

## A DIRECT ESTIMATE OF THE INITIAL CONCENTRATION OF $^{14}\text{C}$ IN THE MOUNTAIN AQUIFER OF ISRAEL

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**ABSTRACT.** Five radiocarbon analyses were performed on 5 different sources within Soreq Cave, which was used as a model for the Judea Group Aquifer of Israel ( $pMC_{q0}$ ). The transit time of rainwater through the roof of the cave to sources within it had been determined with tritium. From this information, the year of deposition of rain on the roof of the cave, which later appeared in one of the sources, was estimated and the atmospheric  $^{14}\text{C}$  concentration at that time was ascertained ( $pMC_{a0}$ ). The parameter  $Q = pMC_{q0} / pMC_{a0}$  was found to be  $Q = 0.60 \pm 0.04$ . This makes it possible to calculate the age of water in any well in the Judea Group Aquifer of Israel by measuring its  $^{14}\text{C}$  concentration ( $pMC_q$ ) by use of the decay equation and applying  $Q$ .

### INTRODUCTION

Water is a scarce commodity in many places in our world. For efficient utilization of this resource, the rate of flow of water in aquifers is of importance and, for this purpose, dating of the groundwater is a useful tool.  $^{14}\text{C}$  is a natural candidate for the dating of groundwater and, indeed, the method had been applied routinely to hydrology soon after its introduction by Münnich (1957).

For hydrological dating, the  $^{14}\text{C}$  decay equation is

$$A_{qt} = A_{q0} e^{-\lambda t} \quad (1),$$

where  $q$  refers to an aquifer,  $A_{qt}$  is the  $^{14}\text{C}$  concentration at the time of collection of the water sample,  $A_{q0}$  was the  $^{14}\text{C}$  concentration in the water when the water has just entered the aquifer,  $\lambda$  is the decay constant of  $^{14}\text{C}$ , and  $t$  is the age of the water.

From the outset, it was realized that the initial level of  $^{14}\text{C}$  when the water has just entered the aquifer,  $A_{q0}$ , is generally not well known. Its relation to the atmospheric value of  $^{14}\text{CO}_2$  at the time of deposition of rain on the soil surface,  $A_{a0}$ , where  $a$  refers to the atmosphere, was defined as

$$Q = A_{q0} / A_{a0} \text{ (Wigley 1975)} \quad (2),$$

where  $Q$  is controlled by processes in the unsaturated region which the water traverses on its way to the aquifer.

Many models have been developed to estimate  $Q$  and many of them are incorporated into the NET-PATH program (Plummer et al. 1991). The program uses the different models and the chemical and isotopic information of the groundwater to calculate its age. Recently, Buckau et al. (2000) applied many of these models to the recharge part of the Gorleben aquifer in Germany and found a conflict between the tritium age of the groundwater, which was <40 yr, and the  $^{14}\text{C}$  age of the water, which calculated with these models was 4000 to 8000 yr. Bouhlassa and Aiachi (2002) used a suit of models to estimate  $A_{q0}$  for a young aquifer in Morocco ( $A_{qt} = 76 \text{ pMC}$ ) and found that the different models yielded very divergent results for  $A_{q0}$ , between 22 and 85 pMC.

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We have tried to get a direct estimate of  $Q$  for the mountain aquifer of Israel and used dripping water in Soreq Cave as a model for information about the fate of water in the unsaturated zone on its way to the aquifer.

### THE MOUNTAIN AQUIFER OF ISRAEL AND SOREQ CAVE

The Judea Group aquifer, several hundreds of meters thick, is of the Upper Cretaceous period. The anticlinal crest of the Judea Mountains dips to the east towards the Rift Valley and to the west towards the Shephela area where Cretaceous rocks are overlain by younger formations.

The karstic Soreq Cave is located within the steep western flank of the Judea Mountains crest, 40 km east of the Mediterranean Sea and 400 m above sea level (Figure 1a). The cave is developed within a 50- to 60-m-thick dolomitic sequence of the Cenomanian Weradim Formation, which is fractured and contains many karstic features. The overlying soil cover is irregular and usually occurs in patches up to 40 cm thick. The thickness of the roof varies between 10 m at the northwestern end to 40–50 m at the southeastern end. The cave ceiling is crossed by 2 main fracture systems in the W-E and NW-SE directions (Figure 1b). The cave is rich with various types of speleothems, straw, conical stalactites, curtains, cave corals, stalagmites, flowstones, etc. The cave is active and drippings of water through the tips of stalactites, through fractures and along the walls, are common and occur throughout the year, but it is more intensive during the winter months. The dripping water accumulates in pools varying in size from several liters to about 500 L.

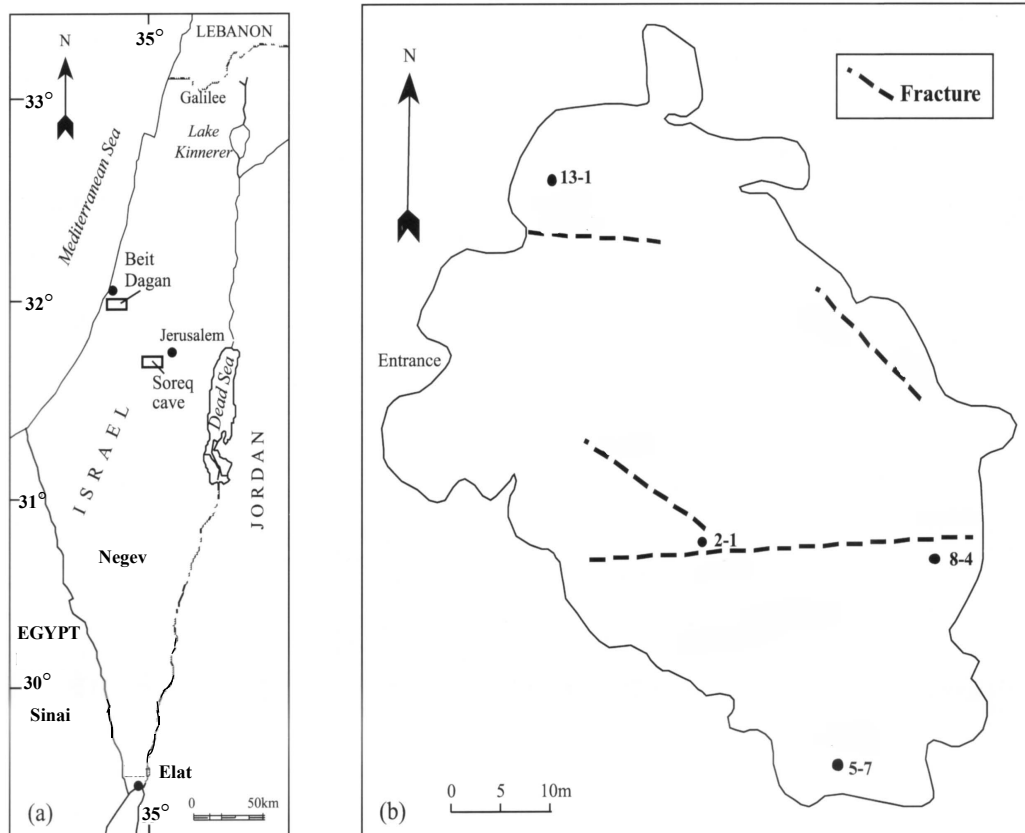


Figure 1 (a) Layout of the Soreq Cave in Israel; (b) sources and fractures in the cave

## SAMPLING AND MEASUREMENT

Water drippings from stalactites and from adjoined pools were collected in April 2002 (sampling #59). Extraction of  $\text{CO}_2$  from the water and its subsequent graphitization was done in the  $^{14}\text{C}$  lab at the Kimmel Center of the Weizmann Institute of Science; AMS measurements were done at the Arizona AMS lab in Tucson;  $^{13}\text{C}$  was measured on an aliquot of the extracted  $\text{CO}_2$  in the Weizmann Institute of Science. The data of dissolved inorganic carbon (DIC),  $^{13}\text{C}$  isotopic composition ( $\delta^{13}\text{C}$ ), and the  $^{14}\text{C}$  activity in percent modern carbon (PMC), is summarized in Table 1. The sampling sites are shown in Figure 1b. It is assumed that these samples represent  $A_{q0}$  for the mountain aquifer of Israel.

Table 1 Water samples collected from Soreq Cave on April 2002, their type (dripping and pool water) and their content of carbon,  $\delta^{13}\text{C}$  and pMC values.

Source	Type	Lab nr	mg C / l	$^{14}\text{C}$ activity (pMC)	$\delta^{13}\text{C}$ (‰)
1-8	Drip	4327	52.7	$82.6 \pm 0.5$	-10.4
2-1	Pool	4325	67.3	$87.9 \pm 0.5$	-10.6
5-7	Pool	4321	66.8	$108.0 \pm 0.6$	-13.5
8-4	Pool	4320	40.0	$99.9 \pm 0.7$	-9.5
13-1	Pool	4322	34.4	$98.2 \pm 0.5$	-9.4

## CALCULATION OF Q

To calculate  $Q$ , the parameters  $A_{a0}$  and  $A_{q0}$  are needed.  $A_{a0}$  is the  $^{14}\text{C}$  concentration in the atmosphere at the time of deposition of rains on the roof of the cave, which subsequently drips from stalactites. For  $A_{a0}$ , we used the atmospheric  $^{14}\text{C}$  concentrations measured in Germany (Levin et al. 1985; Levin and Kromer 1997). Their data is adjusted for  $^{13}\text{C}$ . We have verified that the international  $^{14}\text{C}$  calibration curve is valid for Israel (Carmi, unpublished data) and this justifies the use in Israel of the atmospheric  $^{14}\text{C}$  data from Germany.

To derive the value of  $A_{q0}$  for water collected from dripping water and pools in the cave, we have calculated the transit times and rates of infiltration of water through the roof of the cave by the use of tritium measurements (Kaufman et al. 2003). In the Kaufman et al. (2003) paper, the tritium data from the cave waters were compared with tritium data in rains from the last 50 yr, which included the thermonuclear era. Tritium measured in drippings and pools in the cave was back-corrected for decay and matched with the rain data until a close fit was found. This defined the year in which the rain fell on the cave. The difference between the year in which the rain fell on the roof of the cave and the year of sampling in the cave gave the transit time of water from the surface to the cave. From this and from the thickness of the roof, the average rate of flow of water through the rock above the cave was calculated. Where temporally-spaced data from the same sources were available, a “wiggly match” on the rain data was done.

To derive the values of  $A_{a0}$ , we used the data of the winter and spring months (January to May) because during springtime the most intensive photosynthesis occurs in Israel and the organic matter that is produced is deposited on the ground (Dan Yakir, personal communication).

We neglect the decay of  $^{14}\text{C}$  during the movement of rainwater through the unsaturated region and assume that by the time the water reaches the cave, they are saturated with respect to calcium carbonate (Bar-Matthews et al. 1996).

Because the values of  $A_{a0}$  that we used are adjusted for  $^{13}\text{C}$ , we had to similarly adjust the  $\text{pMC} = A_{q0}$  of the cave waters from Table 1. The data for the sources that were measured for this study, their  $^{14}\text{C}$  concentration adjusted for  $^{13}\text{C}$ , the  $A_{a0}$  values, and the calculated  $Q$  are given in Table 2.

Table 2 Transit time, flow rate of water through the ceiling (inferred for source 1-8), atmospheric ( $A_{a0}$ ), aquifer  $^{14}\text{C}$  concentrations adjusted for  $^{13}\text{C}$  ( $A_{q0}$ ), and calculated  $Q$ .

Source	Roof thickness above the cave (m)	Transit (yr)	Deposition (AD)	Flow $\text{myr}^{-1}$	$A_{a0}$	$A_{q0}$	$Q$
1-8	20	~20	1982	~1.0	123.9	$80.2 \pm 0.5$	.65
2-1	30	33	1969	0.9	154.5	$85.3 \pm 0.5$	.55
5-7	40	36	1966	1.1	169.9	$105.5 \pm 0.6$	.62
8-4	40	35	1967	1.1	163.3	$96.4 \pm 0.7$	.59
13-1	20	35	1967	0.6	163.3	$95.2 \pm 0.5$	.58

## DISCUSSION

The result of the calculations in Table 2 gives an average value of  $Q = 0.60 \pm 0.04$  as a direct estimate for the mountain aquifer of Israel. We compared this result with an estimate based on a mass balance approach with  $^{14}\text{C}$  and  $^{13}\text{C}$  data from wells in the mountain aquifer of Israel in the Judea Mountains. This study was done by Kroitoru (1987) and the estimate was  $Q = 0.62 \pm 0.03$ . Thus, the results from the 2 studies, which differ in methods and are from samples that are different both temporally (some 20 yr) and geographically (more than 10 km), are practically identical. Although when water reaches the aquifer further exchange and loss of  $^{14}\text{C}$  between it and the matrix of the aquifer may occur, our results suggest that this effect is minimal in this part of the aquifer. The result of our study lends support to the approach that a direct estimate of  $Q$  in specific aquifers may help appreciably in dating aquifer groundwater.

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