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Geothermal potential of the St. Lawrence Lowlands sedimentary basin from well log analysis

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A B S T R A C T

The heterogeneous distribution of minerals in different rock types poses several challenges for assessing thermal conductivity, heat flow and temperature of sedimentary basins, especially when databases coming from the oil sector are the only source of information. The objective of this study was to develop a new methodology that uses well log data to better infer the thermal conductivity variations of sedimentary formations in order to evaluate heat flow and extrapolate temperature at depth. The methodology was applied to the St. Lawrence Lowlands basin, with constrains from the available oil and gas database not designed for geothermal exploration purposes. The main idea was to analyze quantitatively well log data with an inversion approach from limited reference wells and derive empirical relationships to calculate a thermal conductivity profile for each available well. Pressure and temperature corrections were then considered. These continuous logs of thermal conductivity were used to estimate the Earth's heat flux density using bottomhole temperatures and to extrapolate temperature at depth. A modified version of Poisson's equation was solved by the finite difference method for this purpose. The average temperature and its standard deviation obtained with this approach for the St. Lawrence Lowlands at 1000, 2500 and 5000 m depth is approximately 32 ± 6.9 °C, 63 °C ± 12.7 °C and 119 °C ± 28.3 °C, respectively. Moreover, temperature ranges from 19 to 52 °C, 41 to 112 °C and 75 to 236 °C at 1000, 2500 and 5000 m depth, respectively.

1. Introduction

Low-enthalpy geothermal resources associated with sedimentary basins have become common targets for extending geothermal development beyond volcanic regions hosting high-enthalpy resources. Previously unexplored basins are now being considered in energy planning, but this requires accurate resource estimates based on potential reservoir temperature. The search to define deep geothermal resources may extend into areas with limited geothermal data, facing high development risk. This is the case of the St. Lawrence Lowlands (SLL) sedimentary basin in southern Quebec, Canada. The basin, which covers approximately 20,000 km^2, contains only three wells where equilibrium temperature profiles and core plug measurements of thermal conductivity were used to assess heat flow at depths of less than 500 m (Saull et al., 1962). However, more than 250 oil and gas exploration wells have been drilled as deep as 4300 m in the basin. Geophysical logs from 90 of these wells are available in a public database (SIGPEG, 2011) and can be used to define geothermal resources and reduce development risk.

Analyzing well log data and converting geophysical signals into reliable geothermal information is a significant challenge due to the heterogeneous distribution of minerals in rocks of stratigraphic sequences. Thermal conductivity and heat generation profiles can be inferred from well logs and combined with bottomhole temperature to evaluate heat flow and extrapolate temperature at geothermal resource depth (Fuchs and Förster, 2014). The estimation of thermal conductivity from well logs is a critical step in this analytical process. Previous studies have demonstrated how thermal conductivity can be inferred from well logs using two approaches (Merkel et al., 1976; Brigaud et al., 1990; Popov et al., 2003; Hartmann et al., 2005; Goutorbe et al., 2006; Fuchs and Förster, 2014). The first is to determine the mineralogical composition of the host rock by inverting the geophysical log data (Savre, 1963; Doveton and Cable, 1979; Quirein et al., 1986) and then calculate the thermal conductivity of the rock using a mixing model (Dove and Williams, 1989; Brigaud et al., 1990; Demongodin et al., 1991; Vasseur et al., 1995; Midttømme et al., 1997). The second approach consists of using empirical relations that directly link thermal conductivity to petrophysical parameters (Beziat et al., 1992; Pribnow et al., 1993; Kukkonen and Peltoniemi, 1998; Sundberg, 2002; Popov et al., 2003; Goutorbe et al., 2006; Sundberg et al., 2009;

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Nomenclature

A	Heat production (W/m^3)
Bl. Riv.	Black River Group
Ch	Chazy Group
D	Density (g/cm^3)
$\mathbf{d}$	Matrix column (6,1)
ER	Relative error [%]
$\mathbf{G}$	Square matrix (6, 6)
GR	Gamma ray [API]
$\mathbf{H}$	Matrix column (N + 1, 1)
$\mathbf{M_1}$, $\mathbf{M_2}$	Matrix ((n + 1), (n + 1))
Min	Minimum
N	Number of layers
$NPHI$	Neutron porosity (−)
P	Pressure (Pa)
PFE	Photoelectric factor (m^2/electron)
r	Specific response of a well log tool
R	Petrophysical property
T	Temperature (K)
U	Volumetric photoelectric factor (m^{-1})
V	Mineral fraction (−)
v	Velocity (m/s)
ΔT	Transit time (s/m)
Tr	Trenton Group
$\mathbf{X}$	Matrix column (6, 1)
$\mathbf{x}$	Matrix column (N-1,1)

Greek Symbols

α	Ponderation weight
λ	Thermal conductivity (W/(m K))
φ	Porosity (−)

Subscripts

atm	Atmospheric
cal	Calcite
cl	Clay
dol	Dolomite
est	Estimated
fsp	Feldspar
i, j	Increment index
mes	Measured
N	Neutron
P	P wave
Qz	Quartz
sh	Shale
T	Transpose operator
W	Matrix of weights (6, 6)
w	Water

Gegenhuber and Schoen, 2012). Both approaches, have been discussed and compared by several authors (Hartmann et al., 2005; Clauser, 2006; Fuchs and Förster, 2014; Fuchs et al., 2015; Gegenhuber and Kienler, 2017). However, applications of the methods to well log databases from the oil sector remains limited. A few recent studies, used as examples for the present work, have shown reliable thermal

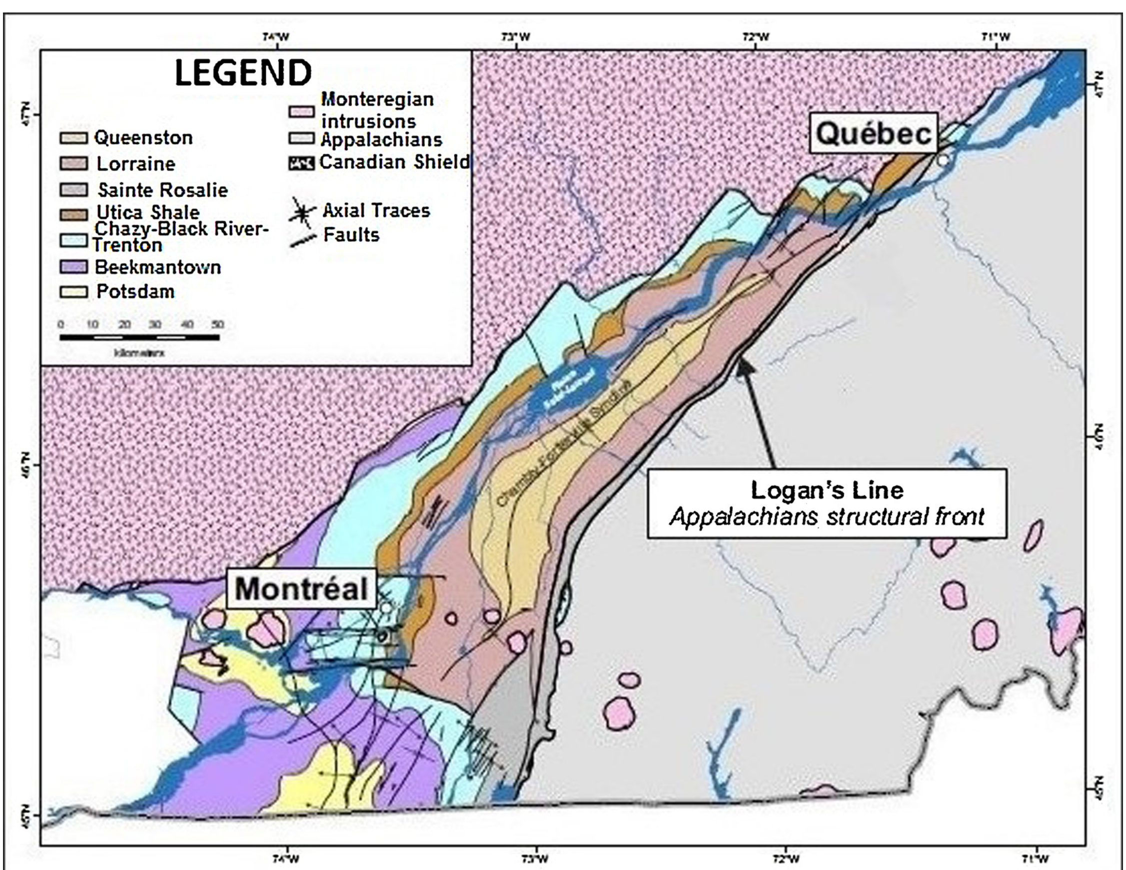

Fig. 1. Geological map of the SLL sedimentary basin (Globensky, 1987).