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Origin of warm springs in Banks Peninsula, New Zealand

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ABSTRACT

Thermal springs present rare opportunities to locate and interpret the geological drivers of upper-crustal fluid flow. Interpreting the conditions through which crustal fluids are heated and released to the surface is important for advancing our understanding of crustal deformation and geothermal resource potential across tectonic contexts. In New Zealand, the majority of thermal springs are associated with magmatic-hydrothermal systems in the central North Island or with the rapidly uplifting bedrock in the South Island's convergent fault systems. However, low enthalpy systems outside of these areas represent attractive targets for potential geothermal resource development. The low enthalpy warm springs of Banks Peninsula, located immediately adjacent to Christchurch, represent a highly understudied but potentially significant resource to the South Island's most densely populated metropolitan area. Hosted within the eroded 11–5.8 Ma volcanic complex of Banks Peninsula, these warm springs (14.5–33.6 °C) represent an anomalous hydrothermal system that has been perturbed by the 2010–2016 Canterbury Earthquake Sequence (CES). The February 22, 2011, Mw 6.2 earthquake induced observable changes to the Banks Peninsula warm springs system, including the appearance of new warm springs within the peninsula's north-western Hillsborough Valley. We assess the origins of the volcanically-hosted Banks Peninsula warm springs post-CES using an integrated isotopic, geochemical, and soil gas flux approach. Additionally, we elucidate the tectonic context and geological drivers of upper-crustal fluid flow in the Banks Peninsula warm spring system. Aqueous phase emissions from the springs predominantly plot within the $Na^+ + K^+/HCO_3^-$ type waters and exhibit $\delta^{18}O$, δD, and $\delta^{13}C$ values of −8.30 to −9.26‰ V-SMOW, −60.15 to −64.19‰ V-SMOW, and −12.37 to −15.06‰ V-PDB, respectively. Soil gas flux surveys of the springs at Rapaki Bay revealed CO_2 fluxes that average 6.93 ± 10 gm^{-2} day^{-1}, with an average $\delta^{13}C$ value of −19.81 ± 5‰ V-PDB, and CH_4 fluxes that average 5.58 ± 12 gm^{-2} day^{-1}, with an average $\delta^{13}C$ value of −59.52 ± 1‰ V-PDB. Our results suggest that the Banks Peninsula warm springs are a structurally controlled, upper-crustal metamorphic hydrothermal heated system, sourced from high-altitude Southern Alps derived meteoric waters. Carbon isotope compositions of gaseous emissions associated with the Banks Peninsula thermal springs are consistent with an upper-crustal metamorphic decarbonation and decarboxylation carbon source. Based on their geochemistry, we propose that the Banks Peninsula warm springs should be considered an outboard extension of the South Island's plate-boundary hydrothermal system. Such connectivity implies that long-lived low-enthalpy geothermal resources may be associated with permeable and distributed fault networks in the periphery of convergent margins.

1. Introduction

Hydrothermal systems have been shown to be a major contributing factor to the development of geological faults and processes which influence earthquake rupture cyles (e.g., Sutherland et al., 2017), and tectonic-hydrothermal systems represent potentially attractive low-enthalpy geothermal resource targets (e.g., Guglielmetti et al., 2013). Many similar systems, associated with active deformation along the Australian-Pacific plate boundary, are present on New Zealand's South Island (Fig. 1A; Beyssac et al., 2016; Cox et al., 2015; Horton et al., 2001; Menzies et al., 2016; Reyes et al., 2010). However, the geological drivers behind the presence of warm springs on Banks Peninsula,

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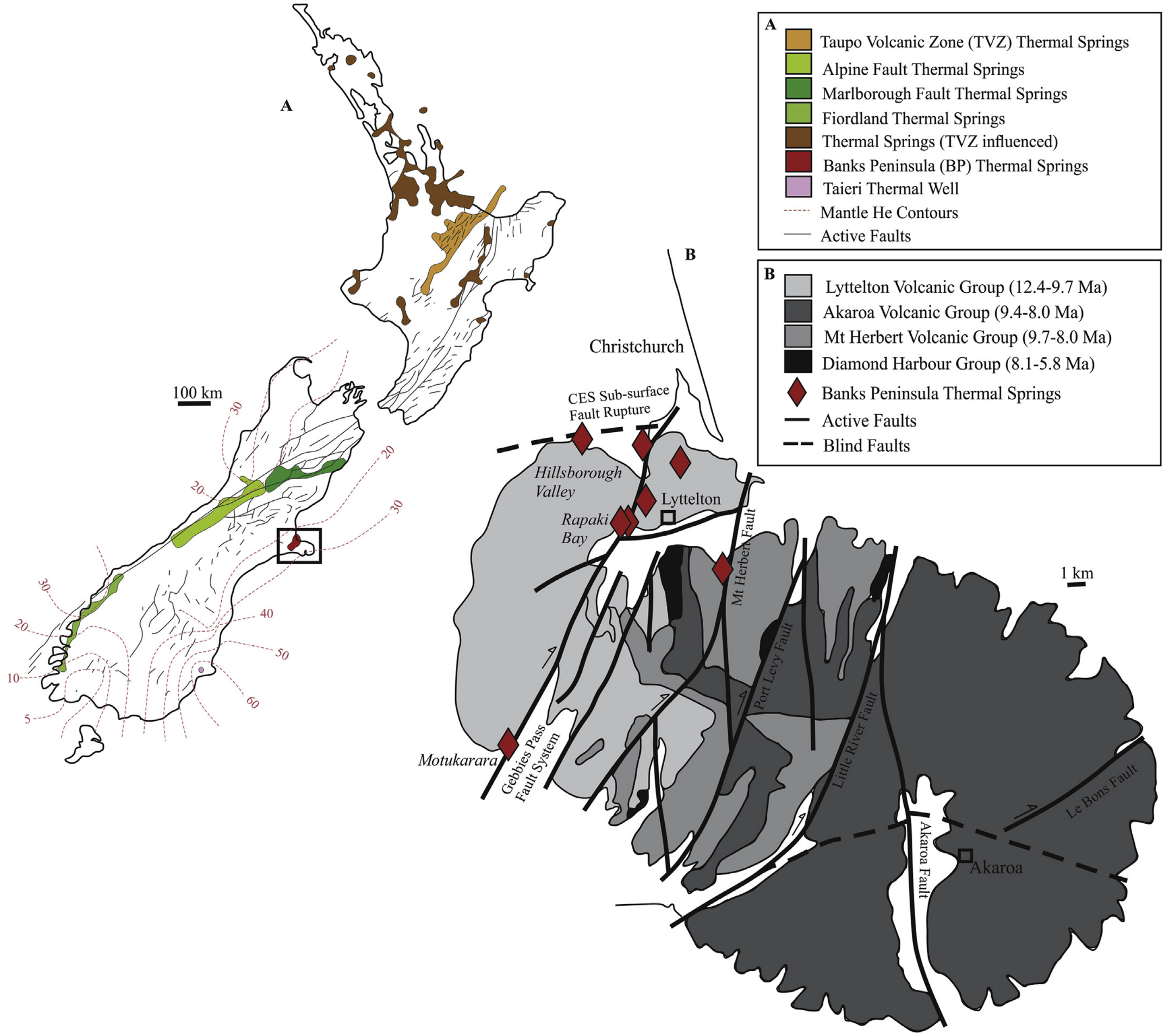

Fig. 1. **A**) Location of study area within the national hydrothermal context of New Zealand. Banks Peninsula (outlined) in the context of mantle He (Hoke et al., 2000). B) Simplified local geology and location of previously reported warm springs of the Banks Peninsula area. Hillsborough Valley, Rapaki Bay, and Motukarara indicate the sample sites of this study.

east coast South Island, remain unknown (Reyes and Jongens, 2005).

Despite the highly eroded Banks Peninsula being comprised of four geochemically distinct volcanic groups (Brown and Weeber, 1994; Hampton et al., 2012; Sewell et al., 1992), the area's warm springs are only observed along the Mt Herbert fault (dextral strike-slip), Gebbies Fault system (normal) and from hydrogeological effects of the Canterbury Earthquake Sequence (CES) subsurface fault rupture (reverse; Fig. 1B). These deformational systems are located within the structurally controlled trachytic-basaltic Lyttleton Volcanic Group (11–9.7 Ma; Beavan et al., 2011; Hampton, 2010; Ring and Hampton, 2012) and are considered to be related to the larger regional Canterbury Horst structure of the deformed slightly metamorphosed argillite and greywacke torlesse of the Rakaia terrane (Forsyth et al., 2008; Ring and Hampton, 2012; Sewell et al., 1992). The Rakaia terrane, which directly underlies the Lyttelton Volcanic Group and encompasses a large section of the South Island including sections of the Southern Alps, is known to host thermal waters that are driven by structural controls directly related to the South Island's plate-boundary system (Barnes et al., 1978; Craw et al., 2013; Horton et al., 2001).

The February 22, 2011, Mw 6.2 earthquake subsurface fault rupture occurred beneath the northwestern flank of Banks Peninsula (Forsyth et al., 2008; Kaiser et al., 2012; Mortimer, 2004; Quigley et al., 2016). Associated effects of this major seismic event include: 1) establishment of groundwater springs in the north-western Hillsborough Valley; and 2) increased activity and localised expansion of pre-existing warm springs at Rapaki Bay and Motukarara (Fig. 1B; Green, 2015; Griffin, 2016; Kaiser et al., 2012). The hydrogeological effects of the CES present a unique opportunity to describe and interpret the upper-crustal fluid flow system responsible for these springs. Here, we utilise aqueous