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Geothermal potential of Foreland Basins: A case study from the Western Canadian Sedimentary Basin

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ABSTRACT

Geotechnical and hydrogeological data from well bore logs and rock cores were used to identify, map, and model the power production potential of geothermal reservoirs in sedimentary formations in the Western Canadian Sedimentary Basin across several municipal districts in western Alberta. We show a general workflow for using oil and gas data to assess geothermal resources in sedimentary basins, present a series of contour maps and stratigraphic grids of salient geothermal reservoir properties and assess the power production potential of these resources using a volumetric (heat-in place) method.

In total, throughout the study area, we identified a potential thermal power capacity of ∼6100 MWt per for a 30-year production period. Reservoir depths ranged from about 2500 m to over 5000 m. Formation temperatures ranged from ∼60 °C to over 150 °C. The calculated thermal power capacity equates to ∼1150 MWe of potential electrical power capacity over the 30 year production period, of which ∼ 800 MWe are considered high grade (> 120 °C) resources that may reliably produce electricity with existing technology.

1. Introduction

1.1. Research overview

Geothermal energy is a baseload renewable resource that has the potential to play a major role in a global transformation away from fossil fuel based resources. The development of utility-scale geothermal power projects has been historically restricted to tectonically active areas, where high heat flow and extensive fracture networks in the shallow (< 10 km) subsurface allow for relatively easy access to hot aqueous fluids. These areas are often remote and difficult to access and develop. Recent development in the geothermal industry, therefore, has focused on sedimentary basins, many of which contain geothermal resources directly underlying potential end users. For example, over 40 MWe of geothermal power has been installed in Germany's Molass Basin in the last decade (Bertani, 2015). While this value is small compared to global geothermal power capacity (∼13 GWe), it indicates a trend with a significant potential for growth (Bertani, 2015).

Similar to the Molass Basin, the Western Canadian Sedimentary Basin (WCSB) is an alpine foreland basin that underlies many population centers and possesses a commercially significant quantity of geothermal energy. The WCSB is best known for its hydrocarbon resources, which include 1845 billion barrels of crude bitumen, 83 billion barrels of crude oil, nearly a trillion cubic meters of natural gas and 100 billion tons of coal (Alberta Energy Regulator, 2017). Prolific development of these hydrocarbon resources has created an extensive set of hydrogeologic and thermodynamic data from the subsurface of the WCSB. In this paper, we use data derived from the oil and gas industry to assess the geothermal resource potential of hot sedimentary aquifers in the central and northern parts of the Alberta foothills, which overlie some of the deepest parts of the WCSB.

Geothermal energy development is important in the WCSB because it can offset the carbon emissions footprint of hydrocarbon production in the basin (Majorowicz et al., 2012b). Furthermore, the Alberta government has mandated the replacement of coal-fueled electricity in the province with at least 5 GWe of renewable power. Geothermal energy may play an important role in meeting this mandate.

On a broader scale, the portion of the WCSB addressed in this study may represent many retro-arc foreland basin around the world, including, for example, the Karoo Basin of South Africa (e.g. Catuneanu et al., 1998), the Carpathian foredeep in Poland (e.g. Matyasik et al., 2007), the Chaco-Parana Basin of South America (e.g. Rosa et al., 2016) and the foreland west of the Ural mountains (Brown et al., 2006). Such basins represent an opportunity for significant global expansion in the geothermal industry. Due to the abundance of oil and gas data, the WCBS serves as good proxy for studying the geothermal potential similar basins around the world. Quantifying the geothermal power potential in the immediate vicinity of population centers overlying the

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WCSB allows us to make meaningful inferences about the geothermal potential of hot sedimentary aquifers worldwide.

Several previous studies (e.g. Grasby et al., 2012; Majorowicz et al., 2012b; Majorowicz and Moore, 2014) have looked at Alberta's geothermal resource base as a diffuse, province-wide commodity. Additional studies (e.g., Weides et al., 2013, 2014a,b; Weides and Majorwicz, 2014) identified specific formations in the WCSB suitable for geothermal exploration and development. These studies made semi-quantitative evaluations of the formations in question using a number of assumptions and some empiric data. This present study is the first in which the geothermal potential of specific formations in the vicinity of population centers has been calculated using a volumetric (heat-in place) method. In addition to mapping geothermal reservoirs in the Alberta foothills and quantifying their geothermal power production potential, this paper presents a method for using oil and gas data to reduce the risk and cost of geothermal energy exploration in sedimentary basins, globally. Specifically, we will show how oil and gas data can be used to make a 3-D models of a reservoir and then apply a volumetric method to that model in order to calculate a variety of metrics related to the reservoirs' power production potential.

1.2. Geologic setting

1.2.1. Overview

The WCSB is a continental scale supercrustal wedge of Proterozoic to Quaternary sediments that is bordered to the west by the Canadian Rocky Mountain Fold and Thrust Belt and to the east by the Precambrian rocks of cratonic North American. Fig. 1 shows the location of the WCSB in its present geographic and tectonic setting. The WCSB approaches 6000 m (Basal Cambrian Sandstone) depth along the eastern margin of the North American Cordillera and gradually thins toward the exposed Canadian Shield in northeastern Alberta, the southern Northwest Territories and most of Saskatchewan. The basin ranges from 600 to 1200 km wide and generally deepens to the SW or WSW. The geologic history of the WCSB is inseparable from the evolution of North America and the formation of the North American Cordillera. A detailed account of this history and the resulting geology is found in the "Geologic Atlas of the Western Canadian Sedimentary Basin," a online resource published by the Alberta Energy Regular (Atlas; Mossop, G.D. and Shetsen, I. [comp.], 1994).

The modern WCSB is a retro-arc foreland basin consisting of a wedge of Phanerozoic sediments overlying the Precambrian Canadian Shield in the northern interior of continental North America. The sedimentary record within the WCSB indicates two distinct first-order phases of deposition. In the first phase, beginning in the Neoproterozoic, the break-up of Rodinia and the opening of the Panthalassa Ocean created a passive margin environment off the west coast of ancestral North America. A westward (relative to modern North America) thickening sequence of continental margin, shallow marine and deep marine sediments were deposited upon this passive margin. This tectonic regime persisted until the onset of the Laramide Orogeny in the Late Jurassic. Subsequently, clastic sediments derived from the uplifting cordillera were deposited in fluvial to shallow marine environments upon the passive margin sediments. Significant downwarping of the passive margin sequence and underlying Precambrian Shield occurred as a response to crustal loading by the growing cordillera. This downwarping accommodated the second phase of sediment infill and created the present-day regional foreland basin geometry.

The compressional tectonic regime induced by the Laramide Orogeny shortened, uplifted and transported distal deposits of the pre-Late Jurassic passive margin more than 100 km to the northeast from their original location. Consequently, most of the oldest stata of the WCSB are not found buried in the foreland basin, but are exposed to the west in the Rocky Mountain Fold and Thrust Belt. Prominent among these exposed strata are the Neoproterozoic Windermere Supergroup and the Early Cambrian Gog Group. The oldest widespread Phanerozoic strata in the buried in the WCSB represent the transgressive-regressive Sauk sequence, beginning in the Middle Cambrian. With the exception of the downwarping described above, the WCSB contains an undeformed record of deposition and erosion from the Middle Cambrian to modern times. This record displays a history of marine transgressions and regressions along a passive margin until the Late Jurassic, with continental detritus supplied by the Appalachian Mountains to the east. Since the Late Jurassic, source material for the basin infill has been derived primarily from the western cordillera. Prominent sedimentary successions are found in the Devonian and the Cretaceous, both of which contain significant hydrocarbon resources. The Devonian section, which sits at the deepest parts of the WCSB is the focus of this study.

1.2.2. Geothermal setting of the WCSB

Geothermal research in Canada dates back to Garland and Lennox (1962), who studied heat flow throughout the western Canadian provinces and territories. Majorowicz and Jessop (1981) first studied regional heat flow patterns specifically in the WCSB. This research was expanded to include thermal conductivity studies throughout the basin (Lam et al., 1985), radiogenic heat production and heat flow from the Precambrian basement underlying the WCSB (Jones and Majorowicz, 1987; Bachu, 1993) and temperature distribution along the Precambrian and various Paleozoic surfaces in WCSB (Jones et al., 1985). Much of this early research was beset by inconsistent temperature data. Thus, extensive work has been done to correct temperature data for hydrodynamic influences (e.g. Majorowicz et al., 1999), paleoclimatic effects (Majorowicz et al., 2012a) and other biases (Gray et al., 2012). Nieuwenhuis et al. (2015) released a revised database at the 2015 World Geothermal Congress that corrected many of the problems with the original temperature measurements in the WCSB.

Recent geothermal research in the WCBS has focused on the potential exploitation of the basin's geothermal energy for heating and electricity. The Geological Survey of Canada (Grasby et al., 2012) performed a country-wide geothermal resource base estimate. Majorowicz et al. (2012b) investigated the possibility of using geothermal energy as a heat source for oil-sands upgrading. Weides et al. (2013) evaluated potential geothermal resources in Paleozoic strata in the Edmonton, Alberta metropolitan area (population ~1.16 million). This research led to further interest in using the basal Cambrian sandstone as a potential electricity producing resource (Weides et al., 2014a). Weides et al, (2014b) also investigated the siliciclastic Granite Wash Formation in the Peace River area of Alberta, where heat and electricity from a geothermal source could be used to offset the environmental footprint of local hydrocarbon production. Both of these formations have marginal electricity producing capacity due to relatively low temperatures in their respective areas, but are sufficient for providing heat for direct use.

This present study is based in part on the work done by Weides and Majorwicz (2014), who analyzed spatial variability in heat flow throughout the entire WCSB. They overlaid the areal extent of known deep basin aquifers on temperature profiles from the surfaces of various geologic strata throughout the Paleo- and Mesozoic. Fig. 2 shows the geothermal gradient across the WCSB, as mapped by Weides and Majorwicz (2014). Gradients are variable throughout the basin. The lowest geothermal gradients are found along the southern sections of the basin, especially in the southwest corner abutting the mountain front between Calgary and Lethbridge. Here, the geothermal gradient is from ~20 - 25 °C/km. Another area of low geothermal gradient is found west of Ft. McMurray. The highest geothermal gradients in the WCSB are found in the far northwest in northeastern British Columbia and the southwest Northwest Territories, where gradients exceed 45 °C/km in many places. Some additional hot spots, notably to the southwest of Edmonton, are found in the central parts of the basin. Throughout the rest of the WCSB, the geothermal gradient ranges from 30 to 40 °C/km, which is representative of global averages.