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Large atmospheric noble gas excesses in a shallow aquifer in the Michigan Basin as indicators of a past mantle thermal event

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ABSTRACT

Significant atmospheric noble gas excesses in aquifer systems have systematically been linked to increased hydrostatic pressure, either due to increased water table levels or due to the development of ice cover. Measured noble gases (Ne, Ar, Kr, and Xe) in the shallow Saginaw aquifer in the Michigan Basin display both moderate (~20–60% Ne excess) and large (~80−>120% Ne excess) excesses of atmospheric noble gases with respect to air saturated water for modern recharge conditions. All large atmospheric noble gas excesses are located in the main discharge area of the Michigan Basin, in the Saginaw Lowlands region.

Here, through a step-by-step analysis, we first show that large atmospheric noble gas excesses in the Saginaw aquifer do not result from increased hydrostatic pressure but, instead, are the result of vertical transport of atmospheric noble gases that are believed to have escaped from deep Michigan Basin brines following a past thermal event of mantle origin. Subsequently, we show that the atmospheric noble gas pattern of the entire Michigan Basin strata appears to result from two distinct end-members: (a) an end-member represented by the deepest, most depleted brines from which most of the atmospheric noble gases escaped; and (b) an end-member with excess atmospheric noble gas values above those displayed by the Saginaw samples. The latter is unconstrained due to the dilution effect exerted by recharge water. Using a Rayleigh distillation model we further show that the greater enrichment of lighter relative to heavier noble gases in the Saginaw aquifer in the Saginaw Lowlands area is compatible with either diffusion or solubility related mechanisms. These findings reinforce the notion that a past thermal event is indeed responsible for the atmospheric noble gas excesses found in the Saginaw aquifer in the Saginaw Lowlands area. They are also consistent with and reinforce previous findings with respect to the occurrence of a thermal event of mantle origin in the Michigan Basin.

1. Introduction

The study of noble gases (He, Ne, Ar, Kr and Xe) in sedimentary basins has proven to be a powerful tool to investigate the origin and history of crustal fluids (e.g., Kennedy et al., 1988; Torgersen et al., 1989; Pinti and Marty, 1995; Castro et al., 1998a, 1998b, 2009; Ballentine and Burnard, 2002; Castro and Goblet, 2003; Lippmann et al., 2003; Prinzhofer and Battani, 2003; Patriarche et al., 2004; Pinti et al., 2011) due to their conservative nature and origin specific isotopic signatures (atmospheric, crustal, mantle).

The atmospheric component of noble gases (^{22}Ne, ^{36}Ar, ^{84}Kr and ^{130}Xe) dissolved in groundwaters is introduced into the subsurface by recharge water and is expected to be in solubility equilibrium with the atmosphere (Air Saturated Water—ASW) at the time of recharge. However, moderate excesses of atmospheric noble gas concentrations with respect to ASW values (~10–60% Ne excess; Wilson and McNeill, 1997) are commonly found in groundwaters and thought to result mostly from incorporation of trapped air bubbles due to water table fluctuations and subsequent dissolution due to increased hydrostatic pressure (Heaton and Vogel, 1981). Although not common, large atmospheric noble gas excesses with respect to ASW (>80% Ne excess) have also been previously identified in sedimentary aquifer systems in Africa (e.g., Beyerle et al., 2003; Kulongoski et al., 2004), Europe (e.g., Ingram et al., 2007; Alvarado et al., 2011) and North America (e.g., Klump et al., 2008; Kulongoski et al., 2009). These large atmospheric noble gas excesses were also attributed to increased hydrostatic pressure, either due to increased water table levels (e.g., Beyerle et al., 2003; Kulongoski et al., 2004, 2009) or to the development of ice cover (e.g., Klump et al., 2008; Alvarado et al., 2011).

A recent noble gas study in the shallow Saginaw aquifer in the Michigan Basin (Castro et al., 2012) has also identified both moderate and large excesses of atmospheric noble gases with

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respect to ASW. While Castro et al. (2012) utilized samples with moderate excesses to develop a late Pleistocene–Mid-Holocene noble gas temperature record in southern Michigan, samples with large atmospheric noble gas excesses were not suited for a paleoclimatic reconstruction and consequently, these samples were not previously explored. Interestingly, all large atmospheric noble gas excesses are located in the main discharge area of the Michigan Basin, in the Saginaw Lowlands (SL) area. The goal of this paper, on the other hand, is to investigate the origin of such large excesses of atmospheric noble gases.

Castro et al. (2005) showed that the occurrence of a ^{4}He/heat flux ratio greater than the crustal production ratio can only result from a past mantle thermal event. The presence of a ^{4}He/heat flux ratio higher than the crustal flux ratio was subsequently identified in groundwaters of the underlying Marshall aquifer in the Michigan Basin (Ma et al., 2005; Castro et al., 2007a), where unusually high He excesses are present. Analysis of deep (~0.5–3.6 km) brines in the Michigan Basin subsequently revealed the presence of a mantle, solar-like component for both He and Ne (Castro et al., 2009). In addition, both the crustal and atmospheric noble gas signatures of these deep brines strongly support the occurrence of this mantle thermal event (Ma et al., 2009a, 2009b). In particular, the atmospheric noble gas component in these deep brines is extremely depleted, up to orders of magnitude lower than those of air saturated seawater/brine under surface conditions. Ma et al. (2009a) have shown that this atmospheric noble gas depletion pattern is best explained by a model involving subsurface boiling and steam separation, consistent with the occurrence of a past thermal event of mantle origin as previously indicated by high ^{4}He/heat flux ratios. These findings are also consistent with the presence of elevated temperatures in the Michigan Basin (e.g., ~80–260 °C) in the past at shallow depths (~1 km) as suggested by previous thermal studies in the basin (e.g., Cercone and Lohmann, 1987; Luczaj et al., 2006). If excess He produced and released by this thermal event at depth is still making its way to the surface and is present in the shallow Marshall aquifer (Castro et al., 2007a; Ma et al., 2005), then it is also expected that heavier atmospheric noble gases (^{22}Ne, ^{36}Ar, ^{84}Kr and ^{130}Xe) that escaped from deep brine formations during the occurrence of this thermal event are also slowly making their way to the surface and are present in shallow groundwaters of this system.

Here, we present measured noble gas (Ne, Ar, Kr, and Xe) concentrations and isotopic ratios from the shallow Saginaw aquifer in the Michigan Basin. Through a step-by-step analysis, with the aid of the closed-system equilibration (CE) model of Aeschbach-Hertig et al. (2000, 2008) and through comparison with the noble gas patterns of an aquifer system in southeast Wisconsin (Klump et al., 2008), we first show that our large atmospheric noble gas excesses do not result from commonly observed water table fluctuations or the development of ice cover, but instead are the result of sources external to the aquifer. Subsequently, we show that the large excesses of atmospheric noble gases found in the SL area are likely the remnants of the previously identified past thermal event in the Michigan Basin and are compatible with Rayleigh type elemental fractionation controlled by diffusion or solubility related mechanisms.

2. Geological and hydrogeologic background

Located in the northeastern United States, the Michigan Basin is a concentric intracratonic depression floored by crystalline

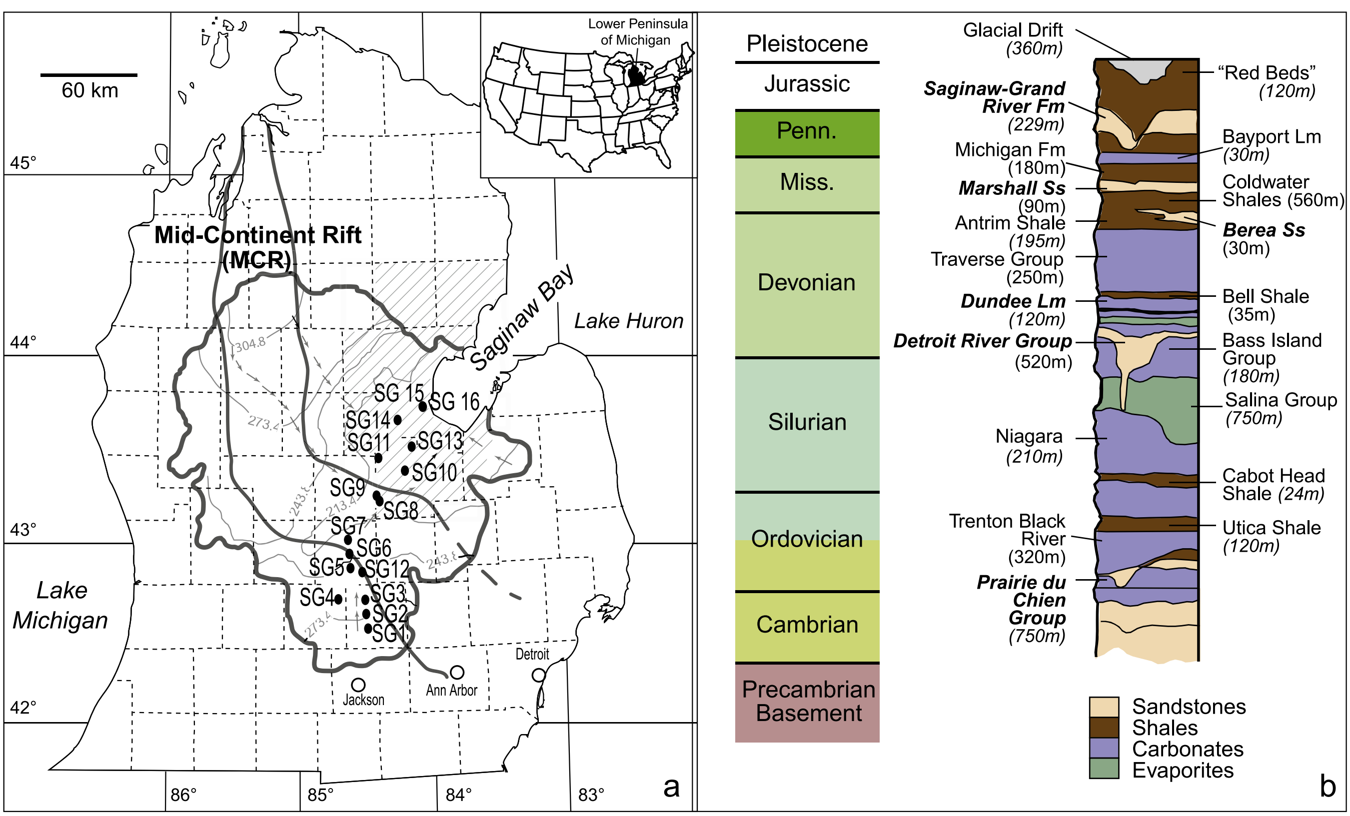

Fig. 1. (a) Location of the Michigan Basin study area in the lower peninsula of Michigan (inset). Locations of Saginaw aquifer samples, Mid Continental Rift (MCR) and the Saginaw lowlands region (hatchered area, after Hoaglund et al., 2004) are indicated. Bold contour represents the Saginaw subcrop. Equipotential line values (contour lines) are shown in meters together with main groundwater flow directions (arrows). (b) Stratigraphic succession of the Michigan Basin together with major lithologies present in the basin are indicated; units for which formation brines were sampled by Ma et al. (2009a) and utilized in this study are highlighted in bold, in addition to the Marshall and Saginaw aquifer. Maximum formation thicknesses are also indicated in brackets next to each unit. Maximum formation thicknesses are found for the central portion of the Michigan Basin and were obtained from the American Association of Petroleum Geologists (1985) and Catacosinos et al. (1991) (indicated in italics).