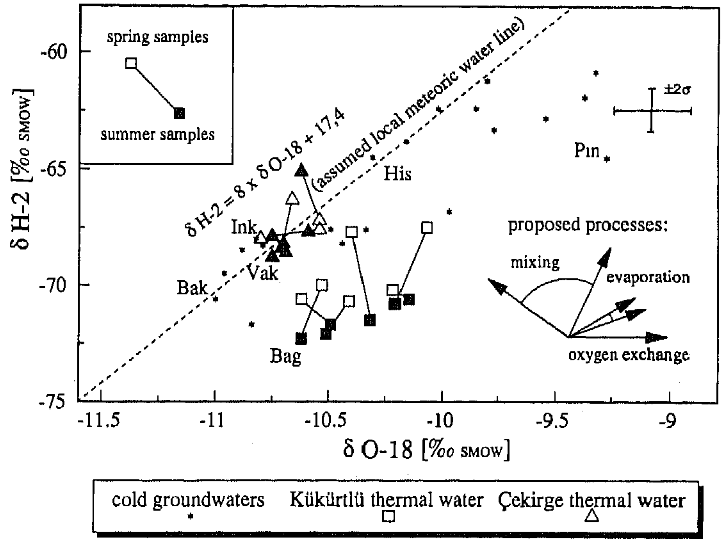

Fig. 8. Stable isotopic values of hot and cold groundwaters of Mount Uludag. All the cold groundwaters were sampled in summer 1989, and each thermal water was sampled twice, once in summer 1989 at the end of the dry season, and once in spring 1990 at the end of the wet season. Error given at 1σ level.

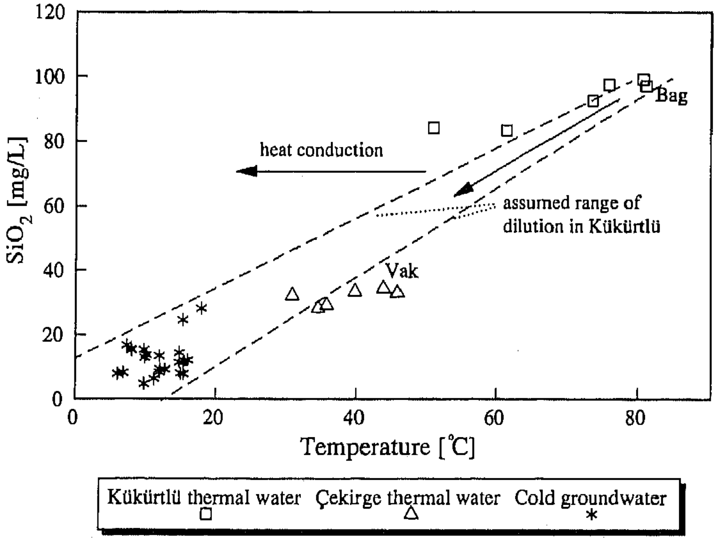

Fig. 9. Temperature and chemical composition of thermal waters, indicative of additional loss of energy by heat conduction.

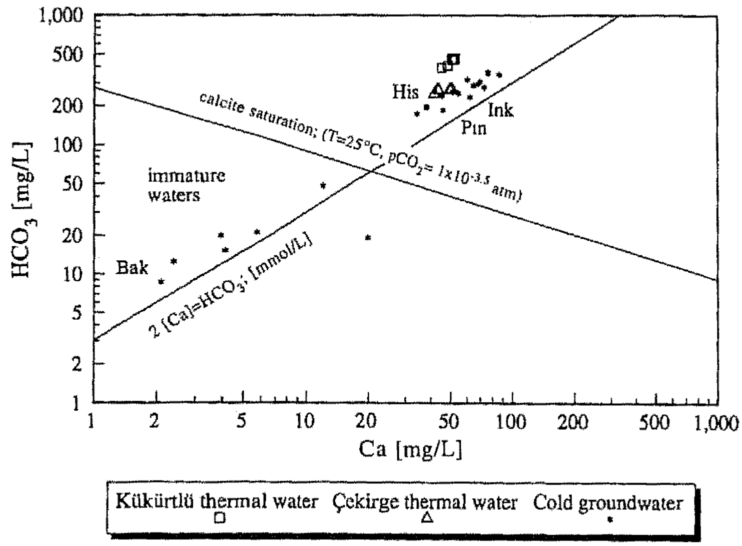

Fig. 11. Calcite dissolution is the dominant process leading to the mineralization of cold and hot groundwaters on Mount Uludag. For the Kükürtlü thermal water an increased association of carbonic acid has to be assumed due to CO_2 pressure of about 1 atm.

$$2[Ca^{2+}] + [H^+] = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-]; \text{ simplified: } 2[Ca^{2+}] \approx [HCO_3^-]; \text{ [mol/L]} \quad (5)$$

The observed relation between Ca^{2+} and HCO_3^- ions $(2[Ca^{2+}] \approx [HCO_3^-]$ [mol/L]) in all cold groundwaters and the contribution of these ions to TDS, which generally amounts to >25 meq% each, implies that carbonate dissolution is the dominant process in most of the groundwaters analysed. The CO_2 pressure of most of the cold groundwaters (except for some immature, very low salinity waters that lie below the calcite saturation line at 25°C) exceeds the atmospheric CO_2 pressure considerably. For these waters pCO_2 values between $10^{-2.5}$ and $10^{-1.4}$ atm have been calculated according to equation (6) (Imbach, 1992). For dissociation constants, see Plummer and Busenberg (1982).

$$\log pCO_{2(eq)} = \log [Ca^{2+}] + 2 \times \log [HCO_3^-] + \log K_2 - (\log K_1 + \log H_H + \log K_C) \quad (6)$$

Assuming equilibrium conditions, a CO_2 pressure of about $10^{-1.3}$ atm, or about 1 atm, was calculated for the Çekirge and Kükürtlü thermal waters. The increased concentration of HCO_3^- in the Kükürtlü thermal water cannot be explained only by carbonate dissolution. Due to the high CO_2 pressure of about 1 atm an increased dissociation of carbonic acid takes place and, in addition to carbonate dissolution, silicate hydrolysis has to be assumed. The high concentration of Na^+ in the thermal water of Kükürtlü, equal to >25 meq%, and the crystalline basement host rock suggest silicate alteration, e.g. equation (7). Both the high CO_2 pressure and the relatively high temperature cause increased water–rock interaction, as the rich oxygen-18 content of the Kükürtlü thermal water shows (Fig. 8) (IAEA, 1981; Blattner, 1985).

$$2NaAlSi_3O_8 + 2H^+ + 9H_2O = Al_2Si_2O_5(OH)_4 + 4H_4SiO_4 + 2Na^+ \quad (7)$$

A maturity index $MI < 2$ for both thermal waters (Giggenbach, 1988) indicates that the chemical composition of the Çekirge and Kükürtlü thermal waters is dominated by isochemical rock dissolution and not by equilibrium reactions between fluid and minerals of the host rock.

MIXING WITH GASES FROM CRUST AND MANTLE

The helium concentrations of the thermal waters deviate from the values characteristic of local cold groundwaters. This proves an overprinting of the thermal waters by gases originating from crust and mantle. Based on the helium ratios of atmosphere, crust, and mantle and on the neon concentration of each sample, the helium content of the thermal water was separated according to its origin using equations (8)–(11). [For calculation see Kipfer (1991) and Imbach (1992); for helium concentrations see Table 3, Appendix 1 and Appendix 2.]

Separation of the calulated non-atmospheric helium to its origin:

Definition:

$^4He_{ex}$, $^3He_{ex}$, according to equations (3) and (4)
$R_{rad} = 2 \times 10^{-8}$, and $R_{man} = 1 \times 10^{-5}$ (Coon, 1949; Ozima and Podesek, 1983; Andrews, 1985)

Calculation of the helium concentration from mantle (man) and crust (rad):

$$^3He_{man} = [^4He_{ex} - (R_{rad}^{-1} \times {}^3He_{ex})]/(R_{man}^{-1} - R_{rad}^{-1}) \quad (8)$$

$$^4He_{man} = [^3He_{ex} - (R_{rad} \times {}^4He_{ex})]/(R_{man} - R_{rad}) \quad (9)$$

$$^3He_{rad} = {}^3He_{ex} - {}^3He_{man} \quad (10)$$

$$^4He_{rad} = {}^4He_{ex} - {}^4He_{man} \quad (11)$$

Calculation of the helium content (%) originating from crust, mantle and atmosphere:

$$\begin{aligned} He_{atm}/He_{meas} &\sim {}^4He_{atm}/{}^4He_{meas} \\ He_{rad}/He_{meas} &\sim {}^4He_{rad}/{}^4He_{meas} \\ He_{man}/He_{meas} &\sim {}^4He_{man}/{}^4He_{meas} \end{aligned} \quad (12)$$

For the hottest thermal waters in Çekirge and Kükürtlü, at least 6–8% of the measured helium originates from the atmosphere, about 87–88% from the crust, and about 5–6% from the mantle.

As already pointed out, the hottest waters of Çekirge and Kükürtlü are almost identical with the deep-seated, tritium-free thermal water of each province at depth. The increasing $^3He/^4He$ ratio of the colder, less saline thermal waters within both thermal water districts proves cold water mixing and gas exchange with the atmosphere (Fig. 10). Nevertheless, the huge amount of helium originating from the crust and even the mantle indicates that an important gas exchange took place during the circulation of these deep-seated groundwaters.

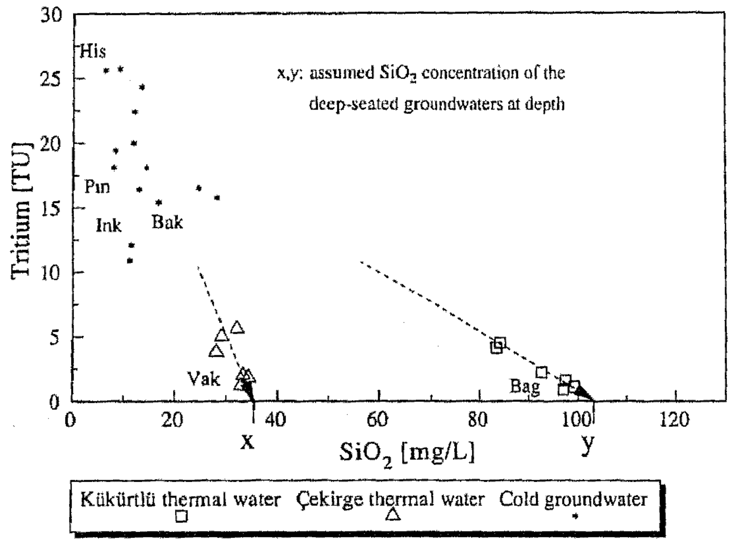

Fig. 12. Characterization of the hot deep water of each province by means of graphic extrapolation.

CHARACTERIZATION OF THE THERMAL WATERS AT DEPTH

Based on tritium and stable isotope investigations for the districts of Kükürtlü and Çekirge, two different thermal water systems can be proposed. The negative correlation betweeen tritium concentrations of the thermal waters and their physical and chemical parameters allow us to define the chemical composition of the original hot deep water of each province by means of extrapolation (Fig. 12).

For the Kükürtlü hot water at depth an electrical conductivity of about 1600 μS/cm and total dissolved solids (TDS) of about 1300 mg/L have to be assumed. Within the Çekirge district, the hottest thermal water is almost identical to the hot water at depth. An electrical conductivity of about 540 μS/cm and total dissolved solids (TDS) of about 500 mg/L have to be expected. As the loss of energy by heat conduction is not taken into account by the graphic extrapolation, the reservoir temperatures must be calculated by geothermometers. The cation geothermometers based on Na^+, K^+, Mg^{2+} and Ca^{2+} cannot be applied, however, because the chemistry of both thermal waters is dominated by isochemical rock dissolution and not by equilibrium reactions between fluid and minerals of the host rock (Giggenbach, 1988). As the amount of Cl^- in both thermal water types is very low (~10 mg/L), temperatures of less than 200°C may be expected, and the chalcedony geothermometer was applied to the extrapolated tritium-free hot water endmenbers of both thermal water districts (Truesdell, 1975): for the Kükürtlü thermal water the result was a minimum reservoir temperature of about 111°C, and for the Çekirge thermal water a minimum reservoir temperature of about 52°C.

RECHARGE AREA OF THE BURSA THERMAL WATERS

According to the physical, chemical and isotopic data, mixing between the Çekirge and Kükürtlü thermal water can be excluded. Even a common origin for the Çekirge and

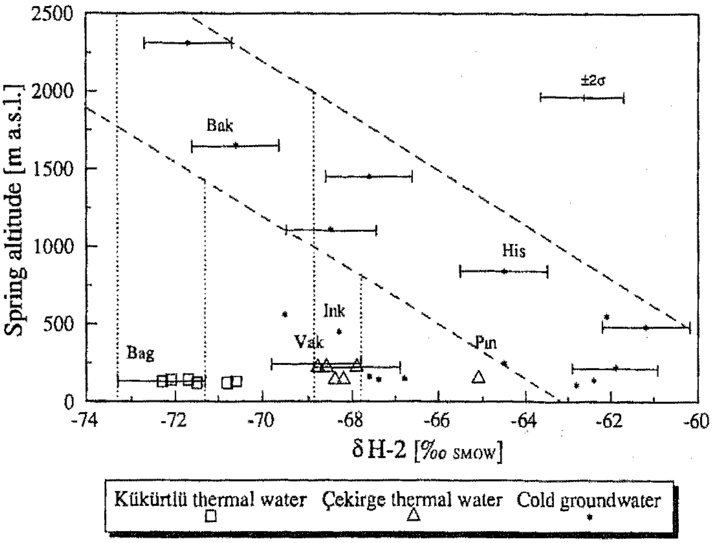

Fig. 13. Graphic determination of recharge altitudes for the thermal waters of each province by means of isotopic data. Error given at 1σ level.

Kükürtlü thermal water has to be negated. However, according to their isotopic characteristics, the Çekirge and Kükürtlü thermal waters can both be related to recharge areas on Mount Uludag. Based on the assumption that the altitude of shallow groundwater springs does not differ considerably from the altitude of the recharge area, a linear correlation between average altitude of groundwater infiltration and isotope concentration was graphically determined (Fig. 13) (Fontes, 1980; IAEA, 1981). Using the deuterium concentration of each province's hottest thermal water as tracer, it may be assumed that the Kükürtlü thermal water recharges at a higher elevation on Mount Uludag (betweeen 2500 and 1500 m a.s.l.) and the Çekirge thermal water recharges in its lower parts (between 2000 and 1000 m a.s.l.).

HYDROGEOLOGICAL CIRCULATION MODEL

Physical, chemical, and isotopic investigation of hot and cold groundwaters made it possible to reconstruct the thermal water evolution from infiltration to discharge, including water–rock–gas interactions, gas exchange, heating, and shallow water mixing.

Meteoric waters (rain, meltwater) infiltrate on Mount Uludag and recharge the thermal waters at Çekirge and Kükürtlü. During their residence times of at least 50 years the waters of the two different systems are mineralized by water–rock–gas interactions in the metamorphics of Mount Uludag. Carbonate dissolution and hydrolysis of silicates are the dominant water–rock interactions. Both waters interact with gases from crust and mantle during their circulation.

The Kükürtlü thermal water, infiltrating at the highest elevation on Mount Uludag (most probably in the marbles on top of Mount Uludag), is mineralized by water–rock–gas interactions governed by elevated CO_2-pressures at temperatures less than 120°C. Residence times of at least 50 years, or even more, are expected.

The Çekirge thermal water infiltrates in the lower parts of Mount Uludag (probably the leucogranite in the region of the Uludag plateau). This water is mineralized by water–gas–rock interactions governed by atmospheric CO_2-pressures in a low temperature environment (>50°C). Residence times of at least 50 years are expected.

These thermal waters follow separate flow paths. The upflow of the two waters occurs in the westernmost part of Mount Uludag along faults that are related to the neotectonic stress regime of northwest Turkey. Within each thermal water district a travertine complex created by the thermal waters covers the upflow zone. During the upflow, especially in the travertine complex, the thermal water interacts with cold groundwater, rock and the atmosphere.

FINAL DISCUSSION: PROTECTION OF THERMAL WATER AND IMPROVEMENT OF ITS USE

On the basis of this conceptual model (Fig. 14), it is possible to discuss the additional use and protection of the thermal waters.

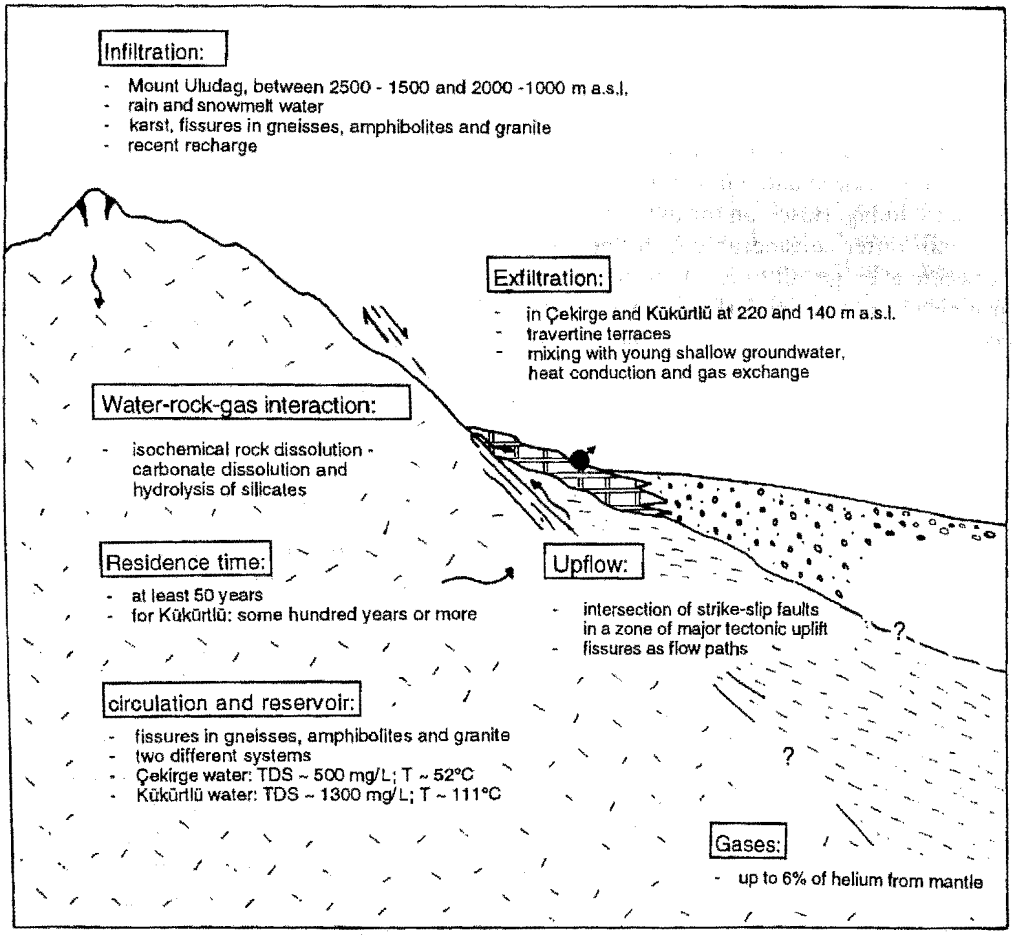

Fig. 14. Conceptual model of the circulation of the Bursa thermal waters.

Thermal water of Kükürtlü

The thermal waters used in different spas within the Kükürtlü district have the same origin. Consequently, local use influences the entire occurrence of thermal water within the travertine aquifer. An overuse of the hot groundwater could impair or even drain the shallow excavations and springs situated on a higher level. Further deepening of existing excavations, on the other hand, would intensify drainage of the thermal water system. Direct use of thermal water by means of drilling into the travertine should be avoided, as the consequences for the entire thermal water system are incalculable. An unknown amount of thermal water flows from the travertine complex into the alluvium of the Bursa plain. The use of thermal water within this plain offers an alternative to its catchment within the travertine terrace. Instead of pumping thermal water out of the karstic travertine aquifer, hot water could be trapped within the unconsolidated sediments of the plain. This procedure would ensure considerable protection of the thermal water system. Protection of thermal waters from infiltration of polluted water is a further pre-condition for long-term use. Potential hazards, such as a petrol station that has already been installed within the travertine terrace without any safety measures, should be eliminated. This can only be achieved by legal procedures to protect the whole travertine complex. In view of an extensive use of thermal water, it also becomes imperative to protect the cold groundwater. To this day, the geothermal potential of the hot waters ($P_{tot} \sim 1.5$ MW; $Q = 5$ L/s, $T_{max} - 10°C = 70°C$) is not exploited in a satisfactory way. In order to obtain a bathing temperature of approximately 40°C, the 80°C thermal water of Kükürtlü is cooled by addition of cold water. Application of heat exchangers would yield a geothermal power of about 0.8 MW ($Q = 5$ L/s, $T_{max} - 40°C = 40°C$). This would avoid the consumption of expensive cold water, and at the same time would reduce or even eliminate oil-fired heating.

Thermal water of Çekirge

As in the case of Kükürtlü, the thermal waters sampled at different localities within the district of Çekirge are of the same origin, and consequently local overuse could influence the thermal water system as a whole. Where the thermal water is tapped by boreholes, a considerable decrease in hydraulic head could also have an impact on the thermal springs located at a higher topographic level. Based on the present outflow rates, the total geothermal potential of the Çekirge thermal water is about 2 MW ($Q = 17$ L/s, $T_{max} - 10°C = 30°C$). Outside of the natural outflow area, but still within the Neogene unit of Çekirge, artesian thermal water is produced by boreholes. It can be assumed that the freshwater limestones represent the aquifer within the Neogene unit. As long as the natural outflow of thermal water is much higher than the amount made available through drilling, no negative effects should occur. However, any reduction of the natural thermal water outflow should first of all be taken as a signal of overuse of the thermal water system.

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Appendix 1 starts on facing page

APPENDIX 1. PHYSICAL, CHEMICAL AND ISOTOPIC DATA OF THE ÇEKIRGE THERMAL WATER

Sample name	Vak	Zey	Ipe	HavA	HavB	SigA
Sampling date	89-Sept-06	89-Sept-06	89-Sept-02	89-Oct-04	89-Sept-07	89-Sept-07
Sampling altitude [m a.s.l.]	220	220	220	160	150	170
Field analyses						
T [°C]	45.7	43.8	44.4	35.8	34.6	30.8
$EC_{25°C}$ [μS/cm]	541	538		537	568	531
Q [L/min]	960	198	270	120	60	
pH	6.7	7.1	7.0		7.0	7.7
Alc [mmol/L]	4.8	4.2	5.2		4.7	5.0
Aci [mmol/L]	0.8	1.1	0.8		1.3	0.7
O_2 [mg/L]	1.3	3.6	1.8		0.8	6.1
Cations [mg/L]						
Li^+	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Na^+	35	32	35	30	28	29
K^+	5.6	4.6	6.5	4.9	4.8	6.1
Mg^{++}	21	21	20	20	20	22
Ca^{++}	65	66	64	75	77	62
Sr^{++}	0.46	0.49		0.44	0.45	0.45
Ba^{++}	0.10	0.11	0.11	0.10	0.09	0.10
Mn^{++}	0.04	0.02	0.01			
Fe^{++}	0.23	0.11	0.28			
Anions [mg/L]						
F^-	0.9	0.9	0.9	0.7	0.8	0.6
Cl^-	5.4	5.4	5.1	10.0	8.6	9.2
I^-	0.050	0.045		0.040	0.040	0.045
Br^-	<0.2	<0.2		<0.2	<0.2	<0.2
HCO_3^-	296	293	310	296	301	273
NO_3^-	0.2	0.2	<1.0	5.8	0.2	7.6
PO_4^{--}	0.38	0.25	0.14	0.28	0.34	0.46
SO_4^{--}	58	57	62	61	63	60

Continued overleaf

Sample name	Vak	Zey	Ipe	HavA	HavB	SigA
Sampling date	89-Sept-06	89-Sept-06	89-Sept-02	89-Oct-04	89-Sept-07	89-Sept-07
Sampling altitude [m a.s.l.]	220	220	220	160	150	170
Balance						
Cations [meq/L]	6.63	6.49	6.52	6.82	6.79	6.32
Anions [meq/L]	6.28	6.20	6.57	6.55	6.54	6.16
Non dissociat. [mg/L]						
As	0.04	0.05		0.04	0.06	0.07
B	0.07	<0.07	0.10	0.05	0.05	0.14
Si	15.35	16.04	14.67	13.63	13.15	15.02
TDS [mg/L]	504	497	519	518	517	485
Environm. isotopes						
^{3}H [TU]	1.2 ± 0.7	1.8 ± 0.7	1.1 ± 0.7	5.0 ± 0.7	3.8 ± 0.7	5.6 ± 0.7
δ^{2}H [‰SMOW]	-68.8 ± 1	-67.9 ± 1	-67.7 ± 1	-68.2 ± 1	-68.4 ± 1	-65.1 ± 1
δ^{18}O [‰SMOW]	-10.75 ± 0.15	-10.75 ± 0.15	-10.59 ± 0.15	-10.70 ± 0.15	-10.71 ± 0.15	-10.62 ± 0.15
δ^{34}S [‰CD] in SO_4	6.0	5.3				
δ^{18}O [‰SMOW] in SO_4	6.8	6.0				
Noble gases						
^{3}He [cm^3/g]		2.32×10^{-13}	8.35×10^{-13}		2.16×10^{-13}	
^{4}He [cm^3/g]		30.75×10^{-8}	118.2×10^{-8}		26.89×10^{-8}	
^{20}Ne [cm^3/g]		15.15×10^{-8}	24.75×10^{-8}		15.69×10^{-8}	
^{20}Ne/^{22}Ne		9.73	9.72		9.79	

APPENDIX 2. PHYSICAL, CHEMICAL AND ISOTOPIC DATA OF THE KÜKÜRTLÜ THERMAL WATER

Sample name	Bag	KükA	KükB	Muh	Oto	KarC
Sampling date	89-Sept-05	89-Sept-05	89-Sept-05	89-Sept-05	89-Sept-07	89-Sept-06
Sampling altitude [m a.s.l.]	130	140	140	130	110	110
Field analyses						
T [°C]	81.1	80.7	73.7	76.0	50.8	61.5
$EC_{25°C}$ [μS/cm]	1456	1460	1370	1400	1142	1110
Q [L/min]	270					
pH	6.5	6.3	6.5	6.5	7.0	6.8
Alc [mmol/L]	8.2	8.8	8.0	8.5	7.8	6.6
Aci [mmol/L]	2.2	4.7	3.0	4.1	2.1	1.7
O_2 [mg/L]	0.4	0.6	0.1	0.7	3.0	3.6
Cations [mg/L]						
Li^+	0.68	0.68	0.64	0.67	0.55	0.54
Na^+	220	223	310	218	198	185
K^+	22.8	23.0	22.8	22.8	20.0	19.0
Mg^{++}	8	7	8	7	11	9
Ca^{++}	90	92	90	93	84	77
Sr^{++}	0.55	0.57	0.54	0.56	0.50	0.48
Ba^{++}	0.07	0.07	0.07	0.07	0.05	0.05
Mn^{++}	0.06	0.06	0.06	0.09	0.03	0.05
Fe^{++}	0.52	0.28	0.62	0.68	0.04	0.05
Anions [mg/L]						
F^-	5.8	5.5	5.2	5.3	4.3	4.5
Cl^-	11.6	12.3	12.5	12.9	13.4	11.3
I^-	0.080	0.060	0.050	0.050	0.040	0.050
Br^-	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
HCO_3^-	531	529	516	534	468	449
NO_3^-	<0.08	0.6	<0.08	0.2	5.0	1.6
PO_4^{---}	0.50	0.50	0.88	0.73	0.49	0.38
SO_4^{--}	268	277	254	274	232	224

Continued overleaf

Sample name	Bag	KükA	KükB	Muh	Oto	KarC
Sampling date	89-Sept-05	89-Sept-05	89-Sept-05	89-Sept-05	89-Sept-07	89-Sept-06
Sampling altitude [m a.s.l.]	130	140	140	130	110	110
Balance						
Cations [meq/L]	15.45	15.59	15.02	15.45	14.31	13.21
Anions [meq/L]	14.93	15.10	14.40	15.13	13.22	12.62
Non dissociat. [mg/L]						
As	0.13	0.09	0.15	0.08	0.11	0.07
B	1.70	1.78	1.64	1.73	1.47	1.41
Si	45.37	46.37	43.29	45.57	39.36	39.00
TDS [mg/L]	1207	1220	1166	1217	1078	1022
Environm. isotopes						
^3H [TU]	0.9 ± 0.7	1.1 ± 0.7	2.2 ± 0.7	1.6 ± 0.7	4.5 ± 0.7	4.1 ± 0.7
δ^2H [‰SMOW]	-72.3 ± 1	-71.7 ± 1	-72.1 ± 1	-70.6 ± 1	-70.8 ± 1	-71.5 ± 1
$\delta^{18}O$ [‰SMOW]	-10.62 ± 0.15	-10.49 ± 0.15	-10.51 ± 0.15	-10.15 ± 0.15	-10.21 ± 0.15	-10.32 ± 0.15
$\delta^{34}S$ [‰CD] in SO_4		13.9				
$\delta^{18}O$ [‰SMOW] in SO_4		1.6				
Noble gases						
^3He [cm^3/g]			1.19×10^{-13}			0.77×10^{-13}
^4He [cm^3/g]			17.9×10^{-8}			7.49×10^{-8}
^{20}Ne [cm^3/g]			4.89×10^{-8}			12.17×10^{-8}
$^{20}Ne/^{22}Ne$			9.86			9.84