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Controls on the Distribution of Thermal Springs in the Canadian Cordillera

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ABSTRACT

Over 140 thermal springs occur in the Canadian Cordillera, the only region in Canada to have such features. With few rare exceptions these springs occur in the bottoms of the major valley systems. Thermal springs can be associated with: 1) volcanic belts, 2) non-volcanic high heat-flow regions, 3) crustal-scale brittle normal faults, and 4) anomalous structural features that locally create deep permeable pathways.

Stable isotope data indicate that all of these springs originate as meteoric water. The temperature of a thermal spring outlet reflects a combination of local geothermal gradient, circulation depth, and flow rate. Estimated circulation depths for springs in the Cordillera suggest circulation depths do not exceed 5 km. Models of deep crustal circulation suggest spring systems can not be used solely as an exploration tool for geothermal resources.

1. INTRODUCTION

The crustal-scale circulation of water is an important factor in heat transfer and mass transport, which leads to rock alternation, ore deposits, and the formation of local ecological niches at thermal spring outlets. The movement of water though the crust and processes that lead to the formation of discrete discharge zones is also of interest for exploration of geothermal energy potential. However, factors that control the development of a crustal-scale circulation system are not always clear, particularly in areas where magmatic activity is minimal or non-existent. This paper examines the controls on the distribution of thermal springs in the Canadian Cordillera, including the role of structural geology and fault plane geometry in low heat flow settings.

2. REGIONAL OVERVIEW

2.1 Geology

The Canadian Cordillera developed in response to the collision of island-arc terranes against the western margin of North America from Jurassic to Tertiary (Gabrielse and Yorath, 1991). The Cordillera is divided into 5 morphogeological belts that show variable heat flow (Figure 1a). These can be roughly defined as deformed sedimentary strata of either North American (Foreland belt) or island arc affinity (Insular and Intermontane belts) that are separated by welts of plutonic and high-grade metamorphic rocks (Coast and Omenica belts). Compressional deformation ended abruptly in the southern Cordillera during the Eocene. At this time crustal-scale extension faults formed in the SE Cordillera, with associated plutonism and volcanism (Armstrong, 1988; Gabrielse and Yorath, 1991). From Eocene to recent, the SW Cordillera has been affected by right-lateral strike-slip faulting. In addition, the Garibaldi volcanic belt developed from late Tertiary to Quaternary (Lewis and Souther, 1978).

2.2 Thermal Springs in Canada

The over 140 thermal springs in Canada occur only in the Canadian Cordillera (Grasby and Hutcheon, 2001) (Figure 1). Spring temperatures vary from 10°C (used as a minimum) to a high of 89°C, with an average of 40°C. The defined minimum temperature is based on 10°C above average annual air temperature or ground temperature in permafrost regions. With few exceptions they occur in the bottoms of major valley systems. While over 10 thermal spring resorts have been developed across the region, most sites occur in remote to very remote regions and are difficult to access without helicopter support. Many locations have only cryptic location and temperature information available and only 1/3 have detailed water geochemistry. For those with geochemistry, stable isotope data indicate that all of these springs originate as meteoric water (Figure 2). The high temperatures reflect circulation of groundwater to depth, where water is heated before returning to surface.

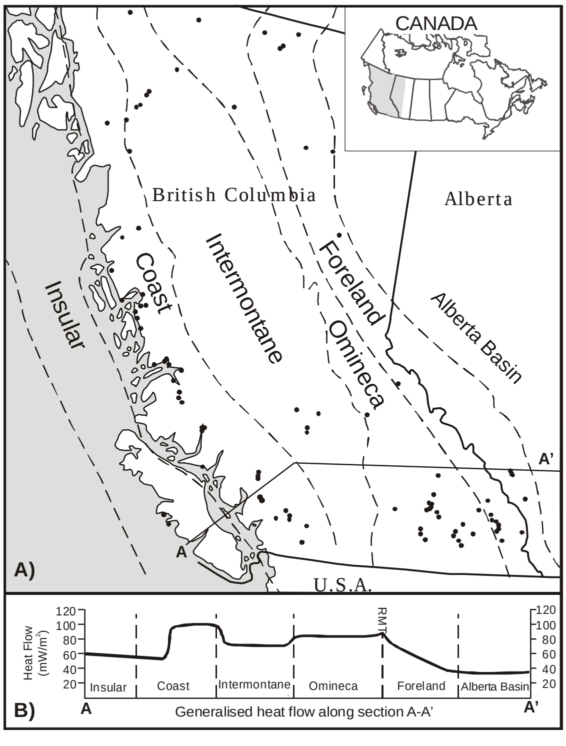

Figure 1: Location map showing distribution of thermal springs in Canada.

Unique aquatic ecosystems are a common feature of thermal spring outlets. The northern limit of most plant and animal species is often a function of climatic factors (e.g., how cold of a winter they can survive). In Canada's northern climate the discharge of thermal waters creates microclimates which often support rare and unique ecosystems. The warm microclimates of thermal springs allow plant species (e.g. the southern Maiden Hair Fern at the Fairmont Spring) to survive as isolated communities at climates much farther north than their normal distribution. There are also documented cases of unique animal species (e.g., the Banff Springs Snail) evolving to adapt to thermal waters (Grasby and Lepitzki, 2002). Along with hosting rare ecosystems, spring outlets often develop extensive travertine mounds as unique hydrogeologic features. These mounds are typically formed by calcium carbonate precipitating from solution in response to degassing of carbon dioxide (CO_2) as the waters equilibrate to atmospheric pressure (Grasby et al., 2003). Unusual precipitate mounds such as barite formation has also been noted (Bonny and Jones, 2008). Precipitate mounds are all relatively recent features formed since deglaciation ~10 ka.

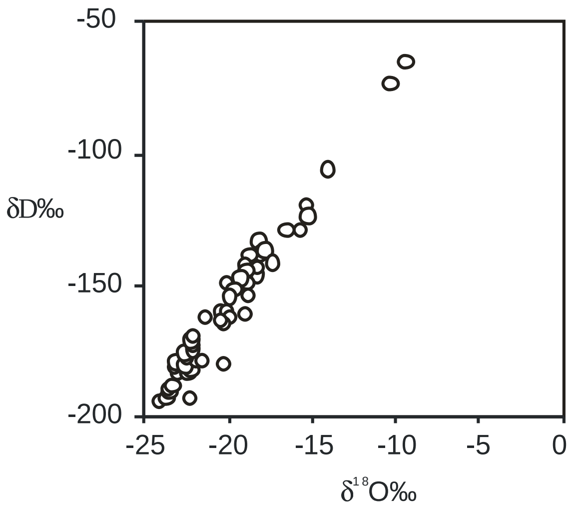

Figure 2: Plot of stable isotope data for thermal springs in Canada.

3. THERMAL SPRING DISTRIBUTION

Thermal springs in Canada are associated with: 1) volcanic belts, 2) non-volcanic high heat-flow regions, 3) crustal-scale brittle normal faults, and 4) anomalous structural features that locally create deep permeable pathways. Volcanic associated springs are consistent with areas of high heat flow, largely in western British Columbia (Clark, 1982). An anomalous high heat flow region occurs in the McKenzie Mountains of the Northwest Territories. While there are no volcanoes in this region the areas is characterized by active tectonics. Over 20 thermal springs are know in this region (Caron et al., 2008). Across southern British Columbia there are numerous thermal spring in moderate heat flow settings that are associated with crustal-scale normal faults associated with Eocene extension of the southern cordillera (Grasby and Hutcheon, 2001; Allen et al., 2006) (Okanagan, Columbia River, Slocan Lake, and Rocky Mountain Trench faults). High heat flow and high geothermal gradients are by no means a prerequisite for thermal spring occurrence, several spring sites are found in the lowest heat flow regions of the Cordillera. The Banff Hot Springs (Grasby et al., 2003) occur in a region of thin skinned tectonics, low heat flow, and low geothermal gradients. Previous work has shown the occurrence of these springs is related to an anomalous lateral ramp on the Sulphur Mountain Thrust fault which locally creates a high permeably pathway allowing deep crustal circulation (Grasby and Hutcheon, 2001). Similarly, to the south of this site a thermal spring in the same geothermal setting is associated with a lateral ramp on the Misty Thrust.

Faults play an important role in the development of thermal springs. Large crustal-scale faults are characterised by a core zone of highly deformed material that is generally broken into small grain sizes (fault gouge, cataclasite, etc.) (Cain et al., 1996). This core zone is surrounded by a damage zone where the protolith is less deformed, but still heavily fractured and characterised by the development of small subsidiary faults. The fault core and damage-zone have contrasting effects on the bulk permeability of the protolith. The fault core tends to decrease permeability, whereas the damage zone enhances permeability. The net effect is an anisotropic permeability structure, where permeability will be higher along the fault plane than across it. The degree of anisotropy will be a function of the relative development of the core and damage zone of the fault. In ideal cases faults become combined conduit/barrier system. These fault types are the most effective in developing spring systems as they inhibit fluid flow across the fault and focus it along the fault. Thus, a major control on the depth to which water circulates in a spring system can be the depth at which the fault occurs beneath the recharge area (Grasby and Hutcheon, 2001).

Thermal springs associated with crustal-scale normal faults and other large fault zones typically are offset from the fault core and are associated with parallel subsidiary faults, consistent with this model of fault plane permeability structure. While numerous thermal springs can be aligned parallel to these large crustal structures, springs are typically found at the intersection of two fault systems, suggesting that these intersecting structures can form particularly effective permeability pathways.

4. CONTROLS ON OUTLET TEMPERATURE

The temperature of a thermal spring outlet reflects a combination of local geothermal gradient, circulation depth, permeability structure, and flow rate. Variability in heat flow and geothermal gradients in the southern Rocky Mountain Trench can be seen to affect thermal springs as shown by Allen et al. (2006). A lower gradient requires greater circulation depths for groundwater to obtain heat. However the ultimate depth of groundwater circulation is typically restricted by the strength of the rock that groundwater is flowing through. Previous studies have shown that permeability is significantly reduced at depth (Ingebritsen et al., 2006). Increasing stress at depth closes fracture networks inhibiting circulation. Empirical evidence from petroleum fields suggests a practical limit for circulation is around 5 km, which is consistent with the deepest estimated circulation depths for springs in the Canadian Cordillera (Grasby and Hutcheon, 2001; Caron et al., 2008). However geological evidence suggests potential circulation to depths of 10 km in areas of active extensional tectonics.

Permeable networks are critical to development of a deep circulating spring system and they also play an important role in influencing the outlet temperature of a spring. Modeling by Foster and Smith (1988a, b) and Ferguson et al. (2009) show that the bulk permeability of country rock can have a strong influence on spring outlet temperature. A permeability 'window' exists in which conditions are ideal to form thermal spring outlets. At lower permeabilities the water flux is reduced and heat flow is transferred predominantly by conduction. At higher permeabilities the high advective heat flux suppresses the geothermal gradient, leading to lower outlet temperatures. Likewise, fault zone permeabilities in excess of 10^{-13} are needed to transmit water to surface without losing heat along the flow path (López and Smith, 1996).

Models created as part of the current study considering variations in permeability with depth as described by Ingebritsen and Manning (1999) suggest that finding these windows could be more difficult in practice. The models were of the same form as those described in Ferguson et al. (2009), with a 45 degree fault dipping toward the east from the top west corner of the model (Figure 3) and identical boundary conditions. Those boundary conditions included: fixed hydraulic heads corresponding to a linear decrease topography from 2500 m to 0 m across the top of the models; zero fluid flux boundaries along the sides and base of the models; a fixed temperature of 10^{o}C across the top of the model; zero heat flux through the sides of the models; and a heat flow of 60 mW/m^2 across the base of the models. No heat flow was permitted through the sides of these simulations. Models were extended into three dimensions by considering flow along the strike of the fault. Flow was focused into a spring by reducing the permeability of the fault to that of the country rock at the surface for all but a 10 m by 10 m area at one end of the model. These integrated finite difference models had grid block sizes ranging from 5 m x 5 m x 5 m where the fault outcropped to 400 m x 400 m x 1000 m at depth in the corner opposite the spring. Boundary conditions considered in these models included fixed hydraulic heads corresponding to a linear decrease in hydraulic head from 1000 m to 0 m across the top of the model and zero flux boundaries along the sides and base of the model. A fixed temperature of 10^{o}C was applied across the top of the model and a heat flow of 60 mW/m^2 was applied across the base of the models. No heat flow was permitted through the sides of these simulations.

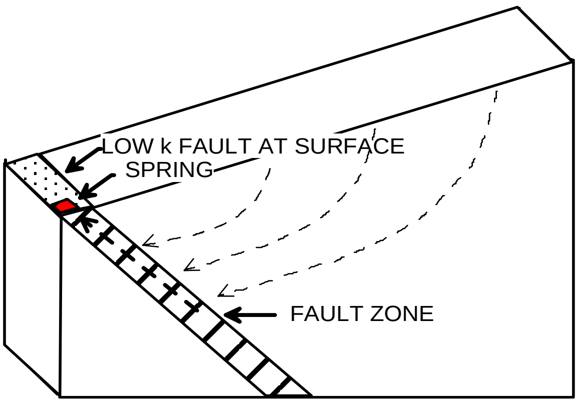

Figure 3: Conceptual model used for numerical models produced in this study.

Simulations including this permeability-depth relationship had less fluid flow at depth, resulting in higher temperatures in deeper areas of the model. Note that although the equipotentials at depth are more closely spaced in Figure 4a, the velocities are in fact much lower because permeability is lower by approximately an order of magnitude. The opposite is true at the top of the model because the permeabilities are several orders of magnitude greater in Figure 4a. As a result, these higher temperatures at depth did not result in higher spring temperatures. Discharge temperature in the simulation where permeabilities were constant with depth was 21.5^{o}C and only 16.1^{o}C in the simulation using a depth dependent permeability. Note that some of this detail is not apparent in the diagram because of the interpolation method used. It is not currently clear that the general relationship proposed by Ingebritsen and Manning, which used data that was global in scope, strictly applies to crustal-scale faults and the surrounding country rock.

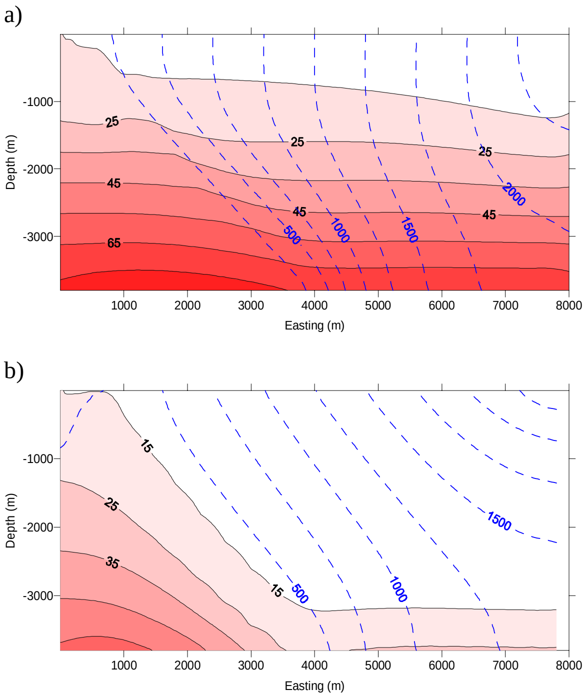

Figure 4: Simulated distribution of temperature (shaded contours) and head (dashed lines) for a) a fault permeability of 10^{-13} m^2 and a country rock permeability of 10^{-16} m^2 at 3800 m and permeabilities at other depths described by a scaled version of the permeability-depth relationship presented by Ingebritsen and Manning (1999) in the cross-section containing the spring and b) a situation with uniform permeability for the country rock and fault set at the geometric mean of a).

5. CONCLUSIONS

Thermal spring distribution in low heat flow regions of Canada is controlled by fault permeability allowing deep circulation of meteoric water that is heated before return to surface. Deep advective systems can have a cooling effect on the crust which may lower geothermal resource potential. The occurrence of thermal springs may not always be a good indicator of geothermal potential of a region.

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