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WATER AGES IN THERMAL SYSTEM OF THE PODHALE BASIN (INNER CARPATHIANS, SOUTHERN POLAND)

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Abstract. Karstified carbonates which outcrop in the Tatras, Inner Carpathians, southern Poland, and dip to the north under the flysch sediments of the Podhale Basin, represent the largest known renewable reservoir of thermal waters in the country, with temperatures up to about 80°C. Measurements of He excess, Ne and Ar unexpectedly revealed the existence of glacial age waters in the northeastern part of the basin, and late Holocene age waters in other parts. The noble gas data are shown to be in accordance with newly interpreted earlier long-term records of ^{3}H, δ^{18}O and δ^{2}H in waters of the karstic springs, and with available determinations of ^{3}H, δ^{18}O, δ^{2}H, ^{14}C and δ^{13}C in cold and thermal well waters.

Key words: thermal waters, environmental tracers, water age, Podhale Basin, Inner Carpathians.

INTRODUCTION

The Podhale Basin is the largest known reservoir of renewable thermal waters in Poland, with temperatures of about 20°C near the outcrop area and above 80°C in its deepest part A simplified geological map of the outcrop and basin areas is shown in Figure 1, with the positions of sampled springs in the recharge area, and wells with cold and thermal water. The reservoir rocks are represented by Mesozoic and Eocene karstified carbonates which outcrop in the Tatras at the altitudes of 1,000–1,800 m and dip to the north under the flysch sediments of the Podhale Basin to the depth of several km as shown in Figure 2. The main direction of flow is to the north for about 15 km, where it is divided into two parts by impermeable formations of the Pieniny Klippen Belt. One part is diverted to the west, and the other to the east, and next both to the south to the main drainage areas in the Danube watershed in Slovakia. A slow upward seepage through poorly permeable flysch formations in the Podhale Basin also contributes to the natural drainage. Due to a karstic character of the permeable formations, the hydraulic conductivity measured in individual wells greatly differs. The lowest value was observed in the Kiry P-1 well ($2\cdot10^{-7}$ m/s) and the largest in the Zakopane 2 well ($3.2\cdot10^{-4}$ m/s) whereas the most common values are from $2\cdot10^{-6}$ to $2\cdot10^{-5}$ m/s. The lowest outflow rate was observed in the Siwa Woda IG 1 well (4.0 m^{3}/h) and the largest in the Bańska IG 1 well (about 500 m^{3}/h).

Concentrations of environmental tracers were measured occasionally in some springs in the Tatras and in newly drilled wells since early seventies. The early environmental tracer data of the Tatras springs and wells with modern waters were summarized by Zuber *et al.* (2008) whereas those of thermal wells by Chowaniec (2009). Spring waters were sampled for ^{3}H, δ^{18}O and δ^{2}H, whereas wells with tritium-free water were additionally sampled for ^{14}C and δ^{13}C. However, quantitative ^{14}C dating of thermal waters in carbonate formations cannot be regarded as reliable due to ex-

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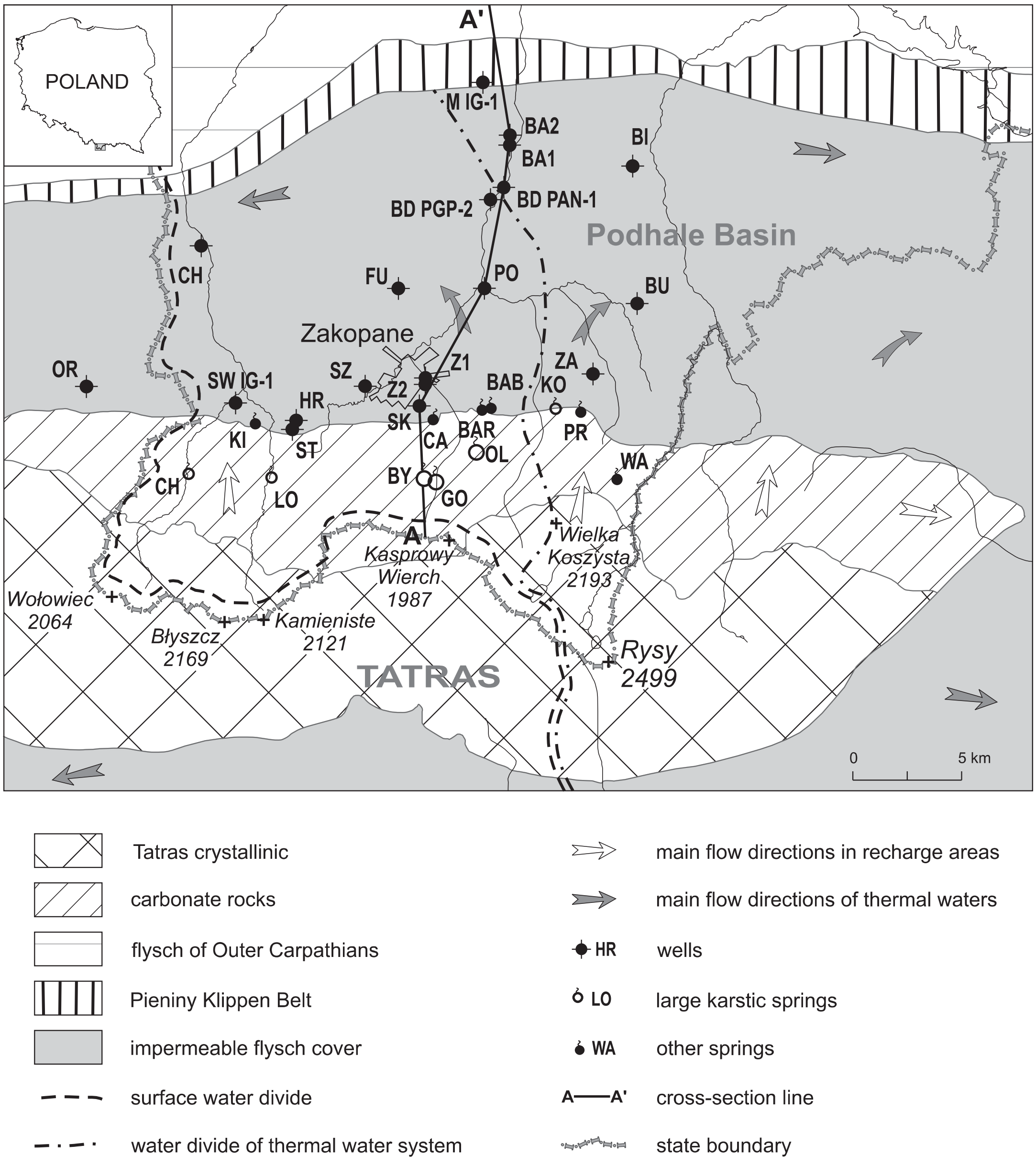

Fig. 1. Simplified geological map of the study area

change between dissolved inorganic carbon and solid carbonates that is particularly intensive in the microporous matrix (Małoszewski, Zuber, 1991). Therefore, a new project was started in the period of 2008–2009, which was aimed at age determinations by the helium method. Helium, or more exactly ^{4}He, serves for groundwater dating in a wide range of ages (Andrews, Lee, 1979; Torgersen, Clarke, 1985; Torgersen, Ivey, 1985), whereas other noble gases are helpful in the identification of waters recharged under different climatic conditions (Mazor, 1972; Stute, Schlosser, 2000) or at different altitudes (Zuber *et al.*, 1995; Aeschbach-Hertig *et al.*, 1999; Manning, Solomon, 2003). Under the project, all the wells exploited at the time of its realization were sampled for He, Ne, Ar and SF_6 determinations. The present paper presents a combined interpretation of earlier isotope data and new noble gas data in terms of the age and recharge altitude of the investigated waters.

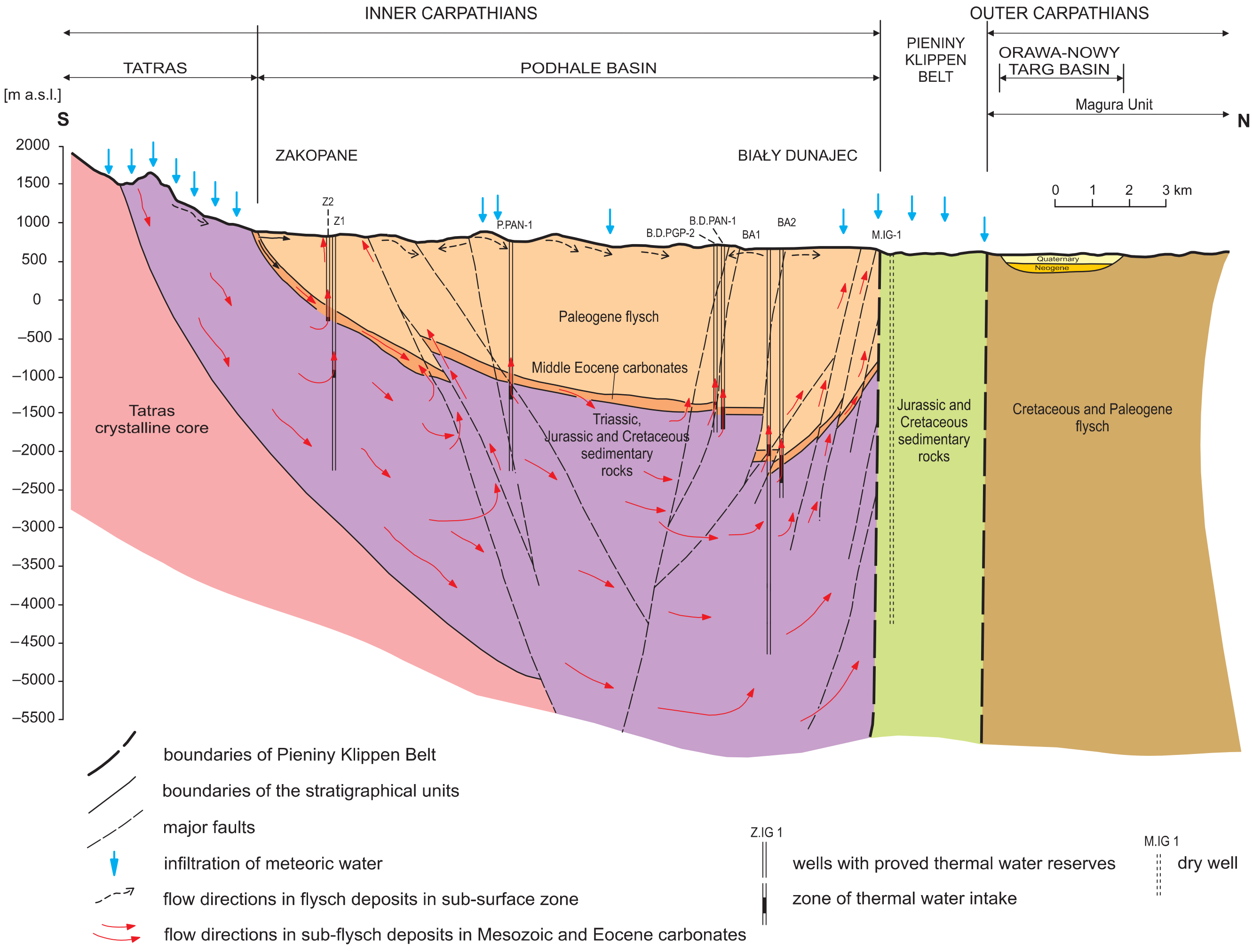

Fig. 2. Simplified geological cross-section

METHODS

Tritium and ^{14}C were analyzed by liquid scintillation technique in a well established laboratory of the AGH – University of Science and Technology, with typical uncertainties reported further in the tables. Stable isotopes of oxygen, hydrogen and carbon were analyzed in the same laboratory by mass spectrometry, with uncertainties of 0.1, 1 and 0.1‰, respectively. In some cases, repeated analyses lead to somewhat lower uncertainties. Samples for $\delta^{18}O$ and $\delta^{2}H$, ^{3}H, and ^{14}C and $\delta^{13}C$ determinations were usually collected into 0.02, 1, and 60 dm^3 plastic bottles, respectively. The stable isotopes of oxygen and deuterium are reported in relation to the Vienna-SMOW standard, and carbon isotopes in relation to the Vienna-PDB standard.

Tritium ages were calculated with the aid of the FLOWPC program (Małoszewski, Zuber, 1996) for sites with tritium records not shorter than a few years (Zuber *et al*., 2008). Radiocarbon and helium were used only for qualitative age estimations because at the present sate of knowledge there was no ground for the quantitative interpretation as explained further.

Mean altitudes of recharge were obtained from the $\delta^{18}O$ and $\delta^{2}H$ data of springs and wells with cold water in the way described in detail by Zuber *et al*. (2008). Namely, for two heaviest and two lightest isotope compositions the altitudes were estimated from the topographic maps under an assumption that recharge takes place at mid-altitude between the altitudes of the outflow and the peak of the elevation from which the discharge occurs. Straight lines connecting these extreme values served for finding the recharge latitudes of all other waters. However, as shown further, due to the shift of $\delta^{18}O$ data caused by isotopic exchange with oxygen in carbonate minerals, only the altitudes obtained from the δ^2H values are reliable for thermal waters. The altitude effects are given by equations [1] and [2] for $\delta^{18}O$ and δ^2H, respectively, with the uncertainties not better than 100–200 m.

$$h_{18}\ (\text{m a.s.l.}) = -445.3\cdot\delta^{18}O - 3{,}704 \qquad [1]$$

$$h_2\ (\text{m a.s.l.}) = -69.1\cdot\delta^2H - 4{,}054 \qquad [2]$$

Noble gases and SF_6 were analyzed in the laboratory of the Nuclear Physics Institute, Kraków, by head-space gas-chromatography (Lasa *et al.*, 2002, 2004; Śliwka *et al.*, 2004; Mochalski *et al.*, 2006; Pusz *et al.*, 2007; Mochalski, Śliwka, 2008). Samples were collected into special stainless-steel 2.9-dm^3 bottles without any contact with the atmosphere, and without degassing by bubbling that easily occurs during withdrawal of water from large depths. The collection bottles also served for the transport and extraction of gases by the head-space method. Each sample was collected into two bottles for a better assurance of the whole sampling and measurement procedure. In 2007, the sample for He was collected to separate bottles, and the detection level was about $4\cdot10^{-8}$ cm^3g^{-1}. In 2008 and 2009, the bottles served for simultaneous determinations of four gases (He, Ne, Ar, and SF_6) which resulted in a poorer detection limit both for He ($14\cdot10^{-8}$ cm^3g^{-1}) and SF_6 (0.06 instead of 0.01–0.02 fmol/dm^3). Concentrations of SF_6 were corrected for the excess air dissolved in water (Heaton, Vogel, 1981; Cook, Herzeg, 2000), which was calculated with the aid of the total dissolution model (Aeschbach-Hertig *et al.*, 1999; Porcelli *et al.*, 2002). He excess (He_{exc}) was obtained from the measured concentration after subtraction of the equilibrium value with the atmosphere and that resulting from the excess air content.

ENVIRONMENTAL TRACER DATA

Table 1 contains the data of karstic springs in the Tatras whereas Table 2 contains similar data obtained for wells situated at the foot of the Tatras, in which measurable tritium concentration was observed. Water temperatures and TDS (total dissolved solids) contents are also given. Table 3 contains the isotope data of wells with pre-modern water (i.e. tritium free), whereas Table 4 presents the results of analyses of noble gases and SF_6. Initial samplings in BA1, BA2 and BI wells failed due to degassing caused by bubbling at well heads.

Table 1

Mean $\delta^{18}O$ and δ^2H data, tritium ages and mean recharge altitudes of karstic springs estimated from $\delta^{18}O$ and δ^2H (for detailed data see Zuber *et al.*, 2008)

Spring/cod/ altidude [m a.s.l.]	Dates	$\delta^{18}O$ [‰]	δ^2H [‰]	Age [years]	h_{18}/h_2 [m a.s.l.]
Bystrej/BY/1160	07.77–06.01	–11.89 ±0.11	–81.4 ±0.6	2–4	1574 ±207[a)]
Goryczkowe/GO/1176	12.86–06.01	–11.82 ±0.13	–81.55 ±0.7	2–4	1581 ±200[a)]
Olczyskie/OL/1042	07.77–06.01	–11.42 ±0.10	–79.85 ±1.3	2–4	1381/1464
Chochołowskie/CH/974	07.77–06.01	–11.66 ±0.11	–78.0 ±1.2	2–4	1491/1335
Lodowe/LO/974	10.84–06.01	–11.45 ±0.11	–76.4 ±1.3	2–4	1394/1225
Koziarczyska/KO/942	12.86–08.01	–11.35 ±0.03	–77.5 ±0.9	2–4	1350/1225
Waksmundzkie/WA/1075	08.87–06.01	–11.18 ±0.07	–77.0 ±0.4	2–4	1274/1267
Kiry/KI/920	08.87–06.01	–10.59 ±0.07	–74.4 ±0.6	~10	1012 ±46[a)]
Pod Capkami/CA/915	12.86–06.01	–10.87 ±0.04	–74.25 ±0.6	~10	1146 ±115[a)]
Babtystów/BAB/915	12.86–08.88	–11.12 ±0.06	–75.95 ±0.8	~10	1247/1194
Barany/BAR/919	12.86–06.01	–11.13 ±0.16	–75.5 ±0.7	~10	1252/1163
Przyporniak/PR/950	08.88	–11.08	–75.5	?	1230/1163

[a)] assumed on the basis of a topographic map; h_{18} – mean recharge altitude according to $\delta^{18}O$; h_2 – mean recharge altitude according to δ^2H; ? – only a single tritium result is available, which is insufficient for the age estimation

Table 2

Selected data for wells with ^{3}H (for detailed data obtained prior to 2008 see Zuber *et al.*, 2008)

Well	Temp./TDS [°C/(g/dm^{3})]	Dates	δ^{18}O [‰]	δ^{2}H [‰]	Tritium [T.U.]	Age [years]	h_{18}/h_{2} [m a.s.l.]
ST	8.0/0.23	06.87–06.01	–11.05 ±0.15	–74.8 ±1.2	38–13	~100	1217/1111
HR	10/0.31	06.87–06.01	–10.92 ±0.05	–74.2 ±1.0	44–15	~100	1350/1301
SK	16.8/0.33	12.86–08.87	–10.70 ±0.10	–73.3 ±0.5	32	–	1061/1011
ZA	22/0.19	12.86–06.01	–11.42 ±0.07	–77.9 ±0.5	55–16	~50	1381/1329
	15.9/n.m.	10.09.2009	–11.38	–77.8 –77.4	8.0 ±0.5	–	–
Z2	26.4/0.33	12.86–06.01	–10.98 ±0.06	–73.4 ±0.5	60–20	~55	1178/1100
		18.03.09	–10.92	–75.7	n.m.	–	
Z1	35.5/0.36	08.69–06.01	–10.87 ±0.05	–73.0 ±0.5	190–11	~85	1136/990
		27.08.08	–10.6	–78.1	10.5 ±0.5	–	1016/1343
		12.08	–10.9	–75.2	n.m.	–	1150/1142
		18.03.09	–10.83	–72.85	n.m.	–	1118/980

TDS – total dissolved solids; h_{18} i h_{2} – altitudes of recharge estimated from δ^{18}O and δ^{2}H, i.e. from Eqs. [1] and [2], respectively; n.m. – not measured

Table 3

Selected data for wells with tritium-free water

Well	Temp./TDS [°C/(g/dm^{3})]	Dates	δ^{18}O [‰]	δ^{2}H [‰]	Tritium [T.U.]	^{14}C	δ^{13}C	h_{18}/h_{2} [m a.s.l.]
FU	60.5/0.58	12.96	–10.6	–73	1.7 ±0.5	37.4 ±1.0	–4.4	1016/990
PO	63.0/1.24	12.96	–11.15	–76.5	0.0 ±0.5	23.2 ±1.0	–5.5	1261/1232
SZ	27.8/0.38	01.07	–10,7	–75	0.6 ±0.4	7.6	–7.1	1061/1128
		07.08			n.m.	n.m.	n.m.	
CH	82.0/1.24	12.96	–11.5	–78	0.25 ±0.3	3.2 ±1.0	–3.0	1417/1336
OR	52.0/–	09.09	–11.15	–77.4	1.4 ±0.3	n.m.	n.m.	1261/1294
BU	64.5/1.49	10.98	–11.2	–79.2	0.1 ±0.5	0.8 ±1.0	–1.4	1283/1413
		07.08	–11.5	–79.2	n.m.	n.m.	n.m.	
BI	73.0/1.69	08.08	–11.4	–83.9	n.m.	n.m.	n.m.	1372/1743
BA1	82.0/2.69	07.92	–10.9	–82.5	0.1 ±1.0	3.4 ±1.0?	–0.4	1194/1612
		07.92	–11.1	–81.5	0.0 ±1.0	0.5 ±1.0	+0.3	
		01.97	–11.5	–81.0	0.0 ±0.5	0.3 ±1.0	–0.6	1417/1543
		05.08	–11.2	–81.8	n.m.	n.m.	n.m.	1283/1612
		09.08	–10.6	–82.8	n.m.	n.m.	n.m.	1016/1671
BA2	86.0/3.12	05.08	–11.2	–84.9	n.m.	n.m.	n.m.	1283/1885

TDS – total dissolved solids; h_{18} i h_{2} – as in Table 1; n.m. – not measured; ? – doubtful result probably due to some contamination

Table 4

He excess, Ne and Ar concentrations in the Podhale Basin well waters as well as NGTs and air temperatures (T) expected for the altitudes estimated from Eq. [2]

Well	Dates	He$_{exc}$ [10^{-8} cm^{3}STP/g]	Ne [10^{-7} cm^{3}STP/g]	Ar [10^{-4} cm^{3}STP/g]	NGT$^{a)}$ [°C]	T [°C]	SF6 [fmol/dm^3]
HR	04.06.09	<14	3.20 ±0.13 3.17 ±0.13	4.66 ±0.10 4.78 ±0.10	2.5 ±0.5	3.7	4.6 ±0.2
ZA	10.09.09	<14	2.18 ±0.09 2.19 ±0.09	3.99 ±0.09 4.05 ±0.09	3.7 ±0.5	2.6	1.1 ±0.1
Z2	18.03.09	<14	2.61 ±0.09 2.60 ±0.09	4.42 ±0.10 4.30 ±0.10	3.2 ±0.5	3.8	0.16 ±0.08
Z1	27.08.08	65 ±6	2.45 ±0.09 2.36 ±0.09	3.7 ±0.1 4.1 ±0.1	7.4 ±1.2	4.3	0.38 ±0.06 0.38 ±0.06
	18.03.09	110 ±28 135 ±30	n.m. 2.49 ±0.09	n.m. 4.03 ±0.09	n.m. 5.2 ±1.0	– 2.5	n.m. 0.08 ±0.06
SZ	26.01.07 04.07.08	33 ±4 21.3 ±3	3.30 ±0.06 3.63 ±0.07	4.46 ±0.08 4.92 ±0.08	5.5 ±0.5 2.8 ±0.8	3.7 3.7	– <0.06
OR	10.09.09.	316 ±40 301 ±39	3.49 ±0.14 3.55 ±0.14	4.93 ±0.10 4.88 ±0.10	1.6 ±0.5	2.9	<0.04
BU	04.07.08	3,467 ±200	3.33 ±0.10	4.66 ±0.04	2.7 ±0.5	2.2	<0.06
BI	21.08.08	2,350 2,595	1.48 ±0.06 1.60 ±0.06	0.27 ±0.06 0.16 ±0.06	degassed		n.m.
	13.05.09	7,980 ±490 9,860 ±610	4.70 ±0.14 3.66 ±0.14	6.04 ±0.13 5.03 ±0.12	<0 for h>600 m	0.5	<0.06
BA1	08.05.08	1,028 ±72	0.18	0.95	degassed		n.m.
	21.08.08	11,770 ±710 9,254 ±560	4.12 ±0.12 3.95 ±0.12	5.50 ±0.20 4.60 ±0.15	<0 for h>780 m	1.1	<0.06
BA2	08.05.08	1,161 ±93	0.817	1.98	degassed		n.m.
	13.05.09	14,390 ±880 14,680 ±890	4.21 ±0.15 3.97 ±0.15	6.08 ±0.13 6.17 ±0.13	<0 for h>0 m	–0.1	<0.06

n.m. – not measured; NGT$^{a)}$ – uncertainties are based only on uncertainties of analytical procedure

DISCUSSION

TRITIUM AND SF$_6$

Measurable concentrations of ^{3}H (Tab. 1) and SF$_6$ (Tab. 4) at the depths of about 500 to 1100 m in wells situated near the northern boundary of the Tatras indicate the presence of fast flows through karstic channels. Details of the interpretation of ^{3}H data were described by Zuber *et al.* (2008), whereas in Tables 1 and 2 only the final results are presented. Though the records of ^{3}H for periods indicated in Tables 1 and 2 were not sufficiently continuous and long to ensure unambiguous age determinations; however, the ages obtained with the aid of box-models seem to be satisfactorily indicative.

The mean age values of 2–4 years and about 10 years were obtained for the baseflows in all large springs and other springs, respectively. The mean ages of water in wells appeared to be of the order of 50 to 100 years. The presence of SF$_6$ (Tab. 4) in all wells containing water with elevated ^{3}H contents confirms the dominant presence of modern water. Particularly long record of ^{3}H in the Z1 well showed the existence of two different channel flows as shown in Figure 3. Quantitative interpretation with the aid of lumped-parameter models yielded the mean age of about 9 years for the fast flow contributing 17% to the total volumetric flow rate and the mean age of 100 years for the slow component. That large mean age results from a wide age distribution, though younger water dominate as seen in Figure 3 from the model curve.

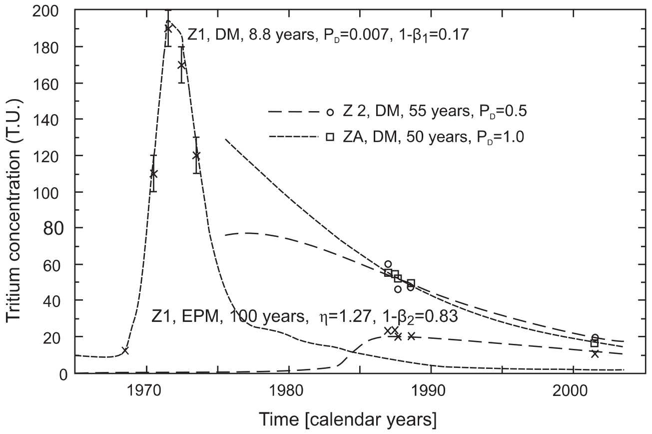

Fig. 3. Tritium records for selected wells and fitted model curves

DM – dispersion model, EPM – exponential and piston flow models in line, P_D – dispersion parameter, η – ratio of the total volume to the exponential flow volume, β_1 and β_2 – fractions of tritium free flows in fitting procedure (Małoszewski, Zuber, 1996)

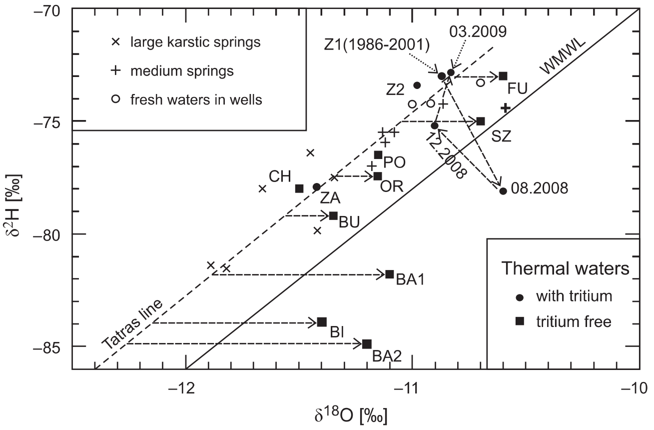

Fig. 4. $\delta^{18}O$–$\delta^{2}H$ relation of spring and well waters with indicated shifts (horizontal lines) of $\delta^{18}O$ from the local meteoric line (see text in relation to changes in the Z1 well)

RADIOCARBON AND ^{13}C

Samples for ^{14}C and δ^{13}C determinations were taken sporadically because already at the beginning of the study the ^{14}C dating was regarded as little promising due to the isotopic exchange. That hypothesis is confirmed by δ^{13}C values which change from −7.1‰ in the SZ well with relatively young water to about 0‰ in the BA1 well in the deepest part of the system.

The highest ^{14}C contents are observed in wells in the central part of the basin (37 pmc in the FU well and 23 in the PO well), intermediate values are observed in the western part (7.6 pmc in the SZ well and 3.2 pmc in the CH well), and the lowest contents in the eastern part (0.8 pmc in the BU well and 0 pmc in the BA1 well).

STABLE ISOTOPES OF OXYGEN AND HYDROGEN

Springs were sampled for δ^{18}O and δ^{2}H determinations at base flows, which resulted in a fairly constant values (Zuber *et al.*, 2008) and low uncertainties of the mean values (Tab. 1). Surprisingly, the isotopic composition of water in the Z1 well shows recently high variations (Tab. 2 and Fig. 4), though it was fairly constant in the period of 1969–2001. These variations are attributed to increased and variable withdrawal rates which probably change the contributions from different karstic channels. That hypothesis is in agreement with the existence of at least two quite different channels deduced from the ^{3}H data (Fig. 3).

Isotope composition of waters from springs and cold wells served for the determination of both the altitude effect and the local meteoric water line which is shifted from the World Meteoric Water Line (WMWL) as shown in Figure 4. The isotope data of most of thermal waters are evidently shifted from the line, supposedly due to the well known effect of the isotopic exchange of oxygen between water and carbonate minerals.

The isotopic composition of thermal waters, when related to the local meteoric water line, does not differ from the isotopic composition of springs. Modern spring waters scatter of along the meteoric line due to altitude effect. On that basis, Małecka and Nowicki (2002) assumed that thermal waters also scatter only due to that effect, and, thus, they are of the Holocene age. However, according to Table 2 and Figure 4, all the wells situated near the Tatras represent young waters with the isotopic composition suggesting the recharge areas at the lowest parts of the outcrops. In other words, the largest springs in the Tatras discharge waters recharged at the highest altitudes whereas other springs and wells near the Tatras discharge waters recharged at low altitudes. In such a case, the lightest isotopic composition of waters in wells situated far from the Tatras may result from the climatic effect, i.e., from the recharge under a cooler climate.

HELIUM

Helium excess concentrations (He_{exc}) listed in Table 4 and shown in Figure 5 differ for about three orders of magnitude whereas those for wells with modern waters they range from less than $14 \cdot 10^{-8}$ cm^3g^{-1} for the HR, ZA and Z2 wells to more than $100 \cdot 10^{-8}$ cm^3g^{-1} for the Z1 well. Water in the SZ well, which is free of ^{3}H and SF_6, is characterized by 3 to 4 times lower He_{exc} than that in the Z1 well. Such results suggest the contribution of highly irregular outside flux, which, at

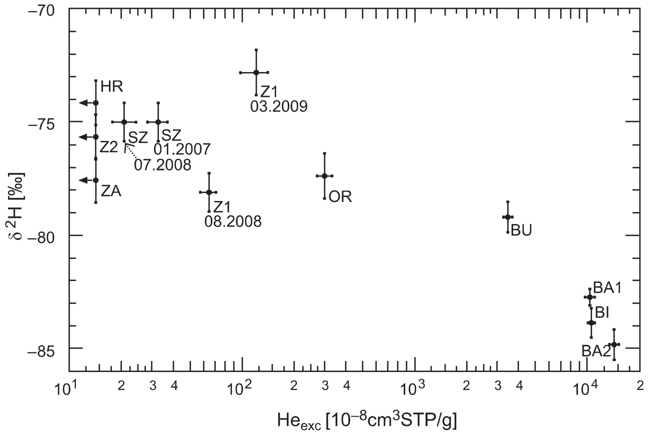

Fig. 5. Hel–δ^2H relation for well waters

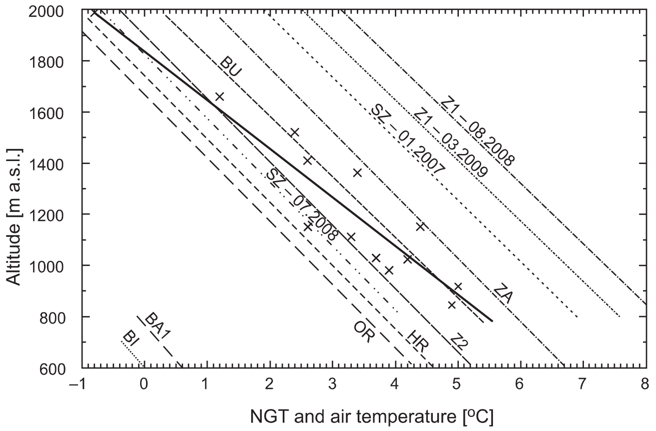

Fig. 6. Dependence of NGT and air temperature on the recharge altitude

Heavy line – air temperature, points after Konĉek and Orlicz (1974)

the present stage of the study, makes difficult any attempt to quantitative age estimations. The highest concentrations observed in the BA1, BA2 and BI wells are of the same order of magnitude as those observed for glacial age waters in the thermal system of the Karkonosze Mts. (Zuber *et al.*, 1995) and for interglacial age waters of the Busko Spa (Zuber *et al.*, 1997). These high concentrations evidently do not result only from a high outside flux but also from a great age of water.

Waters with the highest He_{exc} concentrations (BA1, BA2 and BI wells), i.e., the oldest waters in the system are characterized by the most negative δ^2H values (Fig. 5) that are supposed to result from the recharge under a cooler climate. Thus, these oldest waters were most probably recharged at the final stage of the last glacial period, about 14–10 kyears B.P. Water exploited by the BU well is most probably a mixture of glacial age and Holocene water as suggested by its position in Figure 5. The least negative δ^2H values characterize modern and other Holocene waters which have low and moderate He_{exc} concentrations.

Water in the Z1 well, which is characterized by variable isotopic composition in the period of intensive and variable exploitation rates, is also characterized by changes in He_{exc} concentrations as seen in Figure 5. Most probably, similar explanation can be proposed for He_{exc} changes in the SZ well.

NEON AND ARGON

Zuber *et al.* (1995) and Manning and Solomon (2003) showed that under favourable conditions the noble gas temperature (NGT) found from the concentrations of dissolved atmospheric gases may serve for finding the altitude of recharge. A different conclusion was reached by Aeschbach-Hertig *et al.* (1999) for several groundwater systems in the Swiss Alps. The mean recharge altitude is expected to be given by the cross-point of the NGT line, calculated as a function of the assumed altitude, with the line of the mean air temperature (or rather the temperature of infiltrating meteoric water). Aeschbach-Hertig *et al.* (1999) showed that in most cases the slopes of both lines differ very little what makes the determination of the cross-point uncertain, or both lines differ so much that they do not cross.

NGT lines as a function of altitude are shown for individual wells in Figure 6. In most cases they greatly disagree with the air temperature line deduced from the data of Konĉek and Orlicz (1974). Measurements of soil air and near soil air temperatures performed at different sites of the Polish Tatras showed complicated character depending very much on different local conditions related among other reasons to permafrost, seasonal ground freezing and changes in snow cover (Mościcki, 2008). Due to these reasons, the NGT values may much more depend on local conditions than on the altitude of recharge. They can be additionally disturbed by contacts of flows in karstic channels with the atmosphere at a lower altitude than that of recharge. Thus, it is not surprising that NGT values are not satisfactorily representative for the recharge altitudes in the Tatras.

Both the NGT and air temperature (T) values listed in Table 4 correspond to the recharge altitudes found from Eq. [2], by making use of lines shown in Figure 6. In most cases, they reasonably agree within the uncertainties of determinations. They greatly disagree for the BA1, BA2 and BI wells, which suggests that waters in these wells were recharged under distinctly cooler climatic conditions.

COMBINED INTERPRETATION OF TRACER DATA

None of the environmental tracer methods used in the present study gives assurance in relation to the presence of glacial age waters in the wells situated in the northeastern part of the basin. However, when all the methods are considered together, they yield a consistent picture on the distribution of water ages as shown below.

Near the outcrops, the underground flow in the carbonate formations is very fast as indicated by the presence of high concentrations of ^{3}H (190 T.U.) in early seventies at the depth exceeding 1,000 m in the Z1 well, and also high concentrations (about 50 T.U.) in late eighties in other wells situated near the Tatras.

For waters in the whole basin, the aerial distribution of δ^2H, ^{14}C, He_{exc} and NGT values shown in Figure 7 reveals a consistent picture. The most negative δ^2H values are observed for very young waters discharged by large springs in the Tatras and for presumably old waters in the northeastern part of the basin. These two areas are separated by a belt occupied by modern and pre-bomb era waters recharged at the lowest altitudes of the permeable outcrops, with δ^2H ≥ –75‰. Therefore, waters in the northeastern part were presumably recharged under a cooler climate at the final stages of the last glacial period when in Poland conditions existed for an intensive recharge of groundwater systems (e.g. Zuber *et al.*, 2000, 2004). These waters are also characterized by immeasurably low ^{14}C contents, δ^{13}C values close to zero (not shown in Fig. 7), extremely high He_{exc} concentrations, and immeasurably low NGT values, which confirms the hypothesis of their glacial age.

Majority of wells in the central and western parts of the basin are not accessible at present, and, therefore, only incomplete tracer are available. The ^{14}C data of the PO, FU, SZ and CH wells and He_{exc} in the SZ well suggest the late Holocene age of waters.

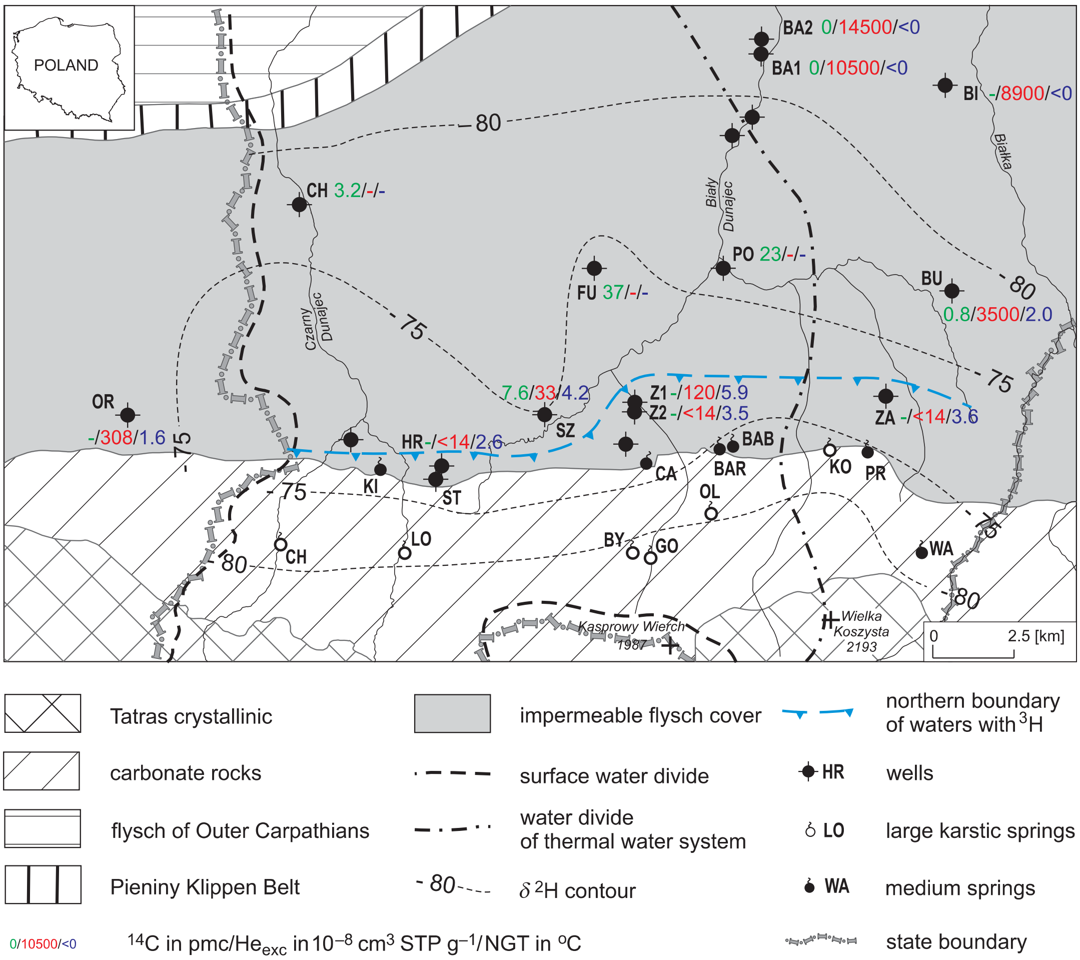

Fig. 7. Aerial distribution of tracers indicating the presence of older waters in the northeastern part of the basin

CONCLUSIONS

On the basis of earlier studies, thermal water of the Podhale Basin were thought to result from recharge during the Holocene. New environmental tracer data unexpectedly revealed that most exploited thermal waters in the northeastern part of the Podhale Basin are of a glacial age, and in other parts of the late Holocene. In spite of a large scatter, the hydraulic conductivity known from pumping tests does not exhibit differences in particular parts of the basin. Therefore, much greater ages, and thus slower flow rates in the northeastern area than in other parts of the basin, can be related to faults which may act as obstacles to horizontal flow.

Very high He_{exc} concentrations in the northeastern part of the basin cannot be attributed only to great water ages, but has to result also from differences in the outside helium flux. According to the geological map of the Polish Tatras the bedrock of the Mesozoic carbonate formations in the eastern part is probably represented by granites in contrast to the metamorphic bedrock in the western part (Bac-Moszaszwili *et al*., 1979), which most probably explains great differences in the outside (crustal) helium flux to the thermal waters.

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