Quaternary Research 81 (2014) 158–167

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Paleoclimate record in the Nubian Sandstone Aquifer, Sinai Peninsula, Egypt

Abdou Abouelmagd [a,b], Mohamed Sultan [a,*], Neil C. Sturchio [c], Farouk Soliman [b], Mohamed Rashed [b], Mohamed Ahmed [a,b], Alan E. Kehew [a], Adam Milewski [d], Kyle Chouinard [a]

[a] Department of Geosciences, Western Michigan University, Kalamazoo, MI 49008-5200, USA
[b] Department of Geology, Suez Canal University, Ismailia, 41522, Egypt
[c] Department of Earth and Environmental Sciences, University of Illinois at Chicago, Chicago, IL 60607-7059, USA
[d] Department of Geology, University of Georgia, Athens, GA 30602, USA

ARTICLE INFO

Article history:
Received 15 April 2013
Available online 4 December 2013

Keywords:
Paleoclimate
Nubian Sandstone Aquifer System (NSAS)
Sinai Peninsula
Noble gases
^{14}C adjusted model age
Paleowesterlies
Paleomonsoon

ABSTRACT

Sixteen groundwater samples collected from production wells tapping Lower Cretaceous Nubian Sandstone and fractured basement aquifers in Sinai were analyzed for their stable isotopic compositions, dissolved noble gas concentrations (recharge temperatures), tritium activities, and ^{14}C abundances. Results define two groups of samples: Group I has older ages, lower recharge temperatures, and depleted isotopic compositions (adjusted ^{14}C model age: 24,000–31,000 yr BP; δ^{18}O: −9.59‰ to −6.53‰; δ^{2}H: −72.9‰ to −42.9‰; <1 TU; and recharge T: 17.5–22.0°C) compared to Group II (adjusted ^{14}C model age: 700–4700 yr BP; δ^{18}O: −5.89‰ to −4.84‰; δ^{2}H: −34.5‰ to −24.1‰; <1 to 2.78 TU; and recharge T: 20.6–26.2°C). Group II samples have isotopic compositions similar to those of average modern rainfall, with larger d-excess values than Group I waters, and locally measurable tritium activity (up to 2.8 TU). These observations are consistent with (1) the Nubian Aquifer being largely recharged prior to and/or during the Last Glacial Maximum (represented by Group I), possibly through the intensification of paleowesterlies; and (2) continued sporadic recharge during the relatively dry and warmer interglacial period (represented by Group II) under conditions similar to those of the present.

Introduction

The Nubian Sandstone Aquifer System (NSAS) is one of the largest fresh groundwater reserves in the world (area: 2×10^6 km^2; volume: 780×10^3 km^3) (Thorweihe, 1990). This transboundary aquifer is present throughout a large area of North Africa, including northwestern Sudan, northeastern Chad, eastern Libya, and western Egypt (inset Fig. 1a). The Nubian Sandstone extends in the Sinai Peninsula; it is exposed at the foothills of the Precambrian basement outcrops in Sinai and in the Negev desert and underlies large segments of the central Sinai Peninsula and the southern part of the Negev desert (Said, 1962; Issar et al., 1972) (Fig. 1). The NSAS is composed of thick (up to 3 km in basin center) sequences of unfossiliferous continental sandstone with intercalated shale of shallow marine and deltaic origin, unconformably overlying basement rocks (Himida, 1970; Shata, 1982; Hesse et al., 1987).

There is a general consensus that the paleoclimatic regimes of the North African Sahara Desert alternated between dry and wet periods throughout the Pleistocene Epoch and that it was during these wet periods that the NSAS was recharged. However, the nature of these wet periods remains a subject of debate. Two main hypotheses have been advocated to address the origin of the fossil water of the NSAS: (1) intensification of paleowesterlies during glacial periods (Sonntag et al., 1978; Sultan et al., 1997; Frumkin et al., 2000; Bartov et al., 2002; Brookes, 2003; Issar, 2003; Issar and Zohar, 2004; Sturchio et al., 2004; Vaks et al., 2006; Issar, 2010; Abouelmagd et al., 2012) or (2) intensification of paleomonsoons during interglacial periods (Yan and Petit-Maire, 1994; Bar-Yosef and Meadow, 1995; Bar-Matthews et al., 2003; Almogi-Labin et al., 2004; Osmond and Dabous, 2004). The model pertaining to intensification of paleowesterlies during the glacial periods is supported by a variety of field, geochronologic, and isotopic evidence. For example, glacial periods were humid in the eastern Mediterranean, as indicated by (1) the isotopic compositions of speleothems collected from a cave in Jerusalem (Frumkin et al., 2000) and from a cave in the central mountain range in Israel (Vaks et al., 2003); (2) the areal extent of deposits from Lake Lisan (precursor of the Dead Sea), which reached its maximum level during the Last Glacial Maximum (Bartov et al., 2002, 2003; Torfstein et al., 2013) or just prior to it (Lisker et al., 2009); and (3) identification of modern westerly wind regimes that produce precipitation that has isotopic compositions similar to those of the NSAS paleowaters (Abouelmagd et al., 2012). The monsoonal hypothesis, in contrast, is supported by a number of arguments including the age record of sapropels over the past 250 ka (Rossignol-Strick, 1983). The organic-rich black layers that were

* Corresponding author at: Department of Geosciences, Western Michigan University, 1903 W. Michigan Avenue, Kalamazoo, Michigan 49008, USA. Fax: +1 269 387 5513.
E-mail address: mohamed.sultan@wmich.edu (M. Sultan).

0033-5894/$ – see front matter © 2013 University of Washington. Published by Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.yqres.2013.10.017

deposited by the River Nile during heavy African monsoons in the eastern Mediterranean were found to coincide in their depositional age with the astronomically driven maximum summer insolation in the northern tropics. Simulations (from general circulation models) also revealed contemporaneous intensification of African monsoons with increasing summer insolation in the Northern Hemisphere (Prell and Kutzbach, 1987).

There is also a general consensus that the NSAS was largely recharged in previous wet climatic periods. However, geochemical data (O, H stable isotope compositions) for groundwater samples from recharge areas in southern Sinai (Fig. 2), geophysical (electrical resistivity soundings) data, and rainfall – runoff modeling have shown that in some areas where relatively high precipitation occurs, as is the case in Sinai, local recharge areas are still receiving modern recharge (Sultan et al., 2011).

In this study, we investigate the nature of the wet climatic periods that recharged the NSAS and examine whether the NSAS was recharging during relatively dry climatic conditions similar to the ones currently prevailing. Our approach involves (1) estimation of ^{14}C model ages of Nubian paleowaters to identify the timing of paleo-recharge periods; (2) estimation of recharge temperatures for paleowaters from dissolved noble gas concentrations and through comparisons to current mean annual air temperature (MAAT) to examine the nature of recharge periods (low temperatures are indicative of recharge during glacial periods, whereas high temperatures are consistent with recharge during interglacial periods); and (3) examination of the tritium activities in the groundwater from the NSAS and comparison of stable isotopic composition with that of modern precipitation in the region to evaluate the extent of additional modern recharge. The Sinai Peninsula in Egypt was selected as our study area for the reasons discussed below.

Study area

Two main groups of rock units are exposed across the Sinai Peninsula (Fig. 1): (1) the Precambrian basement complex consisting of gneisses, volcano-sedimentary successions, and granitoids of the Arabian–Nubian Shield Massif in the south; and (2) the Phanerozoic sedimentary successions to the north (Sultan et al., 1988; Stern and Kroner, 1993; Blasband et al., 2000). The Phanerozoic successions vary in thickness and composition from south to north. Continental facies (up to 2000 m thick) are dominant in the south, and thick marine facies (~8000 m thick) are dominant in the north (Alsharhan and Salah, 1996). From south to north, gently inclined sedimentary rocks of Paleozoic to Eocene age in central Sinai give way to strongly folded Triassic to Cretaceous Formations that are overlain by Paleocene and Eocene formations. These Precambrian rocks and Phanerozoic sequences are covered by dune fields of Quaternary age in northern Sinai (JICA, 1999).

The NSAS is composed of unfossiliferous continental sandstone of Lower Cretaceous age intercalated with shale of shallow marine and deltaic origin of the Malha Formation in central and southern Sinai (Abdallah et al., 1963) and marine limestone of the Risan Aneiza Formation in northern Sinai (Said, 1971). The Malha and the Risan Aneiza Formations are part of the Nubian Sandstone group that rests unconformably on the basement rock units (Shata, 1982) and is overlain by calcareous sequences of Cenomanian to Upper Eocene age (Said, 1962) (Fig. 1b).

The Sinai Peninsula (61×10^3 km^2) receives relatively high amounts of precipitation compared to the other Egyptian desert areas. Using 3-hourly precipitation data (1998 to 2011) from the Tropical Rainfall Measuring Mission (TRMM; v7A), the average annual precipitation over the Western Desert, Eastern Desert, and Sinai was found to be 9 mm/yr, 13 mm/yr, and 70 mm/yr, respectively. TRMM is a joint space mission between NASA and the Japan Aerospace Exploration Agency (JAXA) that was designed to monitor tropical and subtropical rainfall. The mountainous basement complex in southern Sinai receives the highest amounts of precipitation in Sinai (EMA, 1996; Geb, 2000); precipitation is collected and channeled through main streams by the extensive stream network in the area. The main streams at the foothills and north of the basement complex are floored by the NSAS outcrop, which provides opportunities for infiltration and recharge through initial and transmission losses (Fig. 1). Rainfall in the area is caused primarily by cyclonic winter storms passing over the Mediterranean depressions and tracking southeast. Because of their sporadic nature and the presence of extensive stream networks that channel runoff from large watersheds into a few main valleys, these storms are often associated with flash-flooding events.

Analytical methods

Fieldwork was conducted in January and June of 2010 to sample groundwater from 12 drilled wells and from the Ayun Musa spring, which taps the NSAS and from three open wells in the fractured basement. The wells are evenly distributed over the northern, central, and southern parts of the Sinai Peninsula and along the Gulf of Suez coastal zone (Fig. 1). The samples from the NSAS define two groups on the basis of total well depth (TD), depth to static water level (DWL), and proximity to recharge areas. Group I samples were collected from eight deep wells (TD: 747–1250 m; DWL: 137–377 m) and from a spring, all of which are located far (>150 km) from recharge areas (Fig. 1). These include Arif El Naqa 2, El Themed 2, El Hasana 3, Sudr El Hetan 3, El Kuntella 3, Nekhel 5, Egirah El Far 4, El Berouk 4, and Ayun Musa. Group II samples (El Rueikna 3, Mekatab 3, Nadya El Soda, and Regwa 12) were collected from four shallow wells (TD: 63–366 m; DWL: 19–56 m) that are proximal (<40 km) to recharge areas (Fig. 1). Three additional samples were collected from wells (Haroun, Halwagy, and Dir El Banat) tapping alluvial and fractured basement aquifers in southern Sinai. Samples were collected to be analyzed for (1) stable isotopic compositions of hydrogen and oxygen in water and carbon in dissolved inorganic carbon (DIC); (2) ^{14}C abundance in DIC for model age estimation; (3) dissolved noble gas concentrations for estimation of noble gas recharge temperatures; and (4) tritium (^3H) activities. The analytical methods used for each of these analyses are briefly described below.

Wells were pumped for a minimum of 30 min prior to sample collection. The wells were purged until the pH and Ec readings stabilized and the sampled groundwater was clear. Unfiltered and unacidified water samples were collected in tightly capped 30-mL glass bottles for stable isotopic (δ^2H, $\delta^{18}O$, and $\delta^{13}C$) analyses (Tables 1 and 2). The H and O isotopic ratios were analyzed using a Picarro Cavity Ring-down Spectroscopy (CRDS) laser system (Lehmann et al., 2009). Carbon isotope analysis of DIC was performed on CO_2 released by acid digestion using H_3PO_4 and measured by dual-inlet isotope-ratio mass spectrometry. Hydrogen, oxygen, and carbon stable isotope ratios are reported using conventional delta (δ) notation, in units of per mil (‰) deviation relative to the Vienna Standard Mean Ocean Water (V-SMOW) whereby

$$\delta, ‰ = \left[\left(R_{\text{sample}} - R_{\text{std}}\right)/R_{\text{std}}\right] \times 1000$$

and $R = {}^2H/{}^1H$, ${}^{18}O/{}^{16}O$ or ${}^{13}C/{}^{12}C$ (Coplen, 1996). Reproducibility of δ values for ^2H is ± 1‰ and those of ^{18}O and ^{13}C are ±0.2‰ and ± 0.1‰, respectively.

Tritium (^3H), the radioactive isotope of hydrogen, was produced during the atmospheric testing of nuclear fusion bombs between 1953 and 1964 and is used as a tracer for recharge, flow, and mixing processes of young groundwater (Plummer et al., 1993). Because natural background tritium activity in the atmosphere was low (about 5 TU) prior to bomb testing, groundwater with tritium activities less than about 0.5 TU must have been derived from precipitation that fell before 1953. Tritium activity was determined by counting after tritium enrichment by electrolysis of the water. A half-life of 12.43 yr was used to calculate the resulting TU (tritium unit) values, where 1 TU is equal to a tritium/hydrogen ratio of 10^{-18}. Analyses (O, H, ^3H) were conducted at Isotech Laboratories, in Champaign, Illinois.