Chemical Geology 371 (2014) 1–8

Contents lists available at ScienceDirect

Chemical Geology

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

Distinguishing seawater from geologic brine in saline coastal groundwater using radium-226; an example from the Sabkha of the UAE

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ARTICLE INFO

Article history:
Received 1 May 2013
Received in revised form 24 January 2014
Accepted 27 January 2014
Available online 6 February 2014

Editor: J. Fein

Keywords:
Sabkhat
Radium-226
Geologic brine
Seawater

ABSTRACT

Sabkhat (Salt flats) are common geographic features of low-lying marine coastal areas that develop under hyper-arid climatic conditions. They are characterized by the presence of highly concentrated saline solutions and evaporitic minerals, and have been cited in the geologic literature as present-day representations of hyper-arid regional paleohydrogeology, paleoclimatology, coastal processes, and sedimentation in the geologic record. It is therefore important that a correct understanding of the origin and development of these features be achieved. Knowledge of the source of solutes is an important first step in understanding these features. Historically, two theories have been advanced as to the main source of solutes in sabkha brines: an early concept entailing seawater as the obvious source, and a more recent and dynamic theory involving ascending geologic brine forced upward into the base of the sabkha by a regional hydraulic gradient in the underlying formations. Ra-226 could uniquely distinguish between these sources under certain circumstances, as it is typically present at elevated activity of hundreds to thousands of Bq/m^3 (Becquerels per cubic meter) in subsurface formation brines; at exceedingly low activities in open ocean and coastal water; and not significantly supplied to water from recently formed marine sedimentary framework material. The coastal marine sabkha of the Emirate of Abu Dhabi was used to test this hypothesis. The distribution of Ra-226 in 70 samples of sabkha brine (mean: 700 Bq/m^3), 7 samples of underlying deeper formation brine (mean: 3416 Bq/m^3), the estimated value of seawater (<16 Bq/m^3) and an estimate of supply from sabkha sedimentary framework grains (<~6 Bq/m^3) provide the first direct evidence that ascending geologic brine contributes significantly to the solutes of this sabkha system.

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1. Introduction

Sabkhat (salt flats) are extensive geographic features in many arid and hyper-arid coastal environments of the world and are typically associated with highly concentrated brines occurring in the shallow surficial aquifers beneath the surface. As a result, contemporary sabkha environments have become geological analogs for evaporitic environments in the sedimentary record and therefore it is important to identify and correctly understand the processes responsible for accumulation of solutes in these systems.

Early models of sabkha brine formation assumed that the solutes were concentrated by evaporation of seawater (Kinsman, 1969; Butler, 1969; Patterson and Kinsman, 1977, 1981, 1982) or seawater and shallow groundwater (Hsü and Siegenthaler, 1969; Hsü and Schneider, 1973; McKenzie et al., 1980; Müller et al., 1990).

Later, a fundamentally different model was presented whereby the majority of the water making up these brines was supplied by local rainfall, but solutes originated to a large extent from upward migration of geologic brine from deeper formations, with seawater contributing only initially and in a minor way to the composition (Sanford and Wood, 2001; Wood and Sanford, 2002; Wood et al., 2002; Wood et al., 2005; Wood and Sanford, 2007; van Dam et al., 2009).

This ascending brine model (ABM) overcame difficulties inherent in sea water-based models, and was in agreement with solute mass balance, water isotope data, solute ratios and positive hydraulic head in the underlying formations. However, clear direct evidence that the model functioned as described, and is currently active, was lacking. Here we use the presence of Ra-226 to provide such primary evidence based on 1) its elevated activity of several hundred to thousands of Bq/m^3 (Becquerels per cubic meter) in subsurface brines (Kraemer and Reid, 1984; Vengosh et al., 2009), 2) near absence in open ocean and coastal seawater (<16 Bq/m^3, Okubo et al., 1979; Moore et al., 1985; Liu et al., 2010; Su et al., 2010; Ohta et al., 2011; Charette et al., 2013), and 3) lack of supply in significant amounts (as compared to formation brines) by sedimentary grains (<~6 Bq/m^3).

The presence of radium in significant amounts (greater than a few hundred Bq/m^3) in the sabkha brine would therefore be strong evidence for the ultimate source of solutes being from geologic brines, whose accumulation in the sabkha brine, additionally, would have to be recent owing to the geologically short half-life of Ra-226 ($t_{1/2} = 1601$ y).

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0009-2541/$ – see front matter. Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.chemgeo.2014.01.018

2. Site description

Our study area is in the coastal region of the Arab Gulf, southwest of Abu Dhabi City in the United Arab Emirates, the classic site where most studies relating to development of sabkha-hosted hyper-saline brines has taken place. The area (Fig. 1) is a flat, low-lying region approximately 300 km long by 10 km wide. The surficial formation (Abu Dhabi formation, Wood et al., 2002) upon which the sabkha has developed has been inferred by sedimentalogical and ^{14}C methods at 7000 y or older (Evans, 1995) and by the optically stimulated luminescence method at 8000 ± 800 y (Wood et al., 2002), and overlies local cemented Pleistocene age dunes and more regional carbonate deposits of the Middle to Upper Miocene age Gachsaran Fm. (Peebles, 1999).

The wedge-shaped sabkha formation averages 10 m in thickness (thickest toward the Gulf) and is composed of un-cemented, reworked sand dune deposits of uniform grain size (98% of its mass is between 0.16 and 0.22 mm) exhibiting a porosity of approximately 0.38 (+/−5%), spatially uniform hydraulic conductivity of approximately 1 m/d (+/−25%), low hydraulic gradient (0.00014) and seepage velocity of approximately 0.15 m/y. Annual rainfall, associated with Shamal (north) winds in January through March, averages 60 mm over the study area. Annual potential evaporation exceeds 3800 mm (all values from the work of Wood and others, see references cited).

Authigenic mineral precipitation is common and largely limited to the surface and capillary zone below the sabkha surface as water is drawn upward in response to intensive evaporation and regional hydraulic head. Retrograde soluble calcite, dolomite, gypsum, and anhydrite precipitate within the capillary zone, while halite, carnallite, sylvite, and niter precipitate on the sabkha surface.

3. Methods

Three different drilling techniques were used in installing the wells and piezometers from which the samples were taken. The shallow RP-series ("R" designations on Fig. 1) piezometer nests were drilled using mud-rotary equipment in a profile perpendicular to the Gulf shoreline approximately 60 km west of Abu Dhabi City. All piezometer nests, except those at site RP-5, are completed at various depths in the Abu Dhabi formation. Five-centimeter diameter PVC pipe, slotted by a hacksaw on the bottom 0.5 m and fitted with end cap, identification collar, and cap, was installed into the holes immediately after drilling. Water samples from the RP piezometers were collected by peristaltic pump. Pump tubing was rinsed both inside and out in distilled water prior to sampling, and several liters of brine were pumped to waste before installing an in-line filter for sample collection. Three well volumes were discharged before sampling all wells.

The deep GWP-series of wells ("G" designation on Fig. 1) were drilled parallel to the coast using reverse air rotary equipment and penetrated into the underlying bedrock of Miocene age. These wells were finished with approximately 40 m of steel surface casing, with open hole for the remainder of their total depth. All of the GWP wells flowed

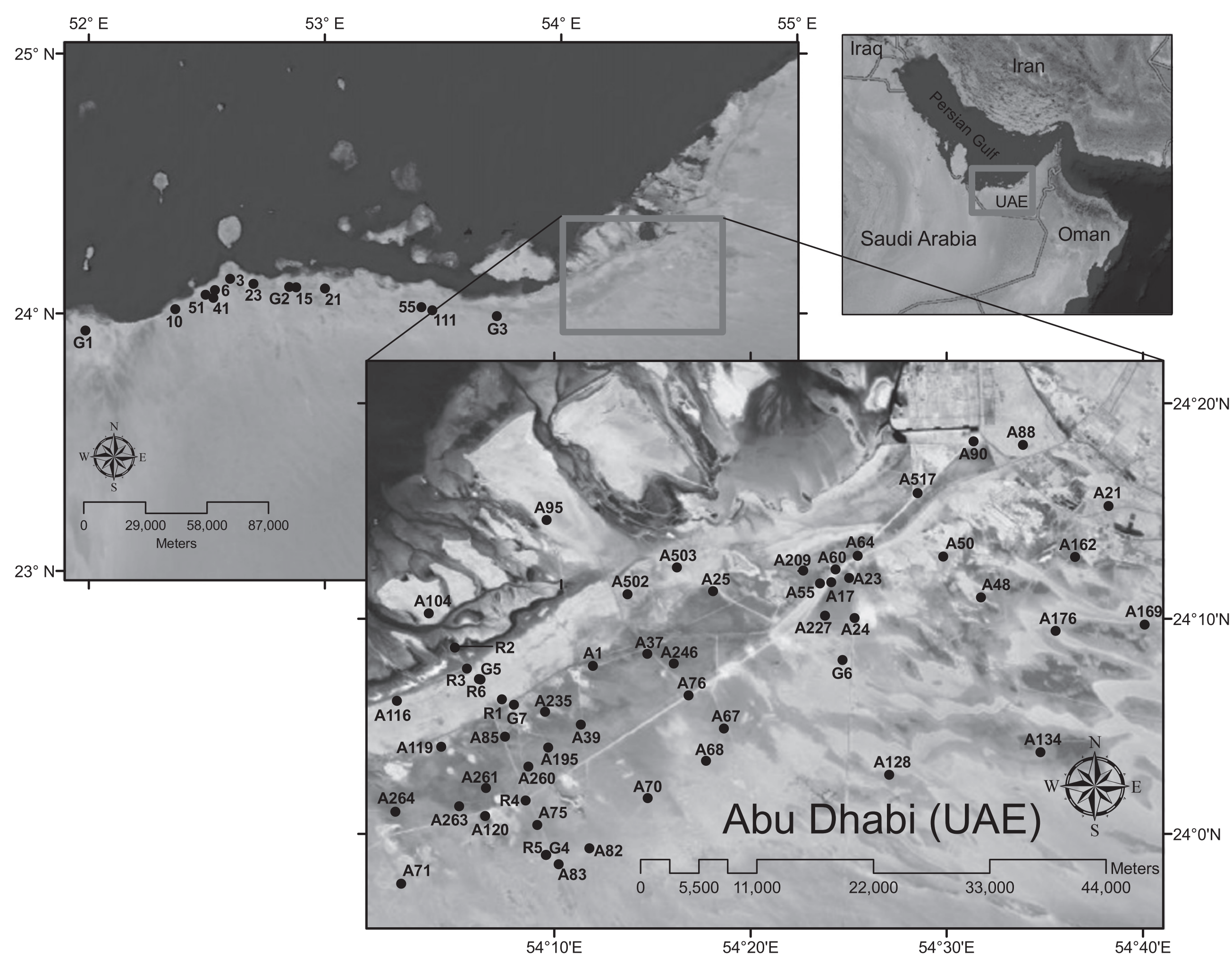

Fig. 1. Location map of study area. Sample designations are described in the text and Table 1. Abu Dhabi City is located just to the north of the expanded box.