



Geochemistry of sediment moisture in the Badain Jaran desert: Implications of recent environmental changes and water-rock interaction



Li Jin ^{a,*}, W. Mike Edmunds ^{b,1}, Zunli Lu ^c, Jinzhu Ma ^d

^a Geology Department, State University of New York College at Cortland, Cortland, NY 13045, USA

^b School of Geography and the Environment, University of Oxford, Oxford OX1 3QY, UK

^c Department of Earth Sciences, Syracuse University, Syracuse, NY 13244, USA

^d Key Laboratory of Western China's Environmental Systems (Ministry of Education), Lanzhou University, 222 South Tianshui Road, Lanzhou 730000, China

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ABSTRACT

Unsaturated zone pore water has the potential to record history of recharge, palaeoenvironment, pollution movement and water-rock interaction as it percolates through and moves towards the water table. In this study, two 6-m cores from the Badain Jaran desert (NW China) were collected to explore this potential using directly extracted moisture. Pore waters in these unsaturated zone sediments (1–5% moisture by wet weight) were directly extracted using immiscible liquid displacement and then analysed for major anions, cations and trace elements. Results show enrichment in pore water chemistry in the top 1–2 m where strong temperature and moisture fluxes occur. The enrichment in cations relative to chloride is primarily due to silicate mineral dissolution during infiltration. High nitrate and low iron concentrations indicate the overall oxidizing environment, which allows the mobility of oxyanions, such as uranium, arsenic and chromium. The trace elements show enrichment in the upper zone of fluctuation where chemical gradients are strong, but with lesser reaction lower in the profile. The calculated groundwater recharge rates using the chloride mass balance are negligible in this arid region between 1.5 and 3.0 mm/year. The modern rainfall infiltration signature contrasts with that of the underlying groundwater body, which has a distant, regional recharge signature.

This reconnaissance study demonstrates the potential for a new geochemical approach to studying geochemical processes in the unsaturated sediments in semi-arid environments due to both natural and human influences. The use of directly extracted water, rather than extraction by dilution (elutriation), facilitates an improved understanding of hydrological and geochemical processes in the unsaturated zone and into the capillary fringe at the water table, because it avoids potential chemical changes induced during elutriation.

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1. Introduction

Rainfall entering the soil moves through the unsaturated zone (USZ) before recharging groundwater. Geochemical profiles of recharging moisture within the USZ have a range of potential applications i) to enable estimation of groundwater recharge rates; ii) to retain information related to antecedent climatic hydrological and land use conditions; iii) to investigate pollution in transit to the

water table, which provides information for source protection and iv) to provide a record of water-rock interaction and solute acquisition for potable and other uses. In view of the low moisture contents most previous studies have relied mainly on moisture extraction by dilution (elutriation) using demineralized water. The use of chloride mass balance (CMB) as a tool for estimating recharge in unsaturated porous mainly sandy profiles has now become a standard procedure in hydrogeology especially in semi-arid regions (Edmunds et al., 1987; Allison et al., 1994; Scanlon et al., 2006). Moreover the recharge records so obtained are generally robust, providing estimates over decades or longer periods. Under favourable conditions, especially in areas with deep USZs, the chloride (Cl) record can act as a proxy of past climatic conditions

* Corresponding author.

E-mail address: li.jin@cortland.edu (L. Jin).

¹ Deceased.

(Edmunds et al., 1991; Scanlon, 1991; Edmunds and Tyler, 2002). Recent records from low rainfall areas of Inner Mongolia, China have provided an archive over 2000 years in USZs of up to 30 m which can be validated against other proxies such as ice cores, tree ring and historical records (Gates et al., 2008a; Ma et al., 2009).

The USZ has also been used extensively in geochemical studies of water quality evolution over decadal timescales using moisture extracting via either elutriation or centrifugation techniques (Edmunds and Bath, 1976). The USZ (as well as saturated zone) profile studies have now become standard procedures for investigating penetration of pollution from agricultural sources such as, agrichemicals and pesticides (Geake and Foster, 1989) and from industrial sources such as landfill (Williams et al., 1991). Centrifugation of USZ porous media however becomes limiting with moisture contents lower than around 8–10%.

Direct investigation of the geochemistry of the USZ at low moisture contents (2–6%) has proved to be a challenging problem. Investigation of inert solutes such as Cl and nitrate (NO₃) under aerobic conditions can be achieved by dilution methods, but investigation of wider geochemical applications requires direct access to the pore solution so as to avoid artifacts from washing off particle coatings and changing the chemical conditions of moisture created by the dilution process. An immiscible displacement method was developed in the 1980s (Kinniburgh and Miles, 1983) using the chlorofluorocarbon Arklone which allowed between 30 and 60% recovery of moisture. This technique was then successfully applied to studies of acid attenuation in the USZ where typically between 2 and 4 ml moisture was used for investigation of exchangeable cations (Moss and Edmunds, 1992). This promising technique was however brought to an abrupt halt by the Montreal Protocol which led to a phasing out and a halt to production of CFCs. Until recently no suitable substitute for Arklone had been found.

A new immiscible liquid (HFE-7100[®]) has however now been successfully trialled (Jin and Edmunds, 2010) and this paper is the first field application of the technique in the research area for which it was designed. The objective of this paper is to investigate the potential of the method for studying directly the USZ moisture geochemistry in an arid region of China (the Badain Jaran Desert) where previous work on the CMB and recharge history has been carried out (e.g. Gates et al., 2008b; Ma et al., 2009). The paper presents the empirical relationships between major ions and key trace elements. This is a reconnaissance study to demonstrate the potential of a new geochemical approach rather than a study of detailed processes.

2. Materials and methods

2.1. Study area

The Badain Jaran desert, located in Northwest China, is a remote region of massive sand dunes with the relative height being 200–500 m above sea level and numerous lakes with diverse composition, from fresh to saline (Fig. 1). It is the second largest desert in China with an area of 49,000 km². The Badain Jaran desert is surrounded by the Heishantou and Yabulai mountains to the south and southeast, respectively; the lowland areas of the Gurinai grassland lie to the west and northwest (Fig. 1). Two sites on the southeast side of the Badain Jaran desert were selected for sampling. The first site, Sayinwusu (abbreviated as SS), is located at 39°34′32.1″ N; 102°20′17.5″ E. Second site, Baoritaolegai (BA), is located at 39°36′22.2″ N; 102°28′54.8″ E.

Badain Jaran desert is located in the basin depression of the Alxa platform (Ma and Edmunds, 2006). The center of the basin is occupied by Quaternary sediments (Ma and Edmunds, 2006). The fringe of the basin is surrounded by Jurassic, Cretaceous and

Tertiary age rocks. The Pleistocene sediments are mostly fine-grained or clayey fluvial and lacustrine origin (Cai, 1986). The Holocene Aeolian sands are deposited above these older sediments and form the dominant desert landscape. The sediments are dominated with mineral quartz with occasional iron coatings and some feldspars.

The desert landscape mainly consists of sparsely vegetated aeolian sand dunes. The interdune areas often contain groundwater-fed lakes and playas, which vary widely in surface area and salinity (Yang and Williams, 2003). The strong continental climate in the Badain Jaran gives mean monthly temperatures from ~–10 °C in January to ~25 °C in July. In summer months the diurnal temperatures range from ~0 to >40 °C (Gates et al., 2008b). About 70% of precipitation falls from July to September, strongly influenced by the Asian monsoon. The mean annual precipitation measured at Zhongqanzi Station (~20 km southeast of the study area) was 84 mm from 1956 to 1999, although it is highly variable (standard deviation 33 mm/yr). The potential evaporation is approximately 2600 mm/yr (Gates et al., 2008b). The major shallow aquifer in the Badain Jaran desert consists of Quaternary sediments, occurring at shallow depth and the water table reaches the surface as lakes in many inter-dune areas. Lacustrine sediments with low porosity may provide local confining layers (Gates et al., 2008b).

2.2. Sampling and methodology

2.2.1. Sample collection

The unsaturated sediments of the USZ were sampled using a hollow-stem hand auger (Dormer Engineering, Murwillumbah South, NSW, Australia) with interchangeable 1.5 m aluminium rods. Two profiles to approximately 6 m depth were obtained, with samples taken at intervals of 12.5–25 cm. Any carryover of sediment from overlying material was usually visible as a colour change at the top of the sample interval and discarded. Samples were rapidly homogenized in plastic bags shortly before transferring to sealed jars to avoid moisture loss.

2.2.2. Rainfall

No rainfall sampling was possible for this study period, neither has there been any regular local monitoring of solute concentrations in rainfall. However, Ma and Edmunds (2006) reported Cl concentration of 1.49 mg/l from a large storm (50 mm that consisted of the majority of the annual rainfall) in the Badain Jaran desert in 1999. Subsequent sampling from Zhongqanzi station during 2001–2002 had a volume weighted mean Cl of 1.5 mg/l (Ma and Edmunds, 2006). Cl concentrations from 10 storm events in the Badain Jaran during 1994–1995 ranged from 0.5 to 3.3 mg/l (Hofmann, 1999) with a simple arithmetic mean of 1.9 mg/l. In this paper, we chose the value of 1.5 mg/l as the best available estimate for Cl concentration in the rainfall in the area. The rainfall input data for all elements used in this paper are given in Table 1.

2.2.3. Moisture content and water extraction

Moisture contents were determined on 50 g samples on a wet weight basis, before and after drying overnight at 105 °C. The moisture contents were then calculated according to the mass difference. The balance is precise down to 0.01 g, sufficient to detect moisture content changes as low as 0.02%.

Approximately 100 g of individual moist sand sample was loaded into 250-ml polypropylene centrifuge bottles. The bottles were thoroughly cleaned and rinsed with deionized water before use, and 230 g of immiscible liquid (HFE-7100) was added. Each sample was centrifuged for 1 h at a speed of 13,000 rpm (2.3 MPa) in a Beckman J2-21 centrifuge with JA-14 fixed angle rotor (Jin and Edmunds, 2010). After centrifuging, the displaced water collected

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