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Snapshot of hot-spring sinter at Geyser Valley, Wairakei, New Zealand, following anthropogenic drawdown of the geothermal reservoir

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ABSTRACT

From the 1950s, extraction of thermal fluids to generate electricity at Wairakei, Taupo Volcanic Zone, New Zealand, heralded a rapid transformation of surface manifestations at nearby Geyser Valley, 1 km NW of the power station. Active geysers and hot-springs fed by alkali-chloride waters ceased by 1968, replaced by acidic steam-dominated conditions. Field relationships indicate geothermal features are fault-controlled. Siliceous hot-spring (sinter) deposits represent spring-vent to distal marsh settings. The dominant mineralogy is opal-A, with some minor clay alteration. Some textures show silica dissolution and re-precipitation. Thus, only minor alteration and diagenesis has occurred, with vegetation overgrowing the extinct sinter.

1. Introduction

Terrestrial geothermal systems tapping reservoirs with temperatures >230 °C commonly occur in active volcanic terrains where plumes of magmatically heated meteoric waters circulate to depths of several kilometres in the shallow crust (Bibby et al., 1995). The impressive surface manifestations of geothermal systems – erupting geysers, effervescing hot-springs, steaming fumaroles, bubbling mud pools and strikingly coloured ground – are of significant scientific, economic, recreational and cultural value in New Zealand. Numerous scientific studies have focused on terrestrial geothermal environments owing to their unique habitats and biota, where extremophile microorganisms flourish in the high temperature and widely variable pH of geothermal areas (Handley and Campbell, 2011; Capece et al., 2013). These geothermal settings serve as extreme environment analogues for the development of early life on Earth (e.g., Westall et al., 2015; Djovic et al., in press), and for exploration for life on other planets (e.g., Farmer and Des Marais, 1999; Farmer, 2000; Preston et al., 2008; Ruff et al., 2011; Ruff and Farmer, 2016).

Geysers and many hot-springs are fed by clear, near neutral pH, alkali-chloride, near-boiling waters oversaturated in silica and typically form sinter at the Earth's surface (Fournier and Rowe, 1966; Weir et al., 1992). Specifically cooling and evaporation around geysers and spring-vent discharge sites cause precipitation of hydrous, non-crystalline opal-A (White, 1967; Jones and Renaut, 2003a,b; Jones et al., 2011). Discharging thermal fluids will precipitate silica and effectively entomb anything in their path; thus, the preservation of physical, chemical and biological signatures in sinters make them valuable records of the environmental, geothermal and geologic processes operating during periods of hot-spring activity (Cady and Farmer, 1996; Lynne et al., 2005, 2008; Handley and Campbell, 2011; Lynne, 2012; Campbell et al., 2015a,b). Sinter facies models correlate distinct macro- and microscopic textures to positions upon the cooling discharge apron (~100 °C to ambient) (e.g. Walter, 1976a,b; Cady and Farmer, 1996; Jones and Renaut, 1996; Jones et al., 1997, 1998; Campbell et al., 2001; Lowe et al., 2001; Guido and Campbell, 2011; Lynne, 2012). In particular, sinter facies assemblages may be broadly grouped into three main categories: vent and proximal slope (>65 °C), mid-apron (<65–45 °C) and distal apron to marsh (<45 °C) (cf. Campbell et al., 2015a, their Fig. 2). In addition, the term geyserite is used here to describe siliceous micro-stromatolites restricted to vent/near-vent areas of geysers and hot springs (Campbell et al., 2015a).

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Upon evaporation of surging, splashing and spraying vent waters (~100 °C), geyseritic sinter typically occurs as columns, spicules and nodules of upwardly-convex, finely and densely laminated silica (White et al., 1956; White, 1967; Walter, 1976a). These high temperature deposits develop from complex abiotic-biotic processes, whereby silica precipitates upon the nucleation surfaces provided by microbial biofilms (Jones and Renaut, 2003a), although microbial evidence may be poorly preserved or destroyed by silica infill in the resulting geyserite build-up (e.g. Walter, 1976a; Handley et al., 2005; Campbell et al., 2015a).

Over time all siliceous sinters naturally undergo a series of silica mineral phase transformations (diagenesis) coupled with the loss of structural water, such that non-crystalline opal-A transitions to opal-A/CT, then to paracrystalline opal-CT opal-C ± moganite, and finally to microcrystalline quartz (Herdianita et al., 2000a,b; Lynne and Campbell, 2003; Jones and Renaut, 2004; Lynne et al., 2005, 2006, 2007, 2008). As hot water ascends within a geothermal system, the ambient hydrostatic pressure progressively decreases until boiling occurs, causing separated H_2S and CO_2 to rise with the resultant steam, dissolving in the steam condensate and perched waters at the ground surface or in the shallow subsurface (Nicholson, 1993). The H_2S oxidises to produce acid sulphate waters that are capable of dissolving their host rocks (Ellis and Mahon, 1977; Nicholson, 1993; Rodgers et al., 2000, 2002, 2004). Acidic steam condensates may react with earlier deposited siliceous sinter to accelerate diagenesis, causing surface corrosion of silica but precipitating it elsewhere as opal-A, -CT, chalcedony or quartz (Lynne et al., 2005, 2008; Jones et al., 2011). A lowering of the steam-water interface will expand the zone occupied by acid sulphate waters, affecting the character of the surface manifestations by a change in pH, temperature, flow rates, and affiliated microbial communities (e.g., Allis, 1981; Simmons et al., 1992; Schinteie et al., 2007; Handley and Campbell, 2011).

At Wairakei in the 1950s, the discharge of exploratory and test drill holes lowered the reservoir pressure and caused a drawdown of the geothermal reservoir. Drawdown accelerated after 1958, when the first geothermal power station at Wairakei was commissioned. With a decline in reservoir pressure, the link between deeply derived thermal waters and the surface geysers and hot springs was effectively severed (Glover, 1977), resulting in a stark transformation of surface thermal activity at nearby Geyser Valley, a popular tourist attraction. Actively playing geysers and discharging hot springs were replaced by empty geyser vents, fumaroles and steaming ground. With a known date for the cessation of aqueous geothermal activity (1968), and therefore the end of sinter formation, sinter deposits at Geyser Valley provide a record of incipient sinter alteration and diagenesis in the transition to a steam-heated acid-dominated regime.

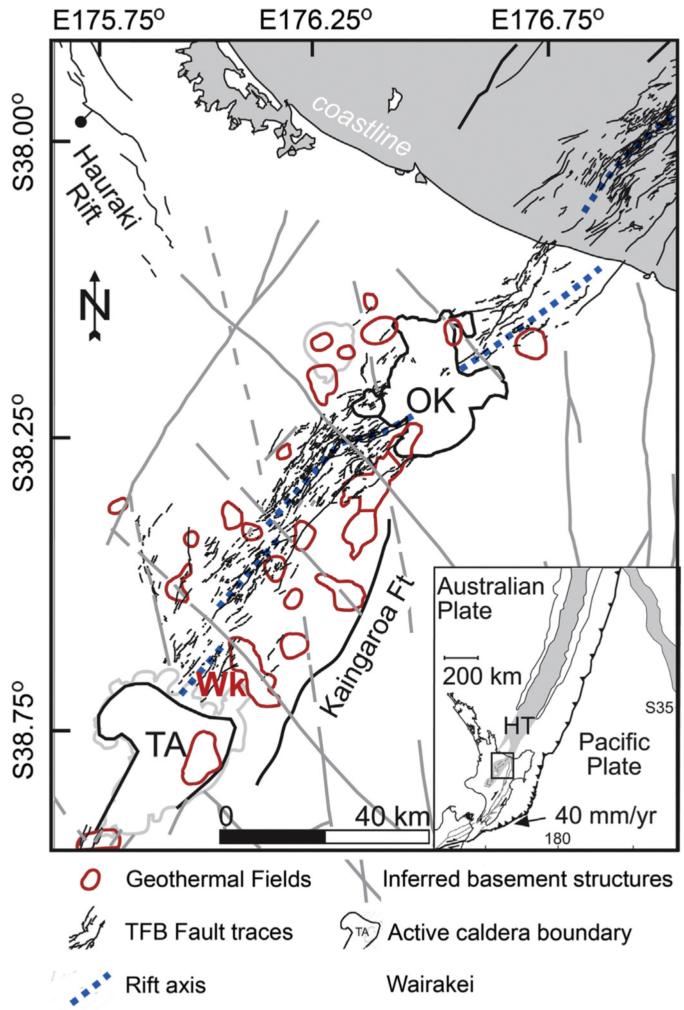

Fig. 1. Map of the Taupo Volcanic Zone (TVZ) showing geothermal fields as indicated by low resistivity boundaries (red outlines), active faults, rift segments and inferred boundaries (black outlines) of the Taupo (TA) and Okataina (OK) active calderas (after Nairn et al., 1994). The Taupo Fault Belt (TFB) is oriented parallel to the SW–NE structural grain of the TVZ and accommodates extensional strain of the rift. Accommodation zones between rift segments are interpreted as basement structures oriented NW-SE (after Wan and Hedenquist, 1981; Rowland and Sibson, 2004). The Geyser Valley study area (star) is located near the northeastern boundary of the Wairakei geothermal field (Wk), in an accommodation zone between rift segments. Inset shows location of the TVZ in relation to the active Hikurangi subduction margin to the east and the Havre Trough (HT) to the north of North Island, New Zealand.

2. Geological and historical context

2.1. Geotectonic setting of the Taupo Volcanic Zone

The Taupo Volcanic Zone (TVZ) extends 200 km in a SW–NE direction through central North Island, New Zealand (Fig. 1) (Wilson et al., 1995; Wilson and Rowland, 2015). This volcanic arc-backarc system constitutes the southernmost expression of the Tonga-Kermadec volcanic arc system, and is undergoing active extension in a NW–SE direction (~8 mm/a) (Rowland and Sibson, 2001, 2004), driven by subduction of the Pacific Plate beneath the Australian Plate (Ellis and Mahon, 1977). Mesozoic greywacke and argillite meta-sediments comprise the basement of the TVZ and are overlain by voluminous Quaternary (<1.6 Ma) volcaniclastic sediments up to several kilometres thick (Wilson et al., 1995). Within the volcaniclastic units of the TVZ, at least 22 convective geothermal plumes occur, channelling anomalously high heat flow (2600 MW/100 km) to the surface, the product of Quaternary volcanism and a thin underlying lithosphere (Fig. 1) (Bibby et al., 1995; Hochstein, 1995; Bibby et al., 2009; Dempsey et al., 2011). An array of active faults accommodate extensional strain across the TVZ parallel to the orientation of the rift, and are collectively referred to as the Taupo Fault Belt (TFB) (Rowland and Sibson, 2001; Rosenberg et al., 2009a). These faults are dominantly NE-striking (Fig. 1), steeply dipping (typically >60°) normal faults associated with major structural depressions in the underlying basement. As in most rift systems, the normal faults of the TFB are partitioned into distinct segments separated by accommodation zones (Fig. 1), suggested to transfer tensional strain between sets of faults (Rowland and Sibson, 2004). These accommodation zones potentially indicate the presence of transverse faults within the underlying basement, oriented approximately parallel to the direction of extension across the TVZ. The spatial distribution of geothermal systems in the