



HAL
open science

Hydrogeochemistry in two adjacent areas in the Pannonian Basin (Southeast-Hungar)

Iren Varsanyi, Jean-Michel Matray, Lajos O Kovacs

► **To cite this version:**

Iren Varsanyi, Jean-Michel Matray, Lajos O Kovacs. Hydrogeochemistry in two adjacent areas in the Pannonian Basin (Southeast-Hungar). Chemical Geology Isotope Geoscience section, 1999, 156 (1-4), pp.25-39. <irsn-03884212>

HAL Id: irsn-03884212

<https://hal.science/irsn-03884212v1>

Submitted on 5 Dec 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Hydrogeochemistry in two adjacent areas in the Pannonian Basin (Southeast-Hungary)

Irén Varsányi ^{a,*}, Jean-Michel Matray ^{b,1}, Lajos Ó. Kovács ^{c,2}

^a Department of Mineralogy, Geochemistry and Petrology, University of Szeged, H-7601 Szeged, P.O. Box 651, Hungary

^b Département Stockage, ANTEA, groupe BRGM, BP 6119, F-45061 Orléans, France

^c Hungarian Geological Survey, H-1440 Budapest, P.O. Box 17, Hungary

Received 12 May 1998; revised 24 August 1998; accepted 22 September 1998

Abstract

Groundwaters from the Quaternary, Pliocene and Pontian layers in two adjacent basin areas of Hungary (Szeged and Körös) and from the intermediate basement high, all belonging to the central part of the Pannonian Basin, have been investigated chemically and isotopically. Most of the waters are NaHCO₃ type with significant quantitative and qualitative regional differences for the Szeged and Körös areas, the intermediate high, and the deepest studied lithostratigraphic zone (the base of the Pontian stage). Hydrogen and oxygen isotopes indicate that most of the waters have a paleometeoric origin. The period of infiltration for the entire studied depth interval (75–2500 m) was within the last cold period in the Szeged and intermediate areas, and during a preceding warmer period in the Körös area. Over the entire studied region, waters in the deepest lithostratigraphic position are mixtures of paleometeoric waters and deep waters squeezed out from the thick sequence of fine-grained (Pannonian) sediments that underlie the Pontian thermal water aquifer. In the Szeged and intermediate areas, the effect of the upward seepage from the deeper (Pannonian) layers was overprinted by the recharge in the last cold period. In the Körös area, due to the lack of infiltration during the last cold period, the mixing with Pannonian waters is seen up to a depth of 1000 m. Based on ⁸⁷Sr/⁸⁶Sr ratios, water flow systems were separated. In the Szeged and intermediate areas, a shallower and a deeper flow systems were distinguished, one in the Pleistocene and Pliocene formations, and another in the Pontian layers. In the Körös area, most of the waters belong to the same flow system that occupies the depth interval from the base of the Pontian (about 2500 m) up to 1000 m. The two shallowest samples studied (above a depth of 1000 m) show lower ⁸⁷Sr/⁸⁶Sr ratios. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Pannonian Basin; Hungary; Hydrogeochemistry

1. Introduction

When investigating the circumstances of infiltration and recharge of formation waters the main

questions are time and location. Elemental and isotope geochemistry of formation waters are often used to investigate the origin of waters, the time and location of recharge, and the water flow direction (Kharaka and Carothers, 1986; McMurtry et al., 1977; Coplen et al., 1975; Andrews et al., 1982; Lambert, 1991; Bullen and Kharaka, 1992; Chaudhuri et al., 1992; Vuataz et al., 1988). In the Pannonian Basin (Fig. 1) two flow systems exist: one in the

* Corresponding author. Fax: +36-62-326479; E-mail: varsanyi@geo.u-szeged.hu

¹ Fax: +33-38-64-33-90; E-mail: jm.matray@antea.brgm.fr.

² Fax: +36-1-2516769; E-mail: okovacs@mgsz.hu.

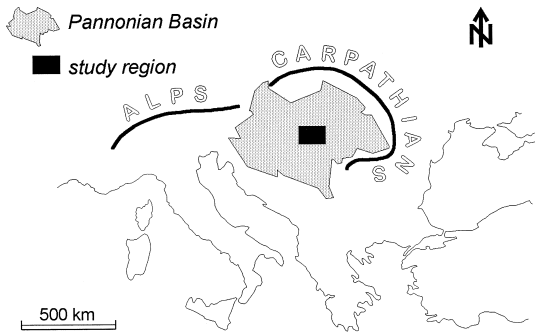


Fig. 1. Location of the study region.

Quaternary layers, and another in the deeper horizons down to a depth of about 2500 m. The base of the deeper flow is at the boundary of the Pontian (lacustrine, Upper Miocene, with delta plain and delta slope facies) and the Pannonian (lacustrine,

Upper Miocene, with delta front and delta slope facies) stages. Below this boundary, practically stagnant NaCl–NaHCO₃ type waters are present (Deák et al., 1987). The Pliocene and Pontian layers are characterised by a NaHCO₃ water type (Erdélyi, 1979), and the Quaternary by Ca–Mg(HCO₃)₂ and NaHCO₃ type waters (Varsányi and Ó. Kovács, 1997).

The Quaternary tectonic events played an important role in the recharge of both flow systems. During the last 700,000 years (Middle and Late Pleistocene), subsidence was general over the studied region, but in places some opposite movements also occurred. The western part of the region as well as the Nyírség area located north-east of the studied region were uplifted at the end of the Pleistocene. These two uplifted regions are the infiltration areas for the Pleistocene layers (Urbancsek, 1963; Rónai,

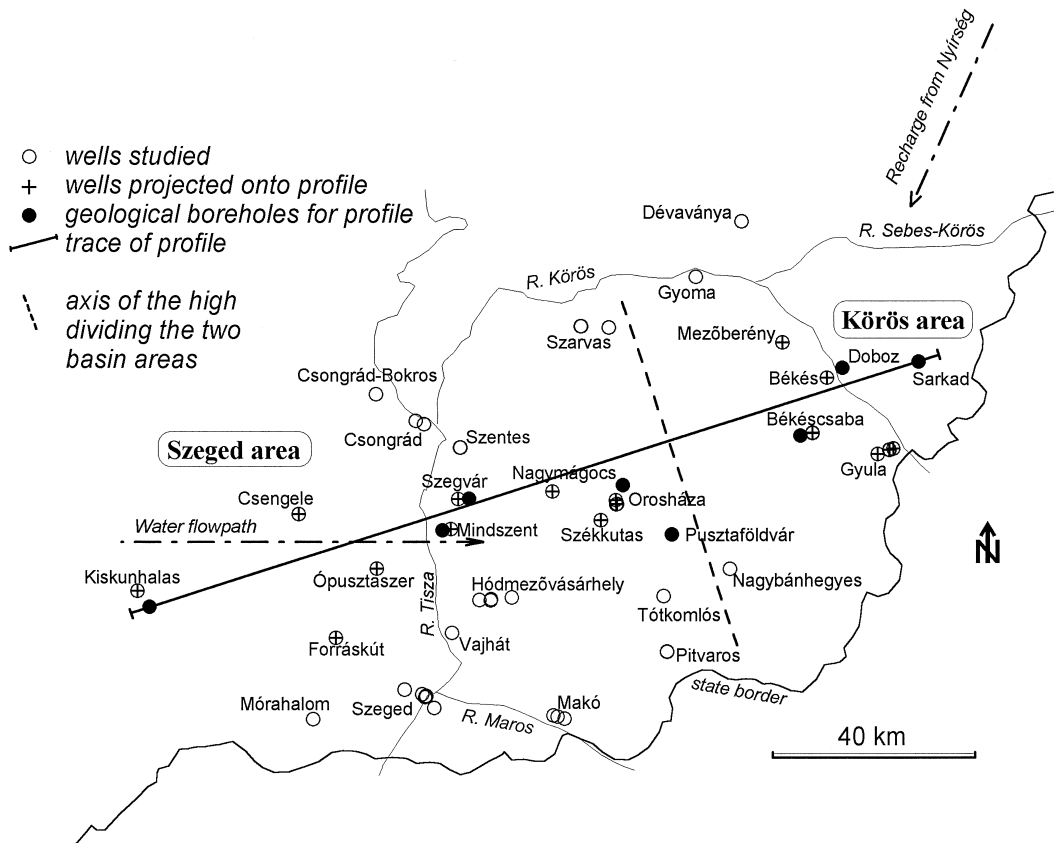


Fig. 2. Location of the studied wells.

1985) with water moving eastwards in the Szeged area and south-westwards towards the Körös area from the Nyírség (Fig. 2). Foothills at the northern margin of the basin are considered to be the recharge area for the deeper layers (Rónai, 1985; Stute and Deák, 1989).

In the present work, two adjacent basins and their vicinity were studied (Fig. 2). These basins do not have a generally accepted name in the Hungarian geological and hydrogeological literature. The basin near the River Tisza is named South Tisza basin (Rónai, 1985), Szentes basin (Urbancsek, 1963), or Makó-Hódmezovásárhely depression (Juhász, 1994). The basin near the River Körös is named Körös (Rónai, 1985) or Békés basin (Urbancsek, 1963). Due to the inclusion of adjacent regions, we utilise here the name 'Szeged area' for the region near Tisza, and 'Körös area' for the one near Körös.

This work is the second instalment of a project initiated in 1995 with the objective of determining the origin and chemical evolution of groundwaters in the two areas. The geochemistry of waters collected in the Szeged area was described in Varsányi et al. (1997). This paper described the role of the decay of sediment and dissolved organic matter (SOM, DOM) as a control of water chemistry. The present work aims at elucidation of the origin, flow pathway and infiltration times for two adjacent areas of south-eastern Hungary.

2. Geological background

The study region is located in the central part of the Pannonian Basin, coincident with the south-eastern part of Hungary (Fig. 1). Its geological evolution is summarised in Varsányi et al. (1997), and we present only a short description here. Stratigraphic subdivision is after Bernor et al. (1993). The entire Pannonian Basin is filled by Neogene sediments: the Palaeozoic–Mesozoic basement is overlain by Miocene, Pliocene and Quaternary sedimentary sequences. The initial formation of deep basins and uplifted highs was related to Middle Miocene tectonics. In the Late Miocene to Pliocene, thermal subsidence over the entire region was accompanied by rapid sedimentation. The Late Pliocene and Pleis-

tocene tectonic events seem to follow the SW–NE tectonic lines developed during the Miocene.

The subsidence and uplift occurred at different rates over the Pannonian Basin (Horváth et al., 1988; Juhász et al., 1998; M. Tóth and Juhász, 1997) with the thickness of sedimentary cover ranging from several hundred to several thousand meters. In the Miocene, 1000–3000 m of marine sediments were covered by 1000–3000 m of lake sediments. The Lower to Middle Miocene pre-Pannonian sediments formed in a marine to brackish environment. The late Miocene Pannonian (M₃Pa) was characterised by lake deposits, followed by Pontian (M₃Po) lacustrine and deltaic sedimentation. The Pliocene (Pl) is characterised by interbedded lacustrine and fluvial sediments (Rónai, 1985). In the Pontian and Pliocene repeated subsidence caused cyclic features of sediments (Molnár, 1973) and diachronous commencement of fluvial sedimentation. The latter commenced in the Szeged area already at the end of the Pliocene while in the Körös area lacustrine-marshy sedimentation prevailed until the early Pleistocene, only later was it replaced by fluvial sedimentation. As a result, the overall thickness of the fluvial sediments varies from 100 to 700 m, often having a cyclic character (Rónai, 1983a,b). After the Pleistocene, eolian sedimentation deposited windblown sand and loess over the region.

Climate evolution during the last 200,000 years was reconstructed from the frequency distribution of spores and from distribution patterns of tree species (Rónai, 1983a,b; Guiot et al., 1989). At about 200,000 years BP a cold period corresponding to the Riss glacial commenced. It was followed by a warm/moderate and slightly wet interglacial (Eemian). During the subsequent 70,000–80,000 years a cold and dry period interspersed by short-time fluctuations in temperature and precipitation was identified as the Würm glacial. This glacial was followed by a slow rise in temperature during the last 10,000–20,000 years.

Although the general geological history and the sediments of the two studied areas are similar (Juhász, 1994), some differences do exist, such as in grain size distribution, location of source areas for the clastic infill, and in infiltration zones. In the Pannonian lacustrine sediments, sandy and clayey layers alternate at short intervals over the entire studied

region. The Pliocene and Pleistocene sediments, on the other hand, show lateral variations in grain size, with predominantly argillaceous sediments in the Körös basin. The Pliocene clays are characterised by a poorly sorted grain size distribution and form almost impermeable layers. In the Szeged area, the predominant lithology is sand, sometimes with gravel and they form the best artesian aquifer in the 200–400 m depth interval. The sediment input into the Körös basin originated from the north-eastern and eastern parts of the Carpathian Mountains, while in the Szeged area it originated from the north-west. Sediments over the studied area contain quartz, plagioclase feldspars (mainly albite), calcite, dolomite, kaolinite, illite–montmorillonite mixed layers and chlorite (Varsányi, 1975; Varsányi and Ó. Kovács, 1994). The two basins are separated by a 1000 m elevated basement high.

3. Results

The present study discusses the chemical and isotopic composition of fifty water samples collected from the Szeged and Körös areas (Fig. 2). These samples are grouped in Table 1 on the basis of their location and stratigraphy. A SW–NE idealised geological cross-section is given in Fig. 3 in order to demonstrate the distribution of producing intervals in the studied areas.

The well-head sampling and sample preservation procedures, the methods for chemical and isotopic analyses, as well as the gas and organic content measurements are described in Varsányi et al. (1997), together with detailed chemical and isotopic data obtained for the first 25 water samples, all from the Szeged area. New data for a second series of 25 water samples were obtained from both the Szeged and Körös areas. Table 2 gives general information on the newly sampled wells, Table 3 shows their dissolved inorganic components, and Table 4 presents their isotopic compositions. The waters in this study originate from the Pleistocene, Pliocene and Pontian layers. Towards the eastern part of the Szeged area the thickness of the sediments is decreasing (Fig. 3) because the basement between the Szeged and Körös areas lies 1000 m higher than that of the surroundings. As this subsurface high (Fig. 3) influ-

ences the hydrology and consequently the water chemistry of the region, samples from the basement high are considered as a separate group.

The chemical composition indicates that the waters from both areas are mostly of Na–HCO₃ type with Ca concentrations never exceeding 36 mg/l, and TDS values ranging between 0.5 and 5.5 g/l. These waters are also characterised by the presence of dissolved organic species with TOC values ranging between 2 and 550 mg/l. Waters produced from the base of the Pontian show a significant difference from the average water quality in the bulk of the Pontian. In these samples, concentrations of bromide, iodine and borate (Table 3) are an order of magnitude higher than for the other samples. These waters have the highest chloride (214 mg/l), sulphate (82 mg/l) and sulphide (3.1 mg/l) contents, as well. It must also be pointed out that, independently of the stratigraphy, some waters show As contents greater than the limit accepted for drinking waters. The concentration of most dissolved compounds increases from the shallower to the deeper formations, and within the formations from west to east, i.e., from the Szeged to the Körös area. Calcium, magnesium and iron, however, are decreasing with depth. The chemistry of samples from the basement high represents an intermediate water quality between the Szeged and the Körös areas.

The isotopic composition of waters may be interpreted by plotting the stable isotope data on a δD vs. $\delta^{18}O$ diagram (Fig. 4). The local meteoric water line (LMWL) is based on 6–7 years of monthly averaged precipitation at Abádszalók village located nearby (Deák et al., 1987). Statistically, the relation is defined by the equation $\delta D = 8\delta^{18}O + 6.4$, and the annual mean values are -68.6 for δD and -9.3 for $\delta^{18}O$. The relationships with the monthly mean temperature (mt) was described by Deák et al. (1987) as $\delta D = 3.2mt - 100$, and $\delta^{18}O = 0.42mt - 13.5$. The samples from the Szeged and intermediate areas may be divided into two groups. Waters produced from the Pontian, Pliocene and Quaternary layers, indicated as Po–Q, plot on the LMWL with values depleted in heavy isotopes by about -20% in deuterium and -3% in oxygen-18, compared to the multiannual monthly average of modern infiltration waters. Those from the boundary between the Pannonian and Pontian formations, identified as Pa/Po,

Table 1
Identification data of the studied wells

No.	Old no.	Location	Name	Stratigraphic position
<i>Szeged area</i>				
1		Szeged	Partfurdo-III	Q
2	25	Szeged	Vizmu	Q
3	24	Hodmezo- vasarhely	Vizmu	Q
4		Szeged	Partfurdo-I	Q
5	23	Vajhat	K.SZ.V.	Q
6		Szeged	Partfurdo-II	Pl
7	22	Szegvar	K.SZ.V.	Pl
8	21	Szeged	Anna	Pl
9	20	Mako	Strand	Pl
10	19	Csongrad	Strand	Pl
11	18	Hodmezo- vasarhely	Strand	Pl
12	14	Csongrad– Bokros	Kossuth	Po
13	12	Mindszent	Agro	Po
14	10	Csongrad– Bokeny	V.G.V.	Po
15	9	Opusztaszer	Makra	Po
16	8	Csengele	Aranyhomok	Po
17	7	Szentes	V.G.V.	Po
18	17	Szeged	Dora	Po
19	15	Mako	Korhaz	Po
20	13	Forraskut	Nemes	Po
21	11	Hodmezo- vasarhely	Korhaz	Po
22	16	Szentes	Korhaz	Po
23	6	Hodmezo- vasarhely	Porcelan	Po
24	4	Kiskunhalas	Strand	Pa/Po boundary
25	3	Szekkutas	Korhaz	Pa/Po boundary
26	2	Szeged	Napsugar	Pa/Po boundary
27	1	Mako	V.G.V.	Pa/Po boundary
<i>High separating the two areas</i>				
28		Pitvaros	Vizmu75	Q
29		Szarvas	Vizmu279	Q
30		Pitvaros	Vizmu314	Q
31		Szarvas	Vizmu570	Q
32		Oroshaza– Gyoparos	Termal1	Pl
33		Totkomlos	Furdo	Pl
34		Oroshaza	Ujtermal-III	Pl
35	5	Morahalom	Strand	Pl
36		Szarvas	Vizmu	Pl
37		Oroshaza	Termal2	Pl
38		Nagymagocs	Termal	Pl
39		Nagyban– hegyes	Termal	Pa/Po boundary
40		Szarvas	Pulykanevelo	Pa/Po boundary

Table 1 (continued)

No.	Old no.	Location	Name	Stratigraphic position
<i>Körös area</i>				
41		Bekescsaba	Furdo-II	Pl
42		Gyula	Furdo-II	Pl
43		Mezobereny	Furdo	Pl
44		Gyoma	Furdo	Pl
45		Bekes	Furdo	Pl
46		Devavanya	Furdo	Pl
47		Gyula	Furdo-IV	Po
48		Gyula	Furdo-I	Po
49		Bekescsaba	Furdo-I	Pa/Po boundary
50		Gyula	Furdo-V	Pa/Po boundary

Pa = Pannonian.

Po = Pontian.

Old no. = number in Varsányi et al., 1997.

show simultaneous deuterium and oxygen-18 enrichments which may be interpreted as a trend intersecting the LMWL at about $-90 \pm 5\%$ in δD and at $-12 \pm 1\%$ in $\delta^{18}O$. In the Körös area, samples produced from the Pliocene layers are situated on the LMWL while those from deeper (Pontian) layers plot below it. The line through the latter and those from the boundary between the Pannonian and Pontian formations, intersects the LMWL at about -76% δD and -10% $\delta^{18}O$. These results raise the question of the mechanism responsible for the observed trends and for the depletion in heavy isotopes for waters that plot on the LMWL.

Since strontium tends to be concentrated in calcium bearing phases (Schultz et al., 1989), the plot of dissolved Sr vs. Ca is used to make assumptions about the source of Sr. In Fig. 5 two trends can be distinguished: a large increase in Ca (3–37 mg/l) associated with a slight increase in Sr (0.1–1.0 mg/l) in the shallower formations (Q and Pl), and a relatively large increase in Sr (0.1–2.2 mg/l) linked with a small increase in Ca (7–9 mg/l) in the deeper (Po and Pa/Po) layers. The plot of $^{87}Sr/^{86}Sr$ vs. $\delta^{18}O$ (Fig. 6) was used to separate groups of waters linked to sediments from different source areas. Three groups can be distinguished. The waters in the Körös area show a very narrow range of $^{87}Sr/^{86}Sr$ ratios, between 0.70947 and 0.71002. The two shallowest samples have even lower values (0.70829 and 0.70929). In the Szeged and intermediate areas the

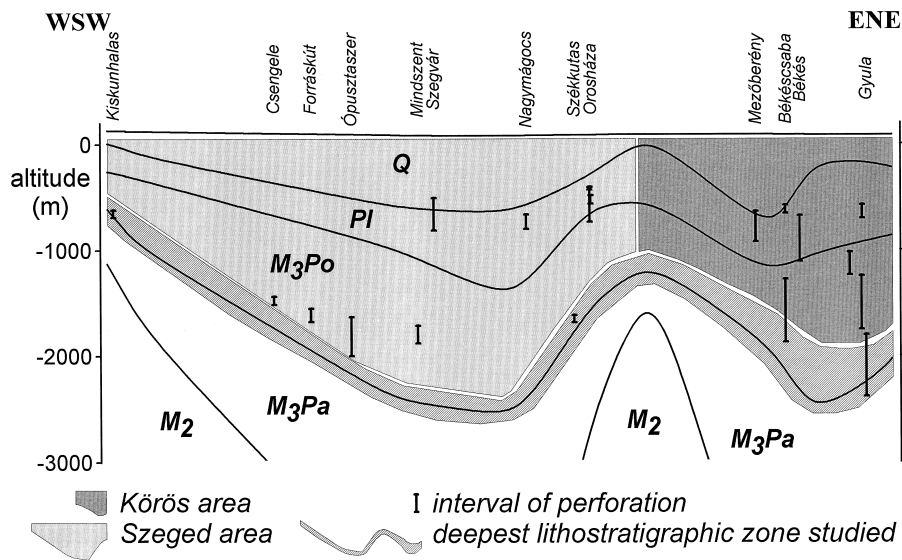


Fig. 3. Idealised geological profile across the study region. M_2 = middle Miocene; M_3Pa = upper Miocene Pannonian stage; M_3Po = upper Miocene Pontian stage; PI = Pliocene; Q = Quaternary.

$^{87}\text{Sr}/^{86}\text{Sr}$ ratios vary from 0.71090 to 0.71223. The third group shows a much wider range of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (from 0.70893 to 0.71130). The plot of $^{87}\text{Sr}/^{86}\text{Sr}$ vs. calcium plus magnesium concentrations (Fig. 7) supports the above separation.

4. Origin of waters

4.1. Evidence for mixing

Isotope exchange reactions and mixing are two possibilities to explain the two trends observed in the δD vs. $\delta^{18}\text{O}$ diagram (Fig. 4). The lack of a general relationship between the isotopic composition and temperature strongly suggests the existence of mixing. Deviations from the LMWL in formation waters are often attributed to mixing of waters of different origin (e.g., Kharaka and Carothers, 1986; Hitchon and Friedman, 1969; Kharaka et al., 1973, 1985). Mixing between a paleometeoric end member and deep formation waters seems to be the process controlling water stable isotope values and concentrations of several chemical components (e.g., chloride, bromide, iodine and borate). In the Szeged and intermediate areas the mixing between waters from the formation below the Pontian and from the deepest

studied lithostratigraphic layers resulted in one of the trends. The other trend, the one in the Körös area, is a result of mixing between waters from the formation below and above the Pannonian–Pontian boundary. These mixing relationships are also supported by the correlation existing between the stable isotope and chloride values (Fig. 8). The two mixing trends (Fig. 4) intersect at a hypothetical end-member that corresponds to the isotopic composition of the deep oilfield water collected in the same area (Mátyás, 1997). These two mixing lines intersect the LMWL at two distinct clusters of stable isotope values, thought to be characteristic of paleometeoric waters (Rozanski, 1985; Deák et al., 1987; Stute and Deák, 1989; Varsányi et al., 1997). These paleometeoric waters show a depletion in heavy isotopes compared to modern meteoric waters suggesting a recharge under lower temperatures (Dansgaard, 1964).

4.2. Infiltration periods

In the Szeged area, the isotopic composition of the paleometeoric water end-member shows a narrow range of values despite the differences in depth (550 to 2500 m). This fact strongly suggests that the waters in the Pliocene, Pontian and partly in the Pleistocene layers infiltrated during the same cold

Table 2
Basic technical data of studied wells

No.	Location	Name	Strat.	N–S coordinate (m)	W–E coordinate (m)	Altitude (m)	Depth (m)	Year of drilling	Water temperature (°C)		Perforated depth	
									bottom	surface	from (m)	to (m)
<i>Szeged area</i>												
1	Szeged	Partfurdo-III	Q	101470	735700	79.65	520.0	1961	42.0	36.0	520.0	649.0
4	Szeged	Partfurdo-I	Q	101560	735600	79.87	664.0	1961	38.0	32.0	470.0	514.0
6	Szeged	Partfurdo-II	PI	101340	735460	79.64	800.0	1973	48.0	44.0	757.5	772.5
<i>High separating the two areas</i>												
28	Pitvaros	Vizmu75	Q	109605	780251	94.10	74.6	1991	16.5	16.5	23.5	26.0
29	Szarvas	Vizmu279	Q	169770	764655	85.27	279.6	1969	26.0	23.0	209.0	271.5
30	Pitvaros	Vizmu314	Q	109690	780263	95.30	314.0	1969	27.0	24.0	233.5	330.0
31	Szarvas	Vizmu570	Q	169780	764620	84.71	570.0	1964	41.0	38.0	499.0	553.0
32	Oroshaza–Gyoparos	Termal1	PI	137660	770930	87.36	510.0	1953	44.5	40.0	493.3	516.3
33	Totkomlos	Furdo	PI	120000	779670	91.88	550.0	1980	48.1	42.0	456.0	533.0
34	Oroshaza	Ujtermal-III	PI	137000	771123	86.92	660.0	1996	47.5	44.8	569.4	649.1
36	Szarvas	Vizmu	PI	169760	764690	84.61	679.0	1959	47.0	40.0	585.0	617.0
37	Oroshaza	Termal2	PI	136900	771000	88.00	834.5	1967	49.0	46.0	491.0	822.0
38	Nagymagocs	Termal	PI	139280	759180	84.72	906.0	1987	56.0	52.0	749.1	883.2
39	Nagybanhegyes	Termal	Pa/Po	124990	791920	94.93	1340.0	1971	93.0	72.0	1065.0	1188.0
40	Szarvas	Pulykanevelo	Pa/Po	169560	769760	83.80	2740.0	1982	115.0	92.0	1519.0	1728.0
<i>Körös area</i>												
41	Bekescsaba	Furdo-II	PI	150060	807250	86.53	800.0	1978	50.5	41.0	662.0	740.0
42	Gyula	Furdo-II	PI	146890	821500	88.34	950.0	1960	49.6	44.0	662.0	790.0
43	Mezobereny	Furdo	PI	166760	801740	84.02	1030.0	1960	65.0	50.0	719.0	1008.0
44	Gyoma	Furdo	PI	178850	785870	86.81	1166.0	1958	70.2	64.0	1035.0	1090.0
45	Bekes	Furdo	PI	160280	809920	84.57	1200.0	1963	73.0	53.0	760.0	1193.0
46	Devavanya	Furdo	PI	189100	794300	87.25	1201.0	1961	69.5	65.0	998.0	1168.0
47	Gyula	Furdo-IV	Po	146120	819260	87.22	1907.0	1964	99.0	59.0	1108.0	1325.0
48	Gyula	Furdo-I	Po	146890	821420	90.15	2004.0	1959	96.3	72.0	1336.0	1843.0
49	Bekescsaba	Furdo-I	Pa/Po	150010	807260	86.54	2000.0	1959	111.0	76.0	1364.0	1959.0
50	Gyula	Furdo-V	Pa/Po	147150	822220	87.26	2500.0	1972	135.0	91.0	1889.0	2473.0

Strat. = stratigraphic position.

Pa/Po = Pannonian–Pontian boundary.

Table 3
Dissolved inorganic components

No.	Location	Name	Strat.	K (mg/l)	Na (mg/l)	NH ₄ (mg/l)	Ca (mg/l)	Mg (mg/l)	Fe (mg/l)	Li (mg/l)	Sr (mg/l)	Ba (μg/l)	Cl (mg/gl)	Br (mg/gl)
<i>Szeged area</i>														
1	Szeged	Partfurdo-III	Q	1.3	50	0.95	35.7	19.1	0.04	n.d.	1.3	190	3	0.00
4	Szeged	Partfurdo-I	Q	1.1	128	1.18	12.3	5.1	0.02	n.d.	0.5	89	3	0.06
6	Szeged	Partfurdo-II	PI	1.5	230	0.77	5.1	1.3	0.02	n.d.	0.2	50	6	0.00
<i>High separating the two areas</i>														
28	Pitvaros	Vizmu75	Q	1.2	250	0.14	30.6	16.1	0.49	n.d.	0.7	100	17	0.05
29	Szarvas	Vizmu279	Q	1.4	280	0.31	17.5	7.6	0.22	n.d.	0.5	130	27	0.07
30	Pitvaros	Vizmu314	Q	1.3	280	1.38	15.7	7.4	0.04	n.d.	0.3	100	32	0.11
31	Szarvas	Vizmu570	Q	2.2	370	3.10	11.7	5.1	0.07	n.d.	0.3	150	15	0.06
32	Oroshaza–Gyoparos	Termal1	PI	2.1	350	3.20	8.0	4.0	0.04	n.d.	0.3	100	24	0.09
33	Totkomlos	Furdo	PI	2.7	480	5.60	9.5	3.3	0.05	n.d.	0.4	170	10	< 0.05
34	Oroshaza	Ujtermal-III	PI	5.0	470	4.70	10.2	3.1	0.38	n.d.	0.3	120	26	0.10
36	Szarvas	Vizmu	PI	4.0	320	3.20	8.7	2.1	0.03	n.d.	0.2	96	15	< 0.05
37	Oroshaza	Termal2	PI	4.0	350	5.90	6.6	1.6	0.05	n.d.	0.3	96	12	< 0.05
38	Nagymagocs	Termal	PI	2.2	300	3.70	5.1	2.1	0.07	n.d.	0.2	60	14	0.09
39	Nagybanhegyes	Termal	Pa/Po	9.0	930	15.70	6.6	1.4	0.11	0.10	1.1	240	192	4.10
40	Szarvas	Pulykanevelo	Pa/Po	24.0	1260	15.20	8.0	2.3	0.04	0.40	1.8	910	214	1.60
<i>Körös area</i>														
41	Bekescsaba	Furdo-II	PI	1.6	250	1.84	8.0	1.2	0.04	n.d.	0.2	45	70	0.06
42	Gyula	Furdo-II	PI	7.0	570	9.70	33.5	2.2	0.25	n.d.	0.9	360	76	0.14
43	Mezobereny	Furdo	PI	2.9	390	0.91	8.0	1.2	0.10	n.d.	0.3	112	17	0.12
44	Gyoma	Furdo	PI	5.0	490	1.92	7.7	1.0	0.07	0.10	0.3	150	42	0.21
45	Bekes	Furdo	PI	6.0	510	2.20	12.0	2.3	0.11	0.10	0.4	195	27	0.22
46	Devavanya	Furdo	PI	2.8	370	1.04	6.6	1.0	0.07	n.d.	0.2	110	68	0.38
47	Gyula	Furdo-IV	Po	8.0	570	5.80	11.7	3.3	0.06	0.10	0.5	320	96	0.22
48	Gyula	Furdo-I	Po	13.0	670	5.10	9.1	1.4	0.08	0.10	0.6	340	82	0.19
49	Bekescsaba	Furdo-I	Pa/Po	40.0	1500	19.10	10.6	1.0	0.10	0.50	2.2	940	196	1.70
50	Gyula	Furdo-V	Pa/Po	11.0	710	5.00	9.5	1.2	0.05	0.10	0.6	320	138	0.30

I (mg/l)	F (mg/l)	SO ₄ (mg/l)	S (mg/l)	PO ₄ (mg/l)	Alkalinity (meq/l)		HBO ₂ (mg/l)	H ₂ SiO ₃ (mg/l)	Al (μg/l)	As (μg/l)	TDS (mg/l)	pH
					total	bicarb						
0.007	0.00	0	< 0.11	0.16	6.1	6.1	0.0	37	3.9	6	536	8.09
0.010	0.06	0	0.14	0.40	6.6	6.6	< 0.5	28	6.3	28	595	8.23
0.029	0.27	< 25	0.22	0.44	10.2	10.2	3.1	29	11.6	29	910	8.67
0.063	0.07	< 25	0.06	1.27	14.2	14.2	4.2	24	6.8	41	1250	8.29
0.140	0.37	43	n.d.	2.84	13.8	13.8	3.8	39	8.2	99	1285	7.93
0.150	0.00	< 25	0.09	0.75	14.8	14.8	7.0	31	11.4	8	1294	8.48
0.078	0.42	31	0.08	1.00	18.1	18.1	3.1	35	11.6	n.d.	1608	7.93
0.082	0.23	< 25	n.d.	0.69	18.4	18.4	6.2	31	16.8	n.d.	1562	8.05
0.035	0.30	< 25	0.11	0.60	20.1	20.1	9.0	42	48.2	< 5	1831	8.03
0.089	0.40	< 25	0.12	0.67	21.8	21.8	6.6	35	21.4	n.d.	1919	7.95
0.067	0.25	< 25	0.07	1.22	15.3	15.3	2.2	35	8.0	n.d.	1341	7.72
0.037	0.57	< 25	n.d.	0.60	17.8	17.8	3.8	44	18.8	n.d.	1511	7.92
0.040	0.40	< 25	0.24	0.69	15.0	15.0	3.2	42	30.0	n.d.	1296	8.00
3.400	2.00	26	1.50	0.62	35.4	35.4	39.0	42	82.3	n.d.	3471	7.72
2.300	1.30	82	0.16	0.32	44.8	35.9	66.0	94	24.2	14	4575	7.84
0.160	0.00	0	0.09	0.75	10.9	10.7	5.4	40	4.5	95	1049	8.28
0.620	0.00	43	0.14	0.81	26.6	26.6	6.0	49	3.7	6	2478	7.87
0.350	0.14	61	< 0.05	0.67	16.6	16.6	13.0	42	10.0	46	1571	7.93
0.320	0.15	< 25	0.10	0.37	19.7	19.7	21.0	53	21.7	23	1869	8.11
0.340	0.00	36	0.22	0.79	23.5	23.4	13.0	47	0.0	36	2143	7.74
0.620	0.25	< 25	0.07	0.28	16.4	16.1	18.0	58	16.2	49	1552	8.11
0.520	0.34	27	n.d.	0.34	24.2	24.2	10.0	63	7.7	21	2309	8.00
0.370	0.69	27	0.41	0.28	25.2	24.9	25.0	62	25.6	32	2498	8.30
3.100	0.70	57	0.20	0.32	59.0	46.6	32.0	82	23.1	41	5563	7.76
0.580	0.85	< 25	3.10	0.17	36.0	35.5	39.0	64	3.9	99	3223	7.82

Strat. = stratigraphic position.

Pa/Po = Pannonian–Pontian boundary.

Table 4
Isotopic composition of waters and of dissolved species

No.	Location	Name	Strat.	$\delta^{18}\text{O}$	$\delta^2\text{H}$ (‰ vs. SMOW)	$\delta^{13}\text{C}$ (‰ vs. PDB)	$^{87}\text{Sr}/^{86}\text{Sr}$
<i>Szeged area</i>							
1	Szeged	Partfurdo-III	Q	-12.6	-93.1	-11.7	0.71036
4	Szeged	Partfurdo-I	Q	-12.3	-92.6	-12.7	0.71077
6	Szeged	Partfurdo-II	Pl	-11.0	-81.7	-13.3	0.71112
<i>High separating the two areas</i>							
28	Pitvaros	Vizmu75	Q	-12.5	-92.2	-12.0	0.70913
29	Szarvas	Vizmu279	Q	-12.5	-93.1	-10.9	0.70962
30	Pitvaros	Vizmu314	Q	-11.6	-86.9	-12.0	0.70893
31	Szarvas	Vizmu570	Q	-12.5	-92.0	-11.1	0.71012
32	Oroshaza–Gyoparos	Termal1	Pl	-12.4	-91.5	-6.7	0.70989
33	Totkomlos	Furdo	Pl	-12.4	-92.2	-7.3	0.70960
34	Oroshaza	Ujtermal-III	Pl	-12.2	-91.2	-8.3	0.70991
36	Szarvas	Vizmu	Pl	-12.6	-92.8	-10.8	0.71021
37	Oroshaza	Termal2	Pl	-12.5	-92.7	-7.4	0.71077
38	Nagymagocs	Termal	Pl	-12.5	-92.7	-8.2	0.71042
39	Nagybanhegyes	Termal	Pa/Po	-6.5	-64.3	-1.6	0.71143
40	Szarvas	Pulykanevelo	Pa/Po	-6.6	-71.7	-4.9	0.71126
<i>Körös area</i>							
41	Bekescsaba	Furdo-II	Pl	-11.8	-85.3	-23.1	0.70829
42	Gyula	Furdo-II	Pl	-10.8	-78.9	-9.3	0.70929
43	Mezobereny	Furdo	Pl	-10.2	-76.2	-12.0	0.70966
44	Gyoma	Furdo	Pl	-8.7	-72.2	-17.1	0.71002
45	Bekes	Furdo	Pl	-10.0	-75.6	-25.7	0.70976
46	Devavanya	Furdo	Pl	-9.1	-71.9	-23.6	0.70982
47	Gyula	Furdo-IV	Po	-9.7	-74.9	-13.8	0.70947
48	Gyula	Furdo-I	Po	-9.0	-73.3	-16.2	0.70968
49	Bekescsaba	Furdo-I	Pa/Po	-7.9	-71.1	-20.2	0.70987
50	Gyula	Furdo-V	Pa/Po	-5.3	-64.7	-4.2	0.70999

Strat. = stratigraphic position.

Pa/Po = Pannonian–Pontian boundary.

period. In the Pleistocene layers radiocarbon ages increase from 3300 (recharge area) to 20,200 years BP (discharge area) along the flowpath, while (D decreases from -67.5 to -93.5‰ and $\delta^{18}\text{O}$ from -9.34 to -12.56‰ (Varsányi and Ó. Kovács, 1997). The groundwater ages together with the stable isotope data indicate that the cold period corresponds to the last (Würm) glacial between 70,000 and 12,000 years BP. The two Po–Q samples with the highest heavy isotope values are a mixture between the paleometeoric source and the present day meteoric water (Varsányi et al., 1997).

In the Körös area, the isotope values suggest infiltration of paleometeoric waters at a warmer period than that in the Szeged area, although two

shallowest Pliocene samples (800 m and 950 m) plot between the two paleometeoric waters suggesting infiltration at transitional times. The mixing between paleometeoric and deep formation waters is seen up to a depth of 1000 m. The above mentioned two samples are not affected by mixing.

In Europe, the last cold period (Würm glacial) that occurred between 70,000 to 10,000 years BP was bracketed by three warmer periods: the last 10,000 years of the Holocene, the preglacial period between 100,000 and 70,000 years BP, and the Eemian interglacial between 120,000 and 100,000 years BP (Lebret et al., 1996). The average temperature in Europe was about +12°C in the Holocene, between +3 and +6°C in the preglacial period, and

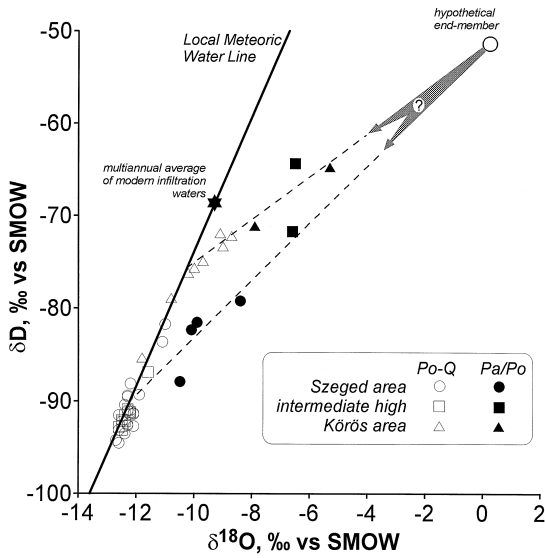


Fig. 4. $\delta^{18}\text{O}$ and δD in the studied waters. Po–Q = Pontian, Pliocene and Quaternary; Pa/Po = the deepest studied lithostratigraphic zone (along the Pannonian–Pontian boundary). The stable isotope composition indicates that waters infiltrated in two periods. Both end-members mix with the same water enriched in heavy isotopes.

+14°C during the last interglacial (Lebret et al., 1996). Based on their depletion in deuterium and

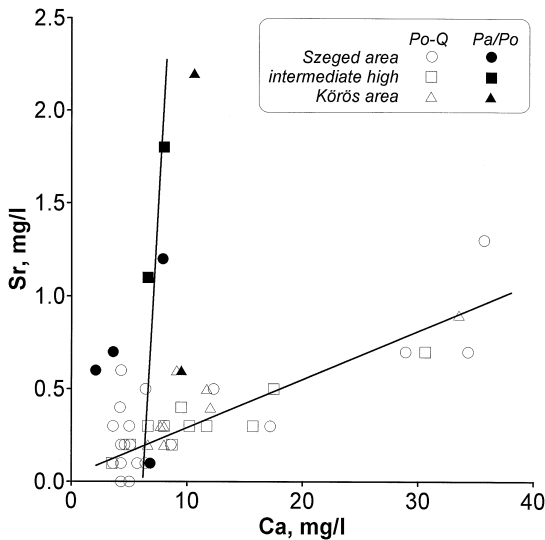


Fig. 5. Plot of Sr vs. Ca.; Po–Q = Pontian, Pliocene and Quaternary; Pa/Po = the deepest studied lithostratigraphic zone; The distribution of samples suggests two different sources for the Sr.

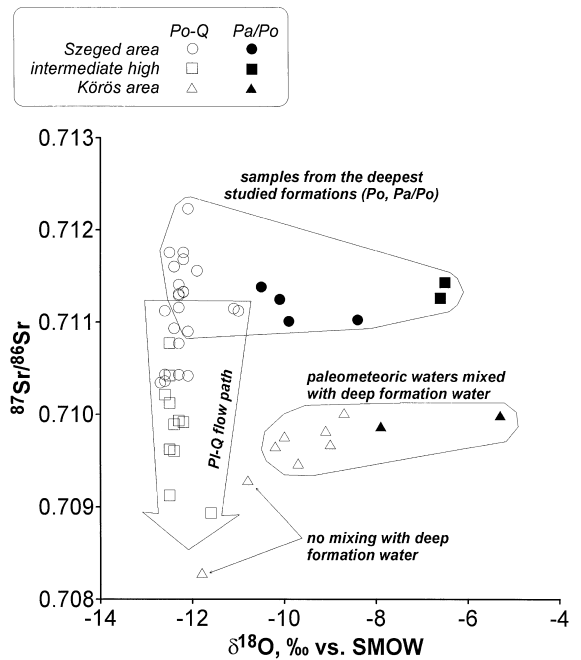


Fig. 6. Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\delta^{18}\text{O}$. Po–Q = Pontian, Pliocene and Quaternary; Pa/Po = the deepest studied lithostratigraphic zone; Sample clusters represent aquifer material types different in source area.

oxygen-18, it is assumed that formation waters in the Szeged area and above the basement high infiltrated during the last cold period (Fig. 9) while in the Körös area infiltration occurred at a temperature slightly lower than the present one (Fig. 4), probably during the preceding warmer period at 100,000 and 70,000 years BP.

5. Separation of water flow systems

Concerning infiltration, not only the ‘when’ but also the ‘where’ is an important question. In general, two flow systems are described in the Hungarian part of the Pannonian Basin, one in the Quaternary, named intermediate, and another one in the deeper layers, named regional (Stute and Deák, 1989). Based on hydraulic head contours decreasing with depth, two recharge areas for the Pleistocene aquifers are defined (Fig. 2): the region west of the River Tisza for the Szeged area, and the region north-east of the

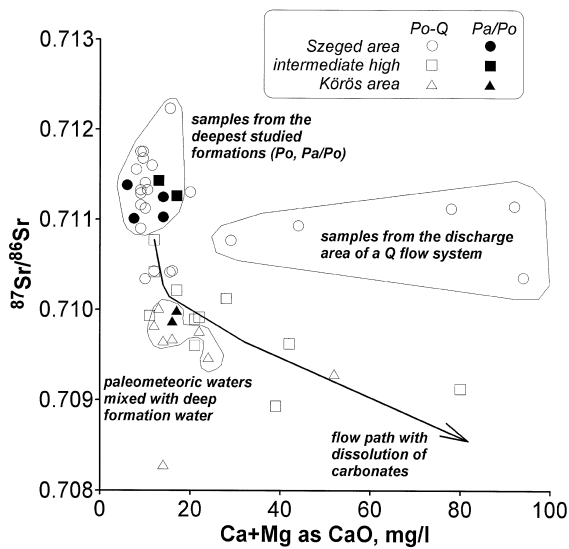


Fig. 7. Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ vs. total hardness. Po–Q = Pontian, Pliocene and Quaternary; Pa/Po = the deepest studied lithostratigraphic zone; Increase of total hardness together with changing $^{87}\text{Sr}/^{86}\text{Sr}$ ratio suggest the presence of a flowpath. For more explanation see text.

Körös area (Urbancsek, 1963; Erdélyi, 1979). Foothills at the northern margin of the basin are considered as the recharge area for the deeper layers (Rónai, 1985; Stute and Deák, 1989). However, a precise distinction between the flow systems down to the base of the Pontian layers has not been done so far.

The Sr isotope ratio is a useful natural tracer. Many studies have analysed Sr isotopic composition of formation waters from sedimentary basins to provide a basis for distinguishing among various lithologic sources of dissolved cations (Bullen and Kharaka, 1992), and to obtain insight into potential mineral–water reactions (Chaudhuri et al., 1992; Vutaz et al., 1988). Unlike the lower mass stable isotopes, Sr isotopes are not measurably mass-fractionated during chemical reactions, and the differences in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio can thus be attributed to local variations in the dominant rock types.

The two trends in Fig. 5 indicate two sources of strontium, one for the shallower, the other one for the deeper layers. It is assumed that in the Pleistocene and Pontian layers carbonate dissolution is the main process controlling strontium concentration,

while aluminosilicates may be the sources of strontium in the Pontian.

The plot of $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\delta^{18}\text{O}$ was used to separate the water flow systems (Fig. 6). The distinct clusters support the separation of waters in the Körös area from those in the Szeged and intermediate areas, and also the separation of the deep (Pa/Po and Po) waters from the shallower (Pl–Q) ones in the Szeged and intermediate areas.

Several samples from the Pleistocene layers of the Szeged area (No. 1–5 in Table 1) belong to a Pleistocene flow system described elsewhere (Varsányi and Ó. Kovács, 1997) where the process controlling water chemistry is ion exchange. Since no carbonate dissolution occurs along the flow pathway it was supposed that the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios do not change from the recharge to the discharge area. The mean $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of these samples is 0.71087, close to the average value for the Pliocene samples in the Szeged area (0.71077), indicating the same recharge area for both flow systems (Fig. 10). This recharge area is located west of the River Tisza, around Kiskunhalas (Fig. 2). In the Pliocene, a west to east decrease in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, together with

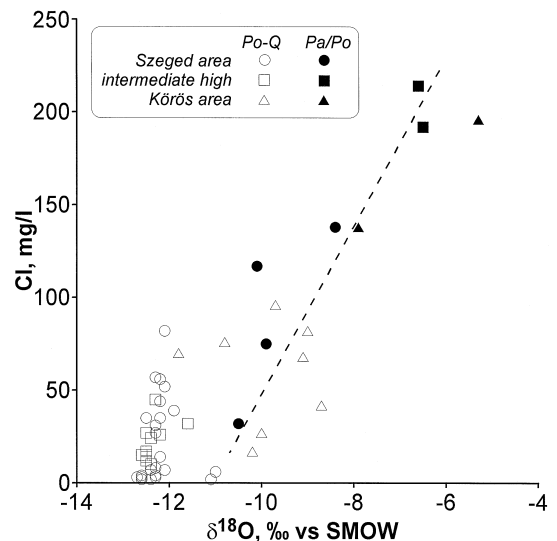


Fig. 8. Plot of Cl vs. $\delta^{18}\text{O}$. Po–Q = Pontian, Pliocene and Quaternary; Pa/Po = the deepest studied lithostratigraphic zone; Both Cl concentrations and $\delta^{18}\text{O}$ values show a mixing of deep formation waters with waters of paleometeoric origin at the Pannonian–Pontian boundary and, in the Körös area, below a depth of 1000 m.

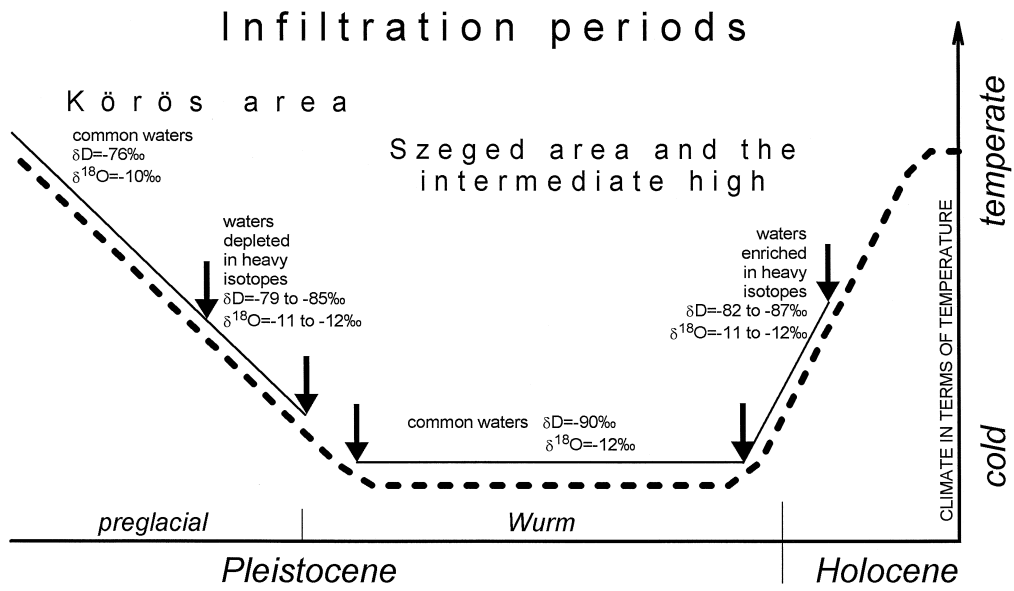


Fig. 9. Suggested infiltration periods for the studied waters.

an increase in Ca + Mg content (Fig. 7), indicate carbonate dissolution along the flow pathway which

may be the process that overprints the original Sr signature. The flow pathway from the recharge area

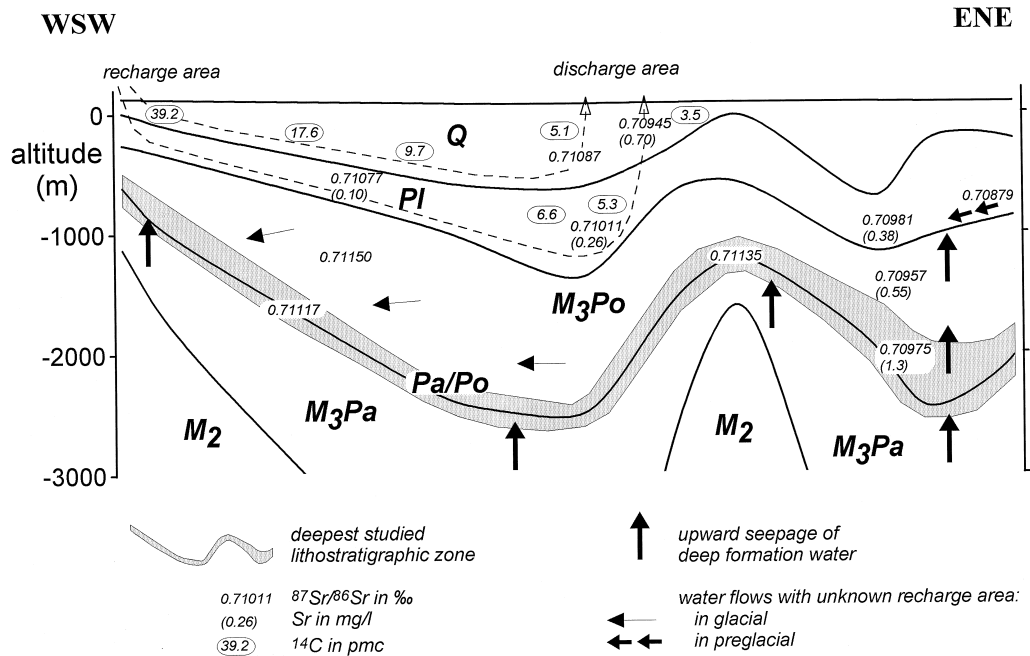


Fig. 10. Suggested hydrogeological model for the studied formations. M₂ = middle Miocene; M₃Pa = upper Miocene Pannonian stage; M₃Po = upper Miocene Pontian stage; PI = Pliocene; Q = Quaternary

runs through the Pliocene layers in the Szeged and intermediate areas towards the Pleistocene layers above the western slope of the basement high.

The other flow system, indicated by the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, is located in the Pontian layers in the Szeged and intermediate areas. However, the recharge area and most of the flow pathway are considered to be outside the study region. Similarly, the recharge area of waters in the Körös area was not identified within the study region. One part of the flow line is represented by the upward seepage of waters from the Pannonian layers through the Pontian, up to the Pliocene. Along this flowpath, the concentration of strontium is decreasing, but the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio remains constant.

6. Conclusions

(1) Based on the comparison of δD and $\delta^{18}\text{O}$ values with the LMWL, the formation waters in the depth interval between 75 and 2500 m have a paleometeoric origin in the central part of the Pannonian Basin.

(2) The infiltration periods are different in the two adjacent areas studied. In the Szeged and intermediate areas a depletion in heavy isotopes relative to the local meteoric water indicates that the infiltration occurred in a period colder than the present temperature. The narrow range of δD and $\delta^{18}\text{O}$ values of formation waters in the 75 to 2500 m depth interval suggests that the infiltration occurred in the same, last cold period. In the Körös area, stable isotopes indicate a warmer infiltration period.

(3) Mixing of deep waters, seeping upward from the Pannonian layers, with paleometeoric water is shown by an enrichment in D and ^{18}O relative to the LMWL. The chemistry of waters especially supports this mixing. In the Körös area, mixing controls the isotopic composition of waters up to 1000 m. In the Szeged area, mixing is detected only in the deepest studied lithostratigraphic zone.

(4) In the Szeged and intermediate areas, the mixing effect above the Pannonian–Pontian boundary was overprinted by an infiltration during the last cold period. In the Körös area, the mixing effect, seen up to a 1000 m depth, suggests that the period of infiltration was prior to the last cold period.

(5) The infiltration areas can be distinguished on the basis of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. It is assumed that the Szeged and intermediate areas contain one flow system in the Pleistocene layers and another one in the subjacent Pliocene–Pleistocene sediments, both having the same recharge but a different discharge area. The recharge and discharge areas of the deeper formations are outside the study region. In the Körös area the presence of upward seepage is supported also by the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

Acknowledgements

This work is the result of a collaborative project between Hungary and France. It was financed by the Hungarian Research Fund (OTKA project No. T 017208 and T 026241), the BRGM (Research Division: project No. P40), and the Ministry of Foreign Affairs of both countries within the frame of a Balaton project (No. 95025 in APAPE, and No. 17 in OMFB). [CA]

References

- Andrews, J.N., Burgess, W.G., Edmunds, W.M., Kay, R.L.F., Lee, D.J., 1982. The thermal springs of Bath. *Nature* 298, 339–343.
- Bernor, R.L., Mittmann, H.W., Rögl, F., 1993. Systematics and chronology of the Götzendorf ‘Hipparion’ (Late Miocene, Pannonian F, Vienna Basin). *Ann. Naturhist. Mus. Wien.* 95, 101–120.
- Bullen, T.D., Kharaka, Y.K., 1992. Isotopic composition of Sr, Nd and Li in thermal waters from the Norris-Mammoth corridor, Yellowstone National Park and surrounding region. *Proceedings of the 7th.*
- Chaudhuri, S., Furlan, S., Clauer, N. (1992) The signature of water–rock interactions in formation waters of sedimentary basins: some new evidence. *Proceedings of the 7th International Symposium on Water–Rock Interaction*, Park City, UT, USA. pp. 907–910
- Coplen, T.B., Kolesar, P., Taylor, R.E., Kendall, C., Mooser, C., 1975. Investigation of the Dunes geothermal anomaly, Imperial Valley, California, Part IV. *Geochemical studies of water, calcite, and silicates.* IGPP-UCR-75-20, pp. 1–42.
- Erdelyi, M., 1979. *Hydrodynamics of the Hungarian Basin.* Proc. 18. VITUKI, Budapest.
- Dansgaard, W., 1964. Stable isotopes in precipitation. *Tellus* 16, 436–468.
- Deák, J., Stute, M., Rudolph, J., Sonntag, C., 1987. Determination of the flow regime of Quaternary and Pliocene layers in the Great Hungarian Plain (Hungary) by D, ^{18}O , ^{14}C , and noble

- gas measurements. International symposium on the use of isotopes techniques in water resources development, IAEA, Vienna, Austria.
- Guiot, J., Pons, A., De Beaulieu, J.L., Reille, M., 1989. A 140,000-year continental climate reconstruction from two European pollen records. *Nature* 338, 309–313.
- Hitchon, B., Friedman, I., 1969. Geochemistry and origin of formation waters in the western Canada sedimentary basin: I. Stable isotopes of hydrogen and oxygen. *Geochim. Cosmochim. Acta* 35, 1321–1349.
- Horváth, F., Dövényi, P., Szalay, Á., Royden, L.H., 1988. Subsidence, thermal, and maturation history of the Great Hungarian Plain. In: Royden, I., Horváth, F. (Eds.), *The Pannonian Basin: A study in basin evolution*: Tulsa, OK. American Association of Petroleum Geologists, pp. 355–372.
- Juhász, A., Tóth, M.T., Matter, A., 1998. Geochemical and petrological evidence for a hydrological connection between fractured crystalline basement and overlying sediments in the Pannonian Basin, SE Hungary. *AAPG Bulletin*. In press.
- Juhász, Gy., 1994. Comparison of the sedimentary sequences in Late Neogene subbasins in the Pannonian Basin, Hungary. *Földtani Közlemény* 124, pp. 341–365.
- Kharaka, Y.K., Berry, F.A.F., Friedman, I., 1973. Isotopic composition of oil-field brines from Kettleman North Dome oil field, California, and their geological implication. *Geochim. Cosmochim. Acta* 37, 1899–1908.
- Kharaka, Y.K., Hull, R.W., Carothers, W.W., 1985. Water–rock interaction in sedimentary basins. In: *Relationship of organic matter and mineral diagenesis*, SEPM Short Course No. 17, pp. 79–174.
- Kharaka, Y.K., Carothers, W.W., 1986. Oxygen and hydrogen isotope geochemistry of deep basin brines. in: Fritz, P., Fontes, J.Ch. (Eds.), *Handbook of environmental geochemistry*, Vol. 2, The Terrestrial environment, B., pp. 305–361.
- Lambert, S.J., 1991. Fossil meteoric groundwaters in the Delaware Basin of southeastern New Mexico. *Stable Isotope Geochemistry: A Tribute to Samuel Epstein*. in: Taylor Jr., H.P., O'Neil, J.R., Kaplan, I.R. (Eds.), *The Geochemical Society Special Publication No. 3*. pp. 135–156.
- Lebreton, P., Dupas, A., Clet, M., Coubouleix, S., Coutard, J.P., Garcin, M., Lautridou, J.P., Levy, M., van Vliet-Lanoe, B., 1996. Modelisation de la profondeur du pergélisol au cours du dernier cycle glaciaire en France. *Bull. Soc. Géol. France* 167, pp. 169–179.
- Mátyás, J., 1997. Stable isotopic mass balance in sandstone–shale couplets: an example from the Neogene Pannonian basin. *Földtani Közlemény* (in press).
- McMurtry, G.M., Pow-foong, F., Coplen, T.B., 1977. Chemical and isotopic investigations of groundwater in potential geothermal areas in Hawaii. *American Journal of Science* 277, 438–458.
- Molnár, B., 1973. Az Alföld harmadidőszak végi és negyedkori feltöltődési ciklusai. [Cyclicality of sedimentation during the Pleistocene and at the end of the Pliocene in the Great Plain] *Földtani Közlemény* 103, 294–310.
- M. Tóth, T., Juhász, A., 1997. Geochemical and petrological evidence for a hydrologic connection between crystalline basement and overlying sediments in the Pannonian Basin, Hungary. *AAPG Annual Meeting*, April 6–9, 1997, Abstract volume, A73, Dallas, TX.
- Rónai, A., 1983a. A Körös medence földtörténete a negyedkorban. [Geological history of the Körös basin during the Quaternary] *Földtani Közlemény* 113/1, 1–25.
- Rónai, A., 1983b. Az üledékképződés szakaszossága az Alföld negyedidőszaki rétegeiben. [Discontinuity of sedimentation in the Pleistocene layers, in the Great Plain] *Földrajzi Értesítő* XXXII, 451–459.
- Rónai, A., 1985. The Quaternary of the Great Hungarian Plain. *Geologica Hungarica*. Tom 21. Institutum Geologicum Hungaricum, Budapest, 426–436.
- Rozanski, K., 1985. Deuterium and oxygen-18 in european groundwaters - Links to atmospheric circulation in the past. *Chemical Geology (Isotope Geoscience Section)* 52, pp. 349–363.
- Schultz, J.L., Boles, J.R., Tilton, G.R., 1989. Tracking calcium in the San Joaquin basin, California: a strontium isotopic study of carbonate cements at North Coles Levee. *Geochim. Cosmochim. Acta* 53, 1991–1999.
- Stute, M., Deak, J., 1989. Environmental isotope study (^{14}C , ^{13}C , ^{18}O , noble gases) on deep groundwater circulation systems in Hungary with references to paleoclimate. *Radiocarbon* 31, 902–918.
- Urbancsek, J., 1963. A földtani felépítés és a rétegyomás közötti összefüggés az Alföldön. [Relationship between the geological structure and hydrostatic pressure in the Great Plain] *Hidrológiai Közlemény* 43, 205–218.
- Varsányi, I., 1975. Clay minerals of the southern Great Hungarian Plain. *Acta Miner. Petr.* XXII (1), 51–60.
- Varsányi, I., Ó. Kovács, L., 1994. Combination of statistical methods with modelling mineral–water interaction: a study of groundwater in the Great Hungarian Plain. *Applied Geochemistry* 9, 419–431.
- Varsányi, I., Matray, J.M., Ó. Kovács, L., 1997. Geochemistry of formation waters in the Pannonian Basin (Southeast-Hungary). *Chemical Geology* 140, 89–106.
- Varsányi, I., Ó. Kovács, L., 1997. Chemical evolution of groundwater in the River Danube deposits in the southern part of the Pannonian Basin (Hungary). *Applied Geochemistry* 12, 625–637.
- Vuataz, F.D., Goff, F., Fouillac, C.H., Calvez, J.Y., 1988. A strontium isotope study of the VC-1 core hole and associated hydrothermal fluids and rocks from Valdes caldera, Jemez Mountains, New Mexico. *Journal of Geophysical Research* 93, 6059–6067.