Chemical Geology 404 (2015) 1–17

Contents lists available at ScienceDirect

Chemical Geology

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

Geochemical evolution and residence time of porewater in low-permeability rocks of the Michigan Basin, Southwest Ontario

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ARTICLE INFO

Article history:
Received 10 July 2014
Received in revised form 22 January 2015
Accepted 9 March 2015
Available online 19 March 2015

Editor: Carla M Koretsky

Keywords:
Sedimentary rock
Diffusion
Oxygen isotopes
Salinity
Porewater
Residence time

ABSTRACT

Drill cores collected from an 860-m-thick Paleozoic (Cambrian to Devonian) sedimentary sequence of the Michigan Basin in southwest Ontario, Canada, were used to develop vertical profiles of natural tracers in porewater from the sedimentary sequence and build a conceptual model regarding processes and timing of solute migration. In this paper, the conceptual model is quantitatively assessed with numerical simulations of diffusion-dominated solute transport (Cl^- and ^{18}O). The conceptual model suggests that the tracer profiles result from mixing between a deep shield brine with isotopic characteristics consistent with water–rock interaction over a long period of geologic time, Ordovician seawater at intermediate depth, and an overlying hypersaline brine formed by evaporation of seawater in a restricted basin during the Silurian. Between the peak of basin consolidation at 300 Ma BP and the Pleistocene (2.6 Ma BP), salinity and isotopic concentration gradients are thought to have driven mixing, dominantly by diffusion. Water isotope data indicate that in the Pleistocene, melt water infiltrated to a maximum depth of 330 m in the Silurian Salina Formation, likely in response to transient glacial loading and elevated sub-glacial hydraulic pressures. Also in the Pleistocene, over-pressured conditions in deep regions of the basin drove high-salinity brine eastward in the basal Cambrian aquifer, interrupting pre-existing tracer-diffusion profiles.

A base case set of boundary and initial conditions provides a good fit between simulated and measured tracer profiles, but requires effective diffusion coefficients (D_e) in the Ordovician limestones that are lower than the average values obtained in laboratory measurements by as much as a factor of 10. The base-case values are still within the overall range of measured values. At the formation scale, relatively low *in-situ* D_e values are attributed to the intermittent occurrence of gas and liquid hydrocarbons in the Ordovician carbonate units and the effect of lithostatic confining pressure; neither of which are accounted for in the laboratory measurements but both would have the effect of decreasing D_e for aqueous solutes. The numerical model is most sensitive to the formation-specific D_e values and geologically reasonable variations in initial and boundary conditions have a relatively small influence on the results. Additional simulations indicate that hydraulic disturbance and ingress of meltwater during the Pleistocene can explain second-order features observed in the measured tracer profiles. This work provides supporting evidence for previous research indicating that the porewater residence time in the Ordovician sequence approaches the age of the rocks.

1. Introduction

Groundwater from permeable units in sedimentary basins around the world has been studied for many decades with the research facilitated primarily by ease of access to samples from petroleum and gas drilling activities. In comparison, there has been a relatively small amount of research on the physical, chemical and biological controls on the composition and movement of porewater. The term porewater, in contrast with groundwater, refers to water in sediments or rocks which cannot flow due to low permeability, or flows at rates that are below measurement thresholds. Studies of porewater in low-permeability geologic systems rely, in part, on hydrogeochemistry in order to elucidate the age and origin of the porewater, and the mechanisms controlling transport of solutes. Hydrogeochemical investigations have been helpful in understanding solute migration and porewater evolution in a variety of low-permeability geologic environments, including glacial-lacustrine clay and silt (Desaulniers et al., 1981), glacial till (Remenda et al., 1994; Hendry and Wassenaar., 1999; Hendry and Wassenaar, 2000; Hendry et al., 2000; Hendry et al., 2003; Hendry et al., 2004), deeply buried sedimentary rocks (Rübel et al., 2002; Gimmi et al., 2007; Mazurek et al., 2011; Clark et al., 2013; Hendry et al., 2013; Hendry and

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http://dx.doi.org/10.1016/j.chemgeo.2015.03.005
0009-2541/

Harrington, 2014) and crystalline rock environments (Waber and Smellie, 2008; Waber et al., 2012).

Interest in the geochemical properties, mobility and residence time of groundwater and porewater deep in sedimentary basins is growing in response to unconventional hydrocarbon production, CO_2 sequestration and waste-management initiatives. The objective of this work was to identify physical and chemical processes that operated over geologic time to influence the residence time of porewater in Paleozoic rocks at the eastern margin of the Michigan Basin. The approach was based on a unique porewater dataset obtained in the course of multi-disciplinary geoscientific research activities at the Bruce nuclear site (Fig. 1) in southwest Ontario. Clark et al. (2013) presented a conceptual model for the hydrogeochemical evolution in this part of the basin. The present study reinforces their conceptual model with the addition of a more detailed synthesis of the geologic setting and paleohydrology, a detailed discussion of the possible end members for solute mixing, presentation of the results of lab-scale diffusion measurements, and a quantitative interpretation of diffusive transport that assists in the evaluation of the conceptual model.

2. Geologic and hydrogeochemical setting

Southwest Ontario is underlain by two main paleo-depositional centers referred to as the Appalachian and Michigan basins (Fig. 1). The former is a foreland basin associated with the Appalachian Orogen, while the latter is a roughly circular intracratonic basin. These basins occur, respectively, on the southeast and northwest flanks of the northeast-trending Algonquin and Findlay arches, which represent elevated crystalline basement beneath southwest Ontario (Fig. 1). The Michigan Basin is bounded along the northwest and northeast by the Fraserdale and Frontenac arches, respectively. These arches acted as structural and topographic controls on depositional patterns during the Paleozoic, rising and falling in response to epeirogenic and orogenic movements (Quinlan and Beaumont, 1984; Coakley and Gurnis, 1995; Leighton, 1996; Howell and van der Pluijm, 1999; Nadon et al., 2000). The stratigraphic sequence in the Michigan Basin ranges in age from Cambrian to Jurassic and is approximately 4800 m thick in the center of the basin. In southwest Ontario, the thickness decreases to approximately 850 m on the Algonquin Arch and the strata dip very gently to the west or southwest at between 0.23 and 1° (Watts et al., 2009).

The Paleozoic stratigraphy below the Bruce site is presented in Fig. 2. A thin unit (17 m) of Cambrian sandstone overlies Precambrian basement and is associated with great thicknesses of Cambrian siliciclastic rocks that occur to the west in the center of the basin. These rocks formed in a northeast–southwest trending trough related to initial rifting and subsidence (Howell and van der Pluijm, 1999). Rocks of Lower and Middle Ordovician age are not present along the east margin of the Michigan Basin at the Bruce site, but to the west in the central

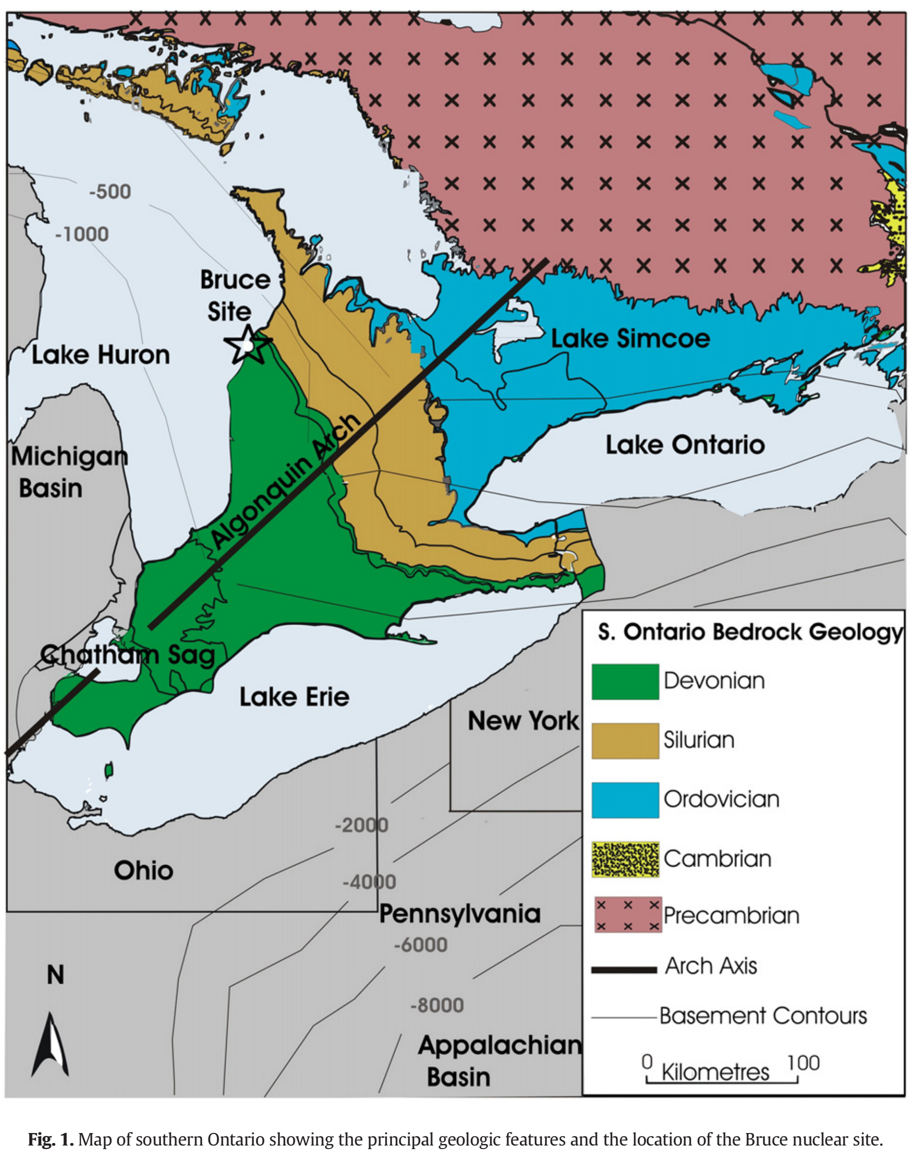

Fig. 1. Map of southern Ontario showing the principal geologic features and the location of the Bruce nuclear site.