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^{4}He dating of groundwater associated with hydrocarbon reservoirs

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Abstract

In this study, we show how physical models describing hydrocarbon/groundwater interaction can be developed by the noble gases in the hydrocarbon phase and, based on these models, initial crustal radiogenic ^{4}He concentrations in the associated groundwater can be calculated. Considering both in situ ^{4}He production and ^{4}He from an external crustal flux, this allows the ^{4}He age of the groundwater associated with each hydrocarbon reservoir to be derived. We illustrate the strengths and weaknesses of this approach using data from case studies from the San Juan Basin coalbed methane gas field in New Mexico, USA, the Magnus oilfield in the UK North Sea and the Hugoton-Panhandle giant gas field that spans Kansas, Texas and Oklahoma, USA.

Keywords: Noble gases; Groundwater; Dating; Hydrocarbon reservoirs; Oil; Gas

1. Introduction

Groundwater interaction with oil and natural gas plays a key role in hydrocarbon migration, filling and lifetime of a reservoir. On the basin scale the hydrodynamic system can physically control the secondary migration of oil and gas (e.g. Toth and Corbett, 1986; England et al., 1987; Ballentine et al., 1991). The interaction of water with the rock controls the creation or destruction of the porosity which in turn determines both the regional and reservoir aquifer quality (Summa, 1995; Ballentine et al., 1996; Lynch, 1996; Heydari, 2000), while extensive contact with groundwater can remove the most soluble phase through the process of 'water washing', degrading the quality of the reservoir hydrocarbons (Lafargue and Barker, 1988). Furthermore, groundwater can transport microbes to isolated or previously sterilized subsurface environments (Scott et al., 1994; Martini et al., 1996, 1998; Colwell et al., 1997; Tseng and Onstott, 1997; Walvoord et al., 1999) with resulting microbial biodegradation and alteration of oil and natural gas (Horstad et al., 1992; Rueter et al., 1994; Zengler et al., 1999). Understanding the timing however, remains a fundamental limiting factor in assessing when and on what time scale these processes have occurred.

At present there are a number of techniques available for dating groundwater. Assuming flow continuity, groundwater ages can be determined hydrologically based on Darcy's law, but remains of limited use when applied to old and deep basinal fluids (e.g. Ward and Robinson, 2000). The most common radiometric dating methods in groundwater research use the decay of cosmogenic or anthropogenic radioactive species to obtain ages, such as ^{14}C, ^{129}I and ^{36}Cl (Fontes and Garnier, 1979; Fabryka-Martin et al., 1987). However,

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these methods have their specific dating ranges, for example, ^{14}C ($T_{1/2}$ = 5730 years) can be used to date groundwaters up to 25,000–30,000 years old, with various correction required to account for the complexity of the local geology, hydrogeology and geochemistry (e.g. Fontes and Garnier, 1979).

Noble gases provide several important additional tracer systems that constrain groundwater residence, each encompassing a specific dating range (Kipfer et al., 2002). For example, ^{222}Rn ($T_{1/2}$ = 3.82 days) is suitable to trace groundwater processes that occur on a time scale of days (e.g. Hoehn and von Gunten, 1989). Anthropogenic radioisotope ^{85}Kr ($T_{1/2}$ = 10.76 years) and tritium decay to ^{3}He ($T_{1/2}$ = 12.32 year) can be used to date and identify young groundwater with ages up to about 60 years (e.g. Weise et al., 1992; Solomon et al., 1993). The cosmogenic radioisotope ^{39}Ar ($T_{1/2}$ = 269 years) dates the groundwater residence time between the ranges which can be dated by ^{14}C, ^{85}Kr and H–^{3}He (100–1000 years) (e.g. Loosli, 1983). In addition, the cosmogenic radioisotope ^{81}Kr ($T_{1/2}$ = 230,000 years) can be used to determine water residence times on time scales of 10^5 years, but because of technical demands remains highly specialised with only a limited number of case studies (e.g. Collon et al., 2000; Lehmann et al., 2003). On typical basinal fluid timescales, by far the most investigated groundwater dating tool remains the accumulation of stable radiogenic ^{4}He and ^{40}Ar in the groundwater, used for estimating groundwater residence on the Kyr to Myr timescales (e.g. Torgersen and Clarke, 1985; Torgersen and Ivey, 1985; Marty et al., 1993, 2003; Castro et al., 1998a,b; Osenbrück et al., 1998; Kipfer et al., 2002; Lehmann et al., 2003; Patriarche et al., 2004).

In this paper, we review how atmosphere-derived noble gases, originally dissolved in the groundwater, have been used to develop physical models to quantify gas/groundwater and oil/groundwater interaction. We show how these models allow us to compute the original ^{4}He in the groundwater phase associated with natural gas and oil reservoirs, and therefore enable a model ^{4}He age estimate of the hydrocarbon associated groundwater to be made. We use data and models from three existing studies to illustrate the application of this approach to very different mechanisms of hydrocarbon–water interaction: (1) The San Juan Basin coalbed methane gas field in New Mexico and Colorado, USA (Zhou et al., in press); (2) The Magnus oilfield, North Sea, UK (Ballentine et al., 1996); and (3). The Hugoton-Panhandle giant gas field in Kansas, Texas and Oklahoma, USA (Ballentine and Sherwood Lollar, 2002).

2. ^{4}He as a groundwater dating tool

2.1. ^{4}He in the groundwater

The accumulation of radiogenic ^{4}He in basin aquifers provides a suitable geochronometer for groundwaters because (1) the production of radiogenic ^{4}He is significant and easily identifiable from the natural atmospheric background and (2) the transfer of the ^{4}He from rock to fluid is fast on a geological time scale in most systems (Ballentine and Burnard, 2002). The use of this geochronometer requires the quantification of the accumulation rate of ^{4}He in groundwater. The amount of ^{4}He accumulated in a groundwater system can be expressed as:

$$[^{4}\mathrm{He}] = [^{4}\mathrm{He}]_{\mathrm{ASW}} + [^{4}\mathrm{He}]_{\text{in situ production}} + [^{4}\mathrm{He}]_{\text{external flux}} \tag{1}$$

Where:

$[^{4}He]$	^{4}He concentration in groundwater
$[^{4}He]_{ASW}$	Atmospheric ^{4}He concentration in air saturated water
$[^{4}He]_{\text{in situ production}}$	In situ crustal radiogenic ^{4}He concentration in the groundwater
$[^{4}He]_{\text{external flux}}$	^{4}He concentration in the groundwater-derived from external sources.

$[^{4}He]_{ASW}$ is a function of temperature and pressure at groundwater recharge and fixed by the equilibrium solution of atmospheric ^{4}He. It is normally low due to the low He solubility in water and the low concentration of He in air. Both $[^{4}He]_{\text{in situ production}}$ and $[^{4}He]_{\text{external flux}}$ are functions of time and are described in details below.

2.2. In situ production and release of ^{4}He into the groundwater

^{4}He is produced in the crust by α decay of the $^{235,238}U$ and ^{232}Th decay chains. In situ ^{4}He concentration in the simplest system is then directly proportional to the concentrations of these radioelements in the crust, and time. There are several mechanisms responsible for the release of ^{4}He from minerals once it is produced, such as recoil loss, diffusive loss, fracturing loss and mineral breakdown caused by diagenesis, metamorphism or alteration (Torgersen, 1980; Ballentine and Burnard, 2002; Farley, 2002). The fractional release of He in the most common minerals can be assumed equal to unity for aquifer temperatures larger than 50–70 °C (Ballentine et al., 1994; Lippolt and Weigel, 1988).