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The "age" of very old groundwater: insights from reactive transport models

C.M. Bethke[a,*], T. Torgersen[b], J. Park[a]

[a]Department of Geology, University of Illinois, Urbana, IL61801, USA
[b]Department of Marine Science, University of Connecticut, Groton, CT06340, USA

Abstract

The distribution of radioactive and radiogenic isotopes such as ^{36}Cl and ^{4}He provides important information about the residence time (or "age") and flow velocity of groundwater in sedimentary basins, but the relationship between the distribution of an isotope and the basin hydrology is not always clear. We use reactive transport modeling to investigate the controls on isotope distribution and groundwater residence time in hypothetical and real flow regimes. Our results show that by moving beyond the simple "piston flow" concept, we can use isotope distributions to constrain internally consistent descriptions of deep groundwater flow regimes within sedimentary basins. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

One of the most fundamental tasks in the study of a groundwater flow regime is determining the groundwater residence time (or "age") and its close relative, flow velocity. Most commonly we calculate velocity using Darcy's law and compute groundwater age from the flow field. This method can be difficult to apply to very old groundwaters, such as those found in sedimentary basins or deep in the Earth's crust, because the distribution of hydraulic conductivity in these environments is unlikely to be known accurately.

We can alternatively compute groundwater age directly from the distribution of an isotope that decays in the subsurface, or is produced there, at a predictable rate. The radioactive isotope ^{36}Cl, for example, is produced naturally in the atmosphere and dissolves in rainwater; in the subsurface, it decays slowly over time. The noble gas isotope ^{4}He, on the other hand, is produced slowly in the subsurface from the radioactive decay of U and Th.

These isotopic methods can provide an independent check on Darcy's law calculations, or an alternative method for determining hydraulic conductivity. In this paper, we consider factors that affect the interpretation of isotopic ages of groundwater, and discuss the relationship of physical residence time to isotopic age.

2. Reactive transport models

Isotopic ages are generally calculated from the distribution of an isotope and its rate of decay or accumulation using the "piston-flow" model, a simple application of reactive transport theory. In this model, a packet of fluid migrates along a flow regime as a closed system.

In the case of ^{4}He, for example, the isotope accumulates in the groundwater due to in situ production

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[*] Corresponding author.
E-mail address: c-bethke@uiuc.edu (C.M. Bethke).

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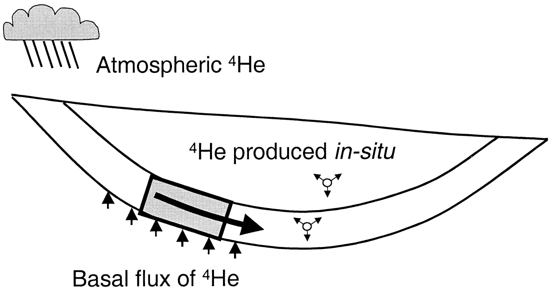


Fig. 1. “Piston flow” model of ^{4}He accumulation in a regional flow regime.

in basin sediments, as well as diffusion from below (Fig. 1). Where helium sources are uniformly distributed and velocity is constant, ^{4}He concentration can be expected to increase predictably with distance along the flow path.

In this paper we employ a basin hydrology simulator (Bethke et al., 1999a) to construct reactive transport models more general than the “piston-flow” concept allows. Our numerical models differ from the “piston-flow” model in that they account for isotope generation and decay across the basin, as well as isotope transport in two dimensions by advection, dispersion, and diffusion.

3. Transport of ^{36}Cl

^{36}Cl is produced naturally in the atmosphere by the interaction of cosmic rays with ^{40}Ar. The ^{36}Cl dissolves in rainwater, enters the groundwater and decays in the subsurface with a half life of 301×10^3 yr. The isotope is also produced naturally in the subsurface by neutron activation of ^{35}Cl.

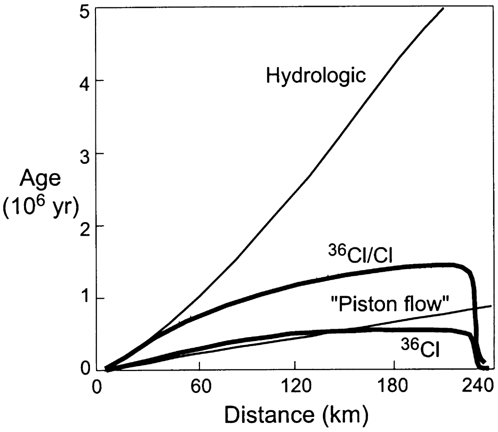


Fig. 3. Comparison of physical age of groundwater in hypothetical basin (Fig. 2) with ages calculated from ^{36}Cl concentration and ^{36}Cl/Cl ratio. Hydrologic age is calculated from rates of advection and dispersive mixing in two dimensions; “piston flow” age reflects only flow along aquifer. Isotopic ages in the simulation return to zero at the discharge area where the aquifer contacts the atmosphere.

Fig. 2 shows the distribution of ^{36}Cl in a hypothetical groundwater flow regime within a simple basin (Park et al., 2000), as calculated using a reactive transport model. The basin consists of a confined aquifer overlying an aquitard; a uniform slope on the water table of 1:800 drives groundwater through the basin.

Near the recharge area, the ^{36}Cl content of groundwater in the aquifer decreases along the flow path due to radioactive decay and diffusion of the isotope into the aquitards. Deeper in the basin, some of the isotope diffuses into the aquifer from the underlying aquitard, where it is produced in situ, more within the saline groundwater found at depth.

Interestingly, the physical or hydrologic (as

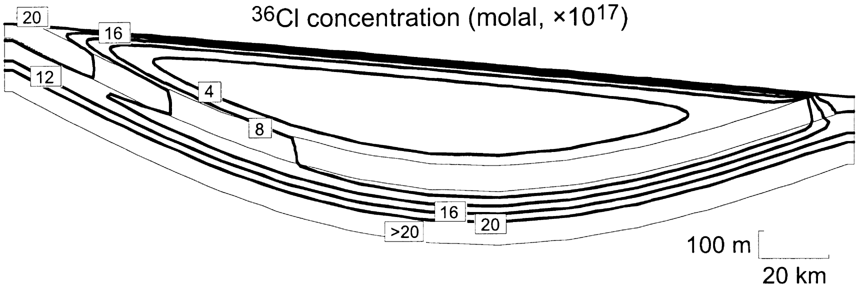


Fig. 2. Result of reactive transport simulation showing distribution of ^{36}Cl (molal, $\times 10^{17}$) in a hypothetical groundwater flow regime within a simple basin.

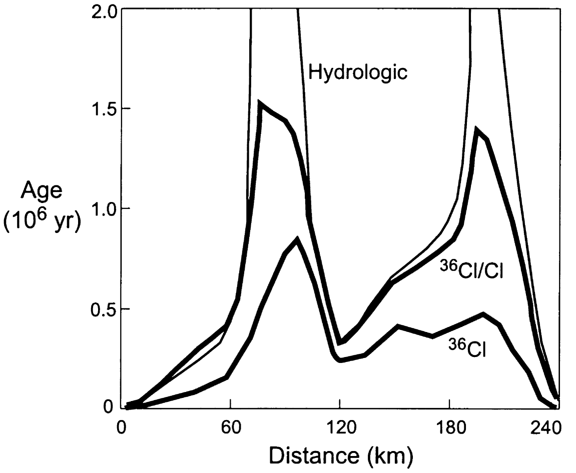


Fig. 4. Hydrologic and isotopic ages of groundwater in hypothetical basin with a slightly irregular slope on the regional water table.

opposed to isotopic) age of groundwater in the aquifer is strongly influenced by the aquitards. When a small amount of the very old groundwater from an aquitard mixes into the aquifer by dispersion or cross-formational flow, it strongly affects average groundwater age. As a result, groundwater within the aquifer is much older than expected from the "piston-flow" model (Fig. 3).

Small amounts of mixing, however, have little effect on the ^{36}Cl concentration within the aquifer. As a result, isotopic ages calculated from ^{36}Cl or the ^{36}Cl/Cl ratio more closely predict the "piston-flow" age than the actual hydrologic age (Fig. 3).

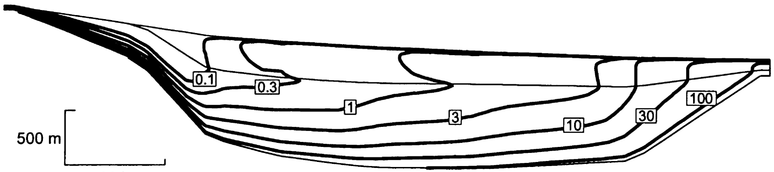
In reactive transport models for more realistic scenarios, the relationship between groundwater age, ^{36}Cl distribution, and groundwater flow becomes more complicated. Fig. 4, for example, shows the results of a simulation that differs from that shown in Fig. 2 only in that the slope on the water table is made slightly irregular, producing subregional flow cells across the confining layer.

Where groundwater recharges the subsurface, cross-formational flow carries old groundwater containing little ^{36}Cl into the aquifer. The old groundwater mixes into the aquifer, significantly affecting its hydrologic age, and to a lesser extent, its isotopic age.

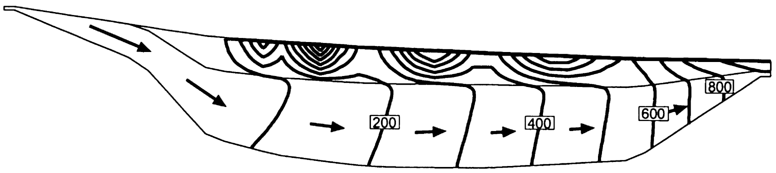
4. Transport of ^{4}He

The relationship of groundwater flow to the distribution of ^{4}He in the Great Artesian Basin of Australia has been an enigma and source of considerable controversy (Bethke et al., 1999b). While we expect from the "piston-flow" model that the isotope will approximately increase linearly in concentration along flow paths (Zhao et al., 1998), the observed ^{4}He content of groundwater increases along trends that are more nearly exponential (or linear in semilog coordinates) than linear.

Our model of the ^{4}He distribution within the basin (Fig. 5) accounts for flow in the basal "J" aquifer and



^{4}He concentration (cm^3 STP cm^{-3}, $\times 10^5$)



Hydrologic residence time (10^3 yrs)

Fig. 5. Numerical simulation of groundwater flow and helium transport in Great Artesian Basin, showing hydrologic age of groundwater (top) and ^{4}He concentration (bottom). Pattern of age in confining layer is an artifact of changes in slope on the discretized water table, and is not physically significant. Basal stratigraphic unit is the "J" aquifer.

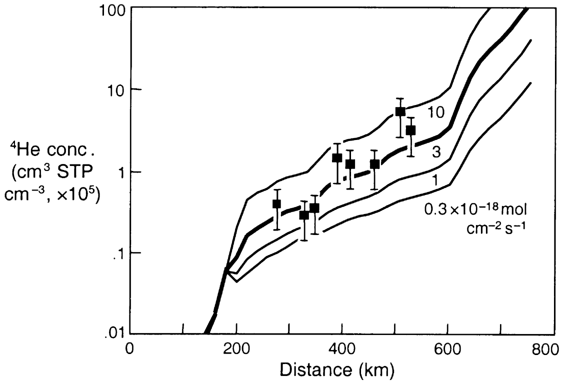


Fig. 6. Predicted ^{4}He concentration at top of the “J” aquifer along a flow path in the eastern basin, shown for varying basal fluxes of the isotope, compared to observed values.

overlying confining beds, as constrained by previous analyses of groundwater flow in the basin. According to the simulation results (Fig. 5, top), helium accumulates most rapidly in the “J” aquifer along the unit’s base, where it is introduced by diffusion from the underlying crystalline crust. Helium is then carried upward toward the top of the aquifer primarily by advective transport in discharge areas. The resulting distribution of the isotope along the top of the aquifer (Fig. 6) agrees well with concentrations measured by Torgersen and Clarke (1985) and Torgersen et al. (1992).

Estimates of groundwater age, therefore, can follow from calibrating the flow model with the helium distribution and then calculating the age distribution from the rates of advective and dispersive transport in the basin (Fig. 5, bottom). In this way, an internally consistent description of helium generation and transport, the groundwater flow pattern, and groundwater age emerges. Interestingly, the helium distribution gives information about the pattern of flow not only along the aquifer (as in the “piston-flow” model), but the rates of recharge and discharge in the vertical direction.

5. Concluding remarks

The simulations in this study serve to emphasize the many factors that control groundwater age and the distributions of radioisotopes in sedimentary basins, as well as the complex nature of the relationship between age and isotope distribution. The “piston-flow” concept, a simple reactive transport model, is unable to address these complexities and in many cases may need to be abandoned in favor of more comprehensive reactive transport models, such as the simulations presented here.

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