

Noble gas signatures of high recharge pulses and migrating jet stream in the late Pleistocene over Black Mesa, Arizona, United States

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ABSTRACT

Many semiarid and arid regions of the world are almost entirely dependent on groundwater for water supply, yet many of these aquifers were primarily recharged during the late Pleistocene. Here we show that new noble gas data record the high pulses of recharge to the Navajo Sandstone aquifer at Black Mesa, Arizona, between 14 and 17 ka, which was associated with the passing of the southern branch of the jet stream. Higher excess neon coincided with high water levels independently deduced from numerical modeling of groundwater flow and ¹⁴C data in previous studies. This development allows the use of noble gases not only as a tool to reconstruct paleotemperatures, but also as a new tool to reconstruct paleohydraulic conditions and to verify the conceptual and hydraulic assumptions of existing groundwater models.

INTRODUCTION

Many semiarid and arid regions of the world depend almost entirely on groundwater as the source of drinking water (International Atomic Energy Agency, 2001). This includes the southwest United States (Robson and Banta, 1995), the Arab peninsula (Sultan et al., 2008), and northwestern China (Edmunds et al., 2006). Due to industrial development and population growth, groundwater systems in these regions are under tremendous stresses, as evidenced by the declination of water tables, deterioration of water quality, and drying of streams that have religious as well as ecological value (e.g., Lopes and Hoffman, 1997). Of particular note is that a high percentage of the groundwater that is currently being heavily mined in these semiarid regions was recharged in late Pleistocene time (11 k.y. before the present), when the temperature was cooler and precipitation amounts were much higher in certain semiarid and/or arid areas (e.g., Beyerle et al., 2003). It is therefore a growing concern that decreased recharge in responses to the global warming trend in the arid and semiarid regions will impose additional stresses on these groundwater systems (Seager et al., 2007).

To adapt to the global warming trend and manage the water resources accordingly, we need to know the dynamics between climate forcing and the responses of hydrological systems. Such relationships are nonlinear, often depending on mathematical models that have many parameters that have large uncertainties. Therefore, it is valuable to examine the relationships between paleoclimatic forcing and paleohydrogeology in the recent geological past as ground truthing, for example, in the late Pleistocene and Holocene (e.g., ca. 40 ka to the present). However, further back in time, fewer data are available. Numerical models of paleohydrogeology developed on these scant data carry large uncertainties because of the many unknown or uncertain parameters. The verification of these models with direct experimental evidences (i.e., noble gases; see the following) is critical for climate change studies.

Numerous studies have established that noble gases can be a valuable tool to reconstruct paleoclimate from the most recent glacial period to the Holocene (Beyerle et al., 1998, 2003; Kipfer et al., 2002; Klump et al., 2008b; Ma et al., 2004; Stute et al., 1995; Weyhenmeyer et al., 2000). It is much less well established whether noble gases can be an effective

tool to reconstruct paleohydraulic conditions. As we show here, the eolian Navajo Sandstone aquifer at Black Mesa, Arizona, has relatively simple geology and hydrogeology, provides abundant hydraulic and hydrogeochemical data, and has been the site of detailed studies of recharge variations from late Pleistocene to Holocene time (Brown and Eychaner, 1988; Lopes and Hoffman, 1997; Zhu, 2000; Zhu et al., 1998, 2003). Therefore, it provides an excellent opportunity to test whether noble gas data can be used as a proxy for the physical conditions during groundwater recharge.

GEOLOGY AND HYDROGEOLOGY CONDITIONS

The Navajo aquifer, in which the Jurassic Navajo Sandstone is the predominant water-transmitting unit, is the only source of potable water in the Black Mesa, Arizona, area (Cooley et al., 1969; Eychaner, 1983; Brown and Eychaner, 1988; Zhu, 2000). The location and groundwater flow directions are shown in Figure 1. The aquifer is recharged seasonally from precipitation in the highlands, principally during the winter and spring. The Shonto area, in the northwestern corner of the mesa, accounts for approximately one-third of the total recharge in the basin and most of

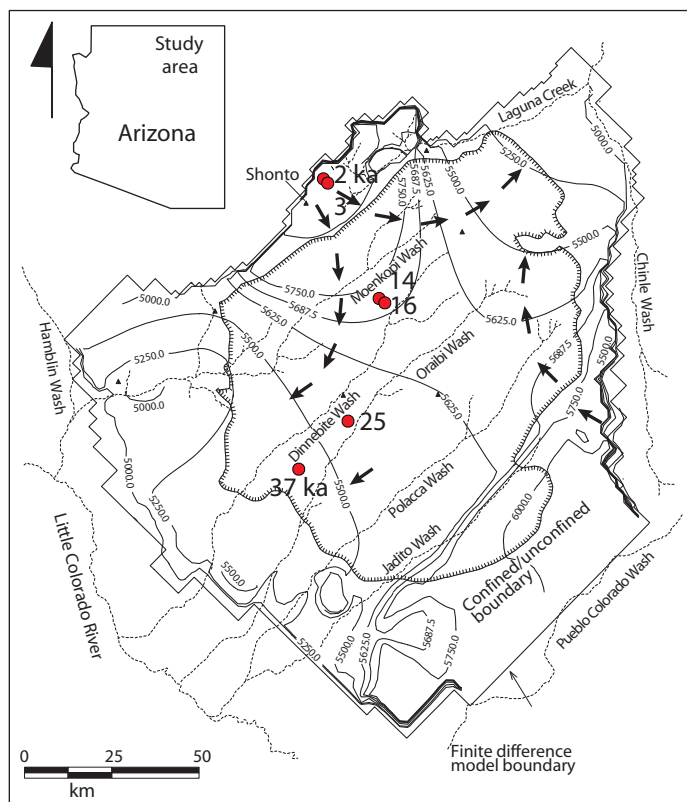


Figure 1. Hydrogeological settings of Black Mesa basin. Contours of present-day hydraulic heads are in feet (Zhu, 2000). Arrows indicate directions of groundwater flow. Dots show groundwater sample locations. From north to south, wells are Shonto PM2, Shonto PM 4, NAV6, NAV 9, Rocky Ridge PM 2, and Hoteville School 2. Corrected ¹⁴C ages are labeled beside location (dots).

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the water that flows into the center of the basin (Cooley et al., 1969). The current climate in the Black Mesa area is semiarid. Mean annual precipitation is <300 mm in much of the area, but as much as 320 mm in areas above 1800 m above sea level. The mean annual temperature is ~10 °C in the Shonto area (Zhu et al., 2003).

The hydrogeology of this area is extensively studied. The U.S. Geological Survey has conducted a quarterly monitoring program since 1971. Recharge rates for the late Pleistocene to Holocene were retrieved using a two-dimensional, finite difference regional groundwater and ¹⁴C transport model (Zhu, 2000; Zhu et al., 1998). These recharge variations were confirmed by estimates from the chlorine mass-balance method (Zhu et al., 2003). Naturally, the paleorecharge estimates were subject to the uncertainties in the ¹⁴C age corrections and flow and ¹⁴C transport models. The development of these models predated the noble gas data presented here. Hence, the noble gas interpretations of paleoclimate and paleohydrogeology are completely independent.

RESULTS AND DISCUSSION

The noble gas temperatures (NGTs), i.e., infiltration temperatures reconstructed from the measured noble gas concentrations in groundwater, represent the paleosol temperatures during recharge (Kipfer et al., 2002, and references therein). In this study, measured noble gas concentrations were converted to NGTs according to the method described previously (Aeschbach-Hertig et al., 2000). NGTs at Black Mesa vary between 6.3 °C (Rocky PM2, 25 ka) and 11.9 °C (Shonto PM2, 3 ka). Figure 2A shows the NGTs plotted against corrected ¹⁴C ages for groundwater (see Tables DR1 and DR2 in the GSA Data Repository¹). The excess ⁴He data from this study corroborated the corrected ¹⁴C ages from previous studies (Zhu, 2000), which gives confidence to the temporal evolution of NGTs. Groundwater with corrected ¹⁴C ages of 2–3 ka have the smallest amounts of nonatmospheric ⁴He, which is produced by radioactive reactions and accumulates in groundwaters (Kipfer et al., 2002). Note that, over the entire area studied, the excess ⁴He concentrations increase almost linearly with the corrected ¹⁴C ages (Fig. 2B).

The high NGTs are found in the youngest samples (2–3 ka). The warm NGTs of ~11–12 °C are slightly cooler than the lowest measured groundwater temperatures (13.6–13.8 °C). These samples represent the last 2–3 k.y. of recharge conditions of the aquifer. It is interesting that these NGTs are 1–2 °C warmer than the modern mean annual temperature of the recharge area (i.e., 10 °C in the past 50 yr), probably due to direct solar soil heating during recharge, as it is quite often observed in semiarid and/or arid areas (Beyerle et al., 2003).

The NGTs during the Last Glacial Maximum (LGM) (25–35 ka) were 5–6 °C cooler than the NGTs in the late Holocene. The cold temperature cluster is characterized by NGTs between 8 and 6 °C. Within the cold temperature cluster, NGTs first decrease from 8 to 6 °C with increasing excess ⁴He and ¹⁴C age. At even higher excess ⁴He, NGTs increase again to 8 °C. Hence, the maximal NGTs decrease of ~5–6 °C (e.g., Rocky PM2) recorded at Black Mesa is consistent with the typical maximal continental cooling during the last ice age in non-ice-covered regions in Europe and America (Kipfer et al., 2002). The NGTs also correlate well with the δD and δ¹⁸O values of the water samples, with low NGTs associated with depleted δD and δ¹⁸O values (Fig. 3). In the Four Corners area (Utah, Colorado, New Mexico, Arizona), packrat midden data from the Colorado Plateau also show that the mean annual temperature was 6 °C cooler during the LGM than present (Betancourt, 1990), and NGTs in the nearby San Juan basin in New Mexico also showed 5–6 °C cooling at the LGM (Stute et al., 1995). Note that the difference between absolute LGM and Holocene NGTs is independent of the NGT correction models used (Aeschbach-Hertig et al., 2000). Therefore, the same maximal continental cooling of 5–6 °C was recorded at Black Mesa (this study) and the San Juan basin (Stute et al., 1995), despite different models for NGTs.

It is common that the actual concentrations of atmospheric (noble) gases in groundwaters exceed the expected equilibrium concentrations for the given physical conditions that prevailed for air-water partitioning during groundwater recharge. Recent research explains, mechanistically, that the typical atmospheric gas surplus, called excess air (Freeze and Cherry, 1979; Heaton and Vogel, 1981), is due to the physical processes that control atmospheric gas exchange in porous media (Holocher et al., 2002; Klump et al., 2008a, 2007). In contrast to surface waters, gas exchange in groundwater does not happen with a free unlimited atmosphere available, but with small single air bubbles that are trapped and immobilized during groundwater recharge in the quasi-saturated zone (Holocher et al., 2003; Kipfer et al., 2002; Klump et al., 2008a). Due to hydraulic loading in response to recharge events, the trapped air is exposed to higher pressure, which leads to the partial (or complete) dissolution of trapped air and the formation of excess air. Thereby a new saturation equilibrium is established between the dissolved atmospheric gas and gas phase

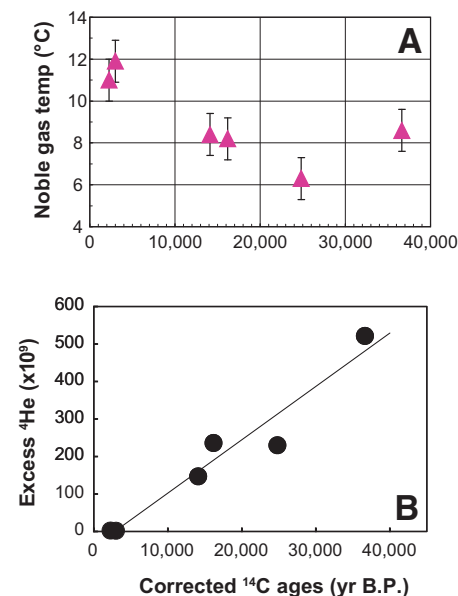


Figure 2. A: Noble gas temperatures against corrected ¹⁴C ages for samples from same well. **B:** Nearly linear correlation between excess ⁴He measured in this study and corrected ¹⁴C ages from Zhu (2000). Note that these two data sets are completely independent.

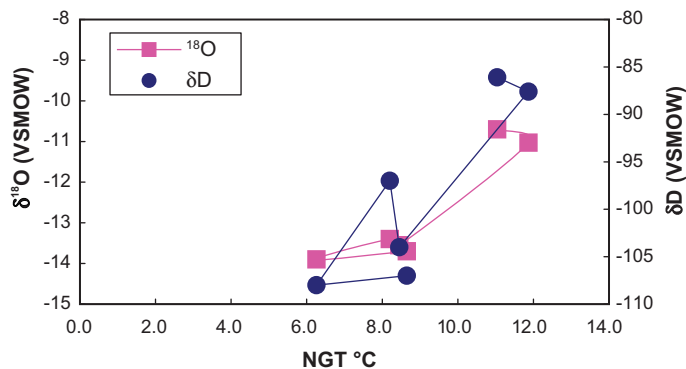


Figure 3. Correlation between noble gas temperatures (NGTs) and δD and δ¹⁸O (‰), which were measured in samples from the same wells and reported in Zhu (2000). Cooler NGTs were associated with depleted δD and δ¹⁸O. VSMOW—Vienna standard mean ocean water.

¹GSA Data Repository item 2010015, Table DR1 (groundwater data from the N aquifer, Black Mesa area, northeastern Arizona), and Table DR2 (noble gas data from the N aquifer), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

under the slightly enhanced pressure condition of the quasi-saturated zone (Aeschbach-Hertig et al., 2000). As the amount of trapped air is limited, the elemental composition of generated excess air is fractionated against atmospheric (free) air. Therefore, excess air is a direct physical measure of the local hydraulic condition at the time of recharge as the noble gas composition, and the amount of excess air is linked to the hydrostatic overburden due to groundwater percolation and the percent of pore space that is occupied by trapped air (Holocher et al., 2002; Kipfer et al., 2002; Klump et al., 2008a). Hence, augmented air entrapment (in dead-end pores) together with the enhanced pressure condition in the quasi-saturated zone as a consequence of groundwater recharge are recognized as the physical constraints of excess air formation (Klump et al., 2008a). Because the solubility of Ne in water is only marginally insensitive to temperature changes, the amount of excess air, expressed as the Ne in excess of equilibrium concentrations with respect to the atmosphere, $\Delta\text{Ne} = ([\text{Ne}]_{\text{measured}} / [\text{Ne}]_{\text{atmospheric equilibrium}} - 1) (\%)$, represents an experimentally measurable quantity for hydraulic conditions (Kipfer et al., 2002; Klump et al., 2008a).

The ΔNe variation at Black Mesa ranged from ~15% to ~300%. The 37 ka sample (Hoteville School 2) and the young groundwater samples (2–3 ka) show almost identical ΔNe values. The observed values of 15% above equilibrium values are common for groundwaters (Kipfer et al., 2002). However, two samples with corrected ^{14}C ages of 14–16 ka have distinctly higher ΔNe values. NAV6 is exceptional, with a ΔNe value of 304%; i.e., the measured Ne concentration exceeds the typical concentration by a factor of more than 20.

The high ΔNe values coincide with the approximately three times higher recharge rates during that period of time as compared to present-day recharge (Fig. 4), predicted independently from numerical flow and transport models calibrated to the distribution of corrected ^{14}C ages and hydraulic data (Zhu et al., 1998; Zhu, 2000). This high recharge rate between 14 and 17 ka is believed to be related to the passing over the Black Mesa area of the split southern branch of the jet stream in the late Pleistocene (Zhu et al., 1998). Because of the presence of the ice sheet, the jet stream was split into two branches during the LGM. The southern branch of the jet stream and its associated storm track were displaced southward, near the current U.S.-Mexico border (Bartlein et al., 1998). The storm track is usually just south of the jet stream. The passing of the jet stream over Black Mesa resulted in both increased precipitation and increased intensity of precipitation, which must have caused rising and fluctuating water tables in the recharge areas and increased entrapment of air, which resulted in high excess air amounts (Beyerle et al., 2003; Klump et al., 2008a). The ΔNe data thus independently provide the signatures of the passing jet stream.

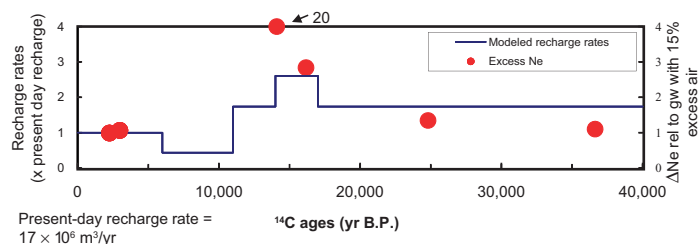


Figure 4. A: Excess ΔNe overlaid on estimate of recharge variations from late Pleistocene to Holocene from numerical modeling of groundwater flow and ^{14}C transport reported by Zhu et al. (1998). Scale for recharge is normalized to present recharge rate. Scale for excess ΔNe is on right, and unit is normalized to 15% excess air typical of groundwater (gw). Surplus ΔNe for sample NAV6 with corrected ^{14}C age of 14 ka is 20 times (or 304% with respect to equilibrium value) average for groundwater (15%).

Evidence of the migration of the withdrawing southern branch of the jet streams northward during the late Pleistocene has been summarized (Thompson et al., 1993; Bartlein et al., 1998; Bartlein and Hostetler, 2004). The pulse of high recharge between 17 and 14 ka coincides with extensive deglaciation in the San Juan Mountains from 19 to 15 ka. Both stable isotope and noble gas data show a 2–3 °C increase in temperature (as shown by the NGTs in this study), but the temperature was still lower than that in the Holocene. The rise and fall of the pluvial lake levels across the Great Basin between 18 and 13 ka is commonly attributed to the progressive northward migration of the jet stream and its associated storm track due to the diminishing ice sheet (Enzel et al., 2003). High water-table conditions before ca. 15 ka, when the jet stream was located in the area, are evident from groundwater discharge deposits in southeastern Arizona (Pigati et al., 2009).

Note that the high ΔNe values do not coincide with the minimum NGTs. That indicates that the recharge peaks were not merely results of lower temperature and reduced evapotranspiration, but correspond to the extreme event of the passing of southern branch of the jet stream in responses to withdrawal of continental ice sheet northward. Thus, the ΔNe peak between 14 and 17 ka indicates a dramatic rise of groundwater table in the groundwater recharge area at that time in response to massively enhanced groundwater recharge.

The excess ΔNe values also match well with δD values of the groundwater. Groundwater dated between 14 and 17 ka have heavier D than that of older groundwater recharged at similar (~8 °C) temperature (Table DR1; –104‰ to –97‰ versus –107‰). These heavier δD values seem to be caused by the volume effect of heavy rainfall (Clark and Fritz, 2000) associated with the passing jet stream. As shown by Beyerle et al. (2003), heavier δD values as the results of strong rainfalls force or foster high ΔNe due to increased hydrostatic loading in the quasi-saturated zone.

CONCLUSIONS

We attempt to establish noble gases as an independent tool to determine groundwater recharge dynamics in the past and to verify groundwater flow models in addition as indicators of paleoclimate. The excellent agreement between numerical models and noble gas data is probably also the result of the relatively simple hydrogeology from this eolian sandstone aquifer, which in turn explains the concordant temporal evolution of excess ^4He and ^{14}C ages. In areas of more complex hydrogeology and hydrogeochemistry, more confounding factors of groundwater flow and chemical reactions would obscure the links between pressure conditions and ΔNe . Therefore, the corroboration of ΔNe data as indicators of the recharge pulses in this well-studied area demonstrates the potential of noble gases as a new tool for studying the relationship between climate forcing and recharge.

Paleohydrogeology plays an important role in providing ground truth to models that forecast the hydrogeological impacts of various global warming scenarios. However, large uncertainties are typically associated with paleohydrogeologic models. Climate variability in the Pleistocene and Holocene has caused transient behaviors in large regional aquifers, reflected in both water tables and groundwater geochemistry (Zhu et al., 1998; Schwartz et al., 2009). However, these variabilities have largely been ignored in development of many regional aquifer models and interpretations of groundwater geochemistry data. Our study shows the potential of ΔNe as a new tool, which will likely find its applications in climate dynamics–groundwater recharge processes.

ACKNOWLEDGMENTS

Zhu thanks the ETH (Eidgenössische Technische Hochschule, Zurich) and Alex Halliday for hosting his guest professorship in Switzerland where this work was conducted. Field sampling was assisted by Margoit Truini of the U.S. Geological Survey and Arndt Schimmelmann of Indiana University. The cooperation and patience of Gregory H. Zhu during the revision of the manuscript is also acknowledged.

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Manuscript received 7 May 2009

Revised manuscript received 6 August 2009

Manuscript accepted 11 August 2009

Printed in USA