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Deep groundwater circulation and associated methane leakage in the northern Canadian Rocky Mountains

S.E. Grasby [a,*], G. Ferguson [b], A. Brady [c,1], C. Sharp [c], P. Dunfield [c], M. McMechan [a]

[a] Geological Survey of Canada, Natural Resources Canada, 3303 33rd St. NW, Calgary, AB T2L 2A7, Canada
[b] Department of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, SK S7N 5A9, Canada
[c] Department of Biological Sciences, University of Calgary, Calgary, Alberta, Canada

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ABSTRACT

Concern over potential impact of shale gas development on shallow groundwater systems requires greater understanding of crustal scale fluid movement. We examined natural deeply circulating groundwater systems in northeastern British Columbia adjacent to a region of shale gas development, in order to elucidate origin of waters, depths of circulation, and controls on fluid flow. These systems are expressed as thermal springs that occur in the deformed sedimentary rocks of the Liard Basin. Stable isotope data from these springs show that they originate as meteoric water. Although there are no thermal anomalies in the region, outlet temperatures range from 30 to 56 °C, reflecting depth of circulation. Based on aqueous geothermometry and geothermal gradients, circulation depths up to 3.8 km are estimated, demonstrating connection of deep groundwater systems to the surface. Springs are also characterised by leakage of thermogenic gas from deep strata that is partly attenuated by methanotrophic microbial communities in the spring waters. Springs are restricted to anomalous structural features, cross cutting faults, and crests of fault-cored anticlines. On a regional scale they are aligned with the major tectonic features of the Liard Line and Larsen Fault. This suggests that while connection of surface to deep reservoirs is possible, it is rare and restricted to highly deformed geologic units that produce permeable pathways from depth through otherwise thick intervening shale units. Results allow a better understanding of potential for communication between deep shale gas units and shallow aquifer systems.

1. Introduction

The rapid development of shale gas resources has provided a major increase to North American gas supply. However, concerns have been raised over potential impacts of development, including contamination of shallow potable groundwater by fugitive gas, and leaking formation waters or fracturing fluids (e.g. Adgate et al., 2014; Chapman et al., 2012; Jackson et al., 2012; Osborn et al., 2011; Rivard et al., 2014; Warner et al., 2012; Werner et al., 2015). Studies in undeformed sedimentary basins have shown that induced fractures do not propagate far (<300 m) from the injection zone, and that injected fluids remain largely isolated from the surface environment (Flewelling et al., 2013). Whether these results are transferable to deformed sedimentary basins is less clear. Natural fracture systems have potential to form conduits, connecting deep gas reservoirs along with injection fluids to the shallow surface environment (Bense et al., 2013). Faults with well-developed brittle fractures systems in the Canadian Cordillera are known to facilitate circulation of meteoric fluids to depths as great as 5 km (Allen et al., 2006; Caron et al., 2008; Ferguson and Grasby, 2011; Grasby and Hutcheon, 2001).

In Canada there are two key regions for shale gas development, the Horn River Basin and the Montney Trend, both located in NE British Columbia adjacent to the deformation front of the Northern Rocky Mountains (Fig. 1) (Rivard et al., 2014). Production to date is restricted to the undeformed portion of the Western Canada Sedimentary Basin, where shales have been buried up to the dry gas window at depths reaching 2500 m. Only limited exploration has occurred within the adjacent deformed belt. While gas-prone shale units are known to extend into that region, there has been minimal

* Corresponding author.
E-mail address: steve.grasby@canada.ca (S.E. Grasby).
[1] Current address: School of Geography and Earth Sciences, McMaster University, Hamilton, Ontario, Canada.

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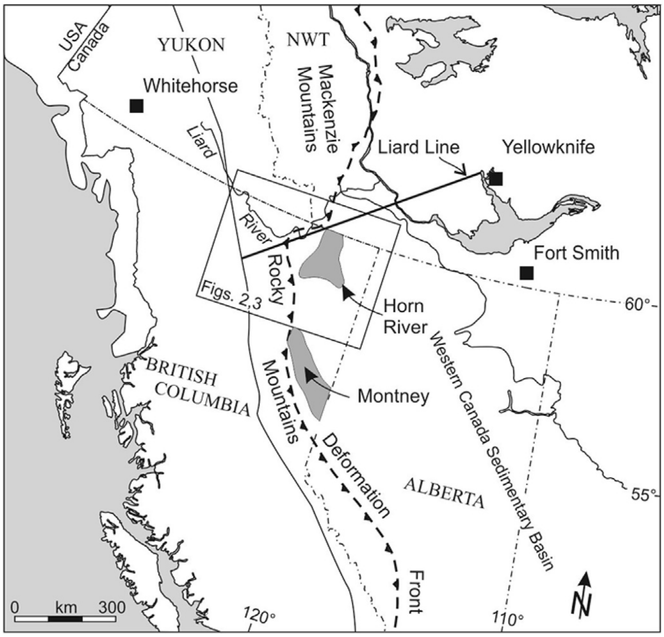

Fig. 1. Regional map showing location of the study area. The major shale-gas plays of the Western Canada Sedimentary Basin, along with the deformation front of the Canadian Cordillera, the Liard Line that defines the transition from the northern terminus of the Rocky Mountains to the Mackenzie Mountains further north, and the detailed study area are shown.

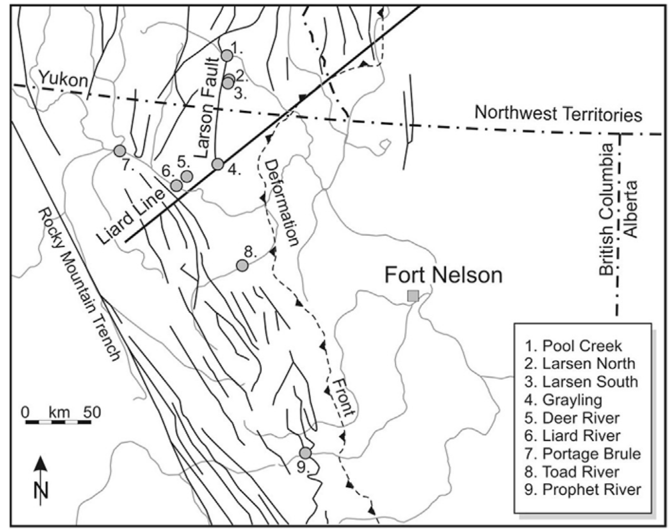

Fig. 2. Location of thermal springs included in the study. Major fault systems (black lines) are shown along with river drainages. Location of map is indicated in Fig. 1.

production to date. Any future development in the deformed belt will occur in a significantly different hydrogeological environment than in the undeformed basin to the east. Tectonic stress could greatly enhance natural fracture systems and increase potential natural pathways for fluid migration (Bell and Grasby, 2012; Chen et al., 2011). Prior to any development in these regions, a better understanding of the unique crustal-scale hydrogeologic systems, and particularly the potential for communication between deep and shallow systems, is required.

To address this, we examined naturally occurring springs in the Northern Rocky Mountains. A focus was placed on thermal springs that inherently represent the deepest circulation systems (greater temperatures require greater circulation depths).

2. Background

The study area is located in NE British Columbia (Figs. 1 and 2), in the region that marks the transition from the Canadian Rocky Mountains in the south to the Mackenzie Mountains to the north. Although in remote and largely uninhabited areas, thermal springs in northern Canada are readily identified in the winter as they generate steam clouds. As well, development of large travertine deposits at the spring outlets, often associated with brightly coloured microbial mats growing in the discharge waters, are easily identified from aerial survey (Supplementary Fig. 1a–c). Traditional knowledge of thermal springs in the region extends back to First Nation usage of many sites. A previous compilation provides locations of verified and unverified thermal springs in western Canada (Fairbank and Faulkner, 1992). Within the study area (Fig. 2) there are 10 reported thermal springs. Of these, nine were visited and sampled (Fig. 2). One site (Lepine Creek) reported by Fairbank and Faulkner (1992) was not located through an aerial helicopter survey. It may exist as an outlet under the forest canopy that does not make any noticeable spring deposits or outflow channel. This would contrast; however, with all other sites that are readily visible from the air, suggesting that if the Lepine Creek spring does exist, the flow would be relatively minor. The nearest climate station to the study area is Fort Nelson (up to 220 km away, Fig. 2), where 30 year average annual temperatures are −0.7 °C, and average annual precipitation is 452 mm (Environment Canada, 2013).

The regional geologic setting is characterised by the transition zone between the northern end of the Canadian Rocky Mountains and the southern extent of the McKenzie Mountains. This transition is marked by a notable deflection from the principal NW directed structural trend of the Rocky Mountains south of the Liard River. North of this river, there is a more northerly structural trend in the McKenzie Mountains (Cecile et al., 1997; Cecile and Norford, 1991) (Figs. 1 and 2). High mountains in the western part are formed by Cambrian to lower Paleozoic carbonates, and the Rocky Mountain Foothills and Liard Fold and Thrust Belt are formed by folded Mississippian and Triassic sandstone and shale (McMechan et al., 2012). The major change in structural trend in the study area is thought to be controlled by a northeast-trending zone called the Liard Line (Cecile et al., 1997) that is defined by the depositional pinch out of Ordovician to Devonian strata against the Macdonald High. The Liard Line is considered one of the most prominent structural features of the Canadian Cordillera and has influenced sedimentation and tectonics throughout much of its history, and is interpreted as an ancestral transfer fault zone (Cecile et al., 1997).

Northeastern British Columbia has long been recognised as having anomalously high geothermal temperatures (Jessop et al., 1984; Majorowicz and Grasby, 2010; Majorowicz et al., 2005). In particular, the Clark Lake field south of Fort Nelson has high geothermal resource potential (Walsh, 2013). Heat flow in NE British Columbia ranges from 40 to 80 mW/m^2 (Majorowicz and Grasby, 2010); however, within the study area heat flow is relatively low, ranging from 40 to 60 mW/m^2 (Fig. 3).

3. Methods

3.1. Field sampling

With the exception of Liard River and Portage Brûlé springs, all sites required helicopter access due to remoteness from any roadway. The Liard River Spring is a developed recreation site adjacent to the Alaska Highway. The Portage Brûlé spring can be