A NEW INVESTIGATIVE APPROACH TO UNDERSTANDING FLUID FLOW MIGRATION PATHWAYS WITHIN THE SHALLOW SUBSURFACE AT ORAKEI KORAKO, NEW ZEALAND.

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ABSTRACT

Sinter analyses, infrared imaging, downhole temperature measurements and Ground Penetrating Radar (GPR), were undertaken in 2012 at Orakei Korako, Taupo Volcanic Zone, New Zealand to investigate the inter-relationship of chemistry, temperature and texture of sinters at shallow subsurface depths (<5 m). Sinter mineralogy and morphology was used to distinguish sinter affected by post-depositional overprinting of acidic steam condensate from unaltered sinter. Ground Penetrating Radar (GPR) imaged strong-amplitude reflections over unaltered sinter deposits and weak-amplitude reflections where the sinter had been altered via acidic steam condensate. GPR also imaged subsurface discontinuities interpreted as conduits for ascending steam, which were confirmed by measured downhole temperatures of >90 ˚C. Infrared imaging of individual sites within the geothermal area provided further information on surface temperatures at Orakei Korako. This new multi-method approach identified: (i) areas of heat in the subsurface where there is no present-day evidence of heat in the shallow surface, and (ii) areas of sustained heat in the subsurface as evidenced by the high level of acidic steam condensate overprinting of surface sinter deposits. Repeated surveys will identify if the surface and shallow subsurface conditions mapped in 2012 are changing and map areas of the field that are heating up or cooling down with time.

1. INTRODUCTION

Numerous surface features are present at Orakei Korako geothermal field, which is located within the Taupo Volcanic Zone (TVZ), New Zealand (Fig. 1). Thermal activity is dominated by alkali chloride features typically hot springs and pools and expansive sinter terraces. Sinters are hot spring rocks formed as silica precipitates and accumulates from discharging alkali chloride hot spring waters (Fournier and Rowe, 1966; Fournier, 1985; Williams and Crerar, 1985; Lynne 2005). Acid features such as mud pools, fumaroles, and steaming ground are also found at Orakei Korako.

Lloyd (1972) provides a first detailed account of the surface thermal activity at Orakei Korako, followed by Hamlin (1999). Surface thermal activity is sensitive to even subtle changes in hydrology. For example, a decrease in reservoir pressure can be reflected at the surface by an increase of discharging steam and gas and a decrease in flow rate of alkali chloride hot springs, as seen in many fields exploited for electricity generation (e.g., Bixley et al., 2009).

Often when discharging alkali chloride hot spring water has ceased, steam and gases ascend through the sinter and discharge at the surface by way of fumaroles or steaming ground. As the ascending steam and hydrogen sulphide gas mix with atmospheric oxygen it forms sulphuric acid and is referred to as acidic steam condensate. This acidic condensate descends through the ground and/or sinter dissolving or altering the surrounding rock. Clay minerals may form from this alteration process or dissolution textures in rock and sinters such as pitting of surfaces can result (Lynne et al., 2008).

Sinter undergoes diagenesis through a series of silica phase transformation from opal-A to opal-A/CT to opal-CT ± opal-C to quartz (Lynne et al., 2005, 2007). Such transformations require both heat and a fluid medium to move silica within the micro-pores of the sinter (Iler, 1979). Acidic steam condensate overprinting supply both heat and fluid to a pre-existing sinter and can accelerate sinter diagenesis (Campbell and Lynne 2006; Lynne et al., 2006).

Siliceous sinter deposits are an important geothermal exploration surface feature as sinters can be associated with both extinct and active vents of geothermal fluid. Sinters remain at the surface for thousands of years after discharging hot spring fluid ceases. Potentially usable resources can remain at depth for many thousands of years after hot spring flow stops. While sinters generally form from discharging alkali chloride hot spring water, they can also form from silica-rich but chloride-poor discharging hot springs (Sepulveda et al., 2004). Sinters preserve evidence of changing hydrological conditions and particularly changes in fluid type (water versus steam) and temperature.

GPR profiles can show high- moderate- or low-amplitude reflections, depending on the subsurface rocks. Strong competent materials that are relatively continuous laterally and unaltered such as siliceous sinter deposits (including all silica phases from opal-A to quartz) produce strong- or high-amplitude reflections which appear as white or grey colours (see Figs. 4-7). Moderately-altered rocks produce green and yellow coloured GPR reflections (see Figs. 4-7). Highly-altered rocks such as rocks rich in clays produce weak- or low-amplitude reflections which appear as black or red coloured reflections (see Figs. 4-7). Vertical fractures or conduits where steam and/or water can ascend to the surface appear as vertical black areas.

This study outlines a new approach to mapping shallow subsurface fluid flow migration pathways by combining sinter analyses with Ground Penetrating Radar (GPR), downhole temperature measurements and infrared imaging. Mapping subsurface fluid flow migration pathways can be challenging but it is important to establish shallow subsurface geothermal fluid flow trends as it provides useful information as to whether a system is discharging or cooling down or whether a system's boundaries are shifting with time.

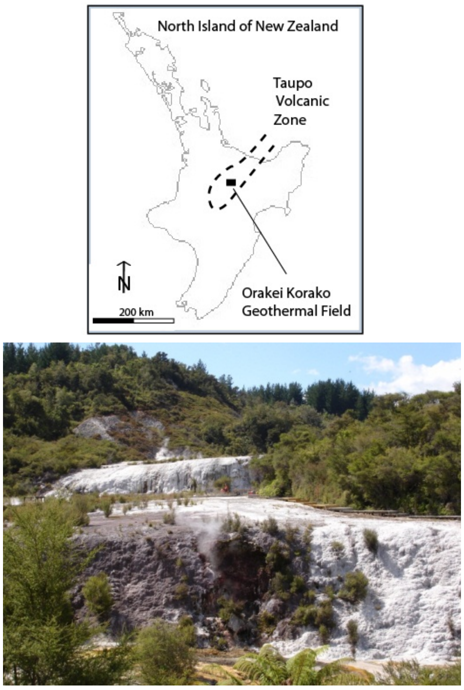

Figure 1: Location map of Orakei Korako within the Taupo Volcanic Zone, North Island of New Zealand, and photograph of extensive sinter terraces at Orakei Korako.

2. METHODOLOGY

2.1 X-Ray Diffraction (XRD)

XRD was used to determine the silica phase within a sinter and the degree of silica phase maturation, which is calculated using the Full Width and Half Maximum value (FWHM; Lynne et al., 2005). XRD operating conditions were 40 kV and 20 mA, using CuKα radiation (λα1=1.54051 Å). Dry, untreated samples were scanned at 0.6°2θ/min, with a step size of 0.01°, from 10–40°2θ.

2.2 Scanning Electron Microscopy (SEM)

SEM was used to examine the morphological characteristics of the sinter. Each sample was mounted on aluminium stubs using epoxy resin and coated with platinum. Energy Dispersive Spectroscopy (EDS) was performed on samples to provide quantitative data on the elemental composition of the sample.

2.3 Ground Penetrating Radar (GPR)

The GPR unit used was a GSSI SIR-2000 with a GSSI 200 MHz antenna. Settings included continuous run mode, range of 200 ns, and a dielectric constant of 6 over ground surfaces.

2.4 Downhole Temperature Measurements

Downhole temperature measurements were taken at depths of 0.5 m, 1.0 m and 1.5 m using a GSI Ltd designed K-type digital temperature probe incorporating a quick response tip.

2.5 Infrared Imaging (IR)

IR imaging was performed using a TI32 infrared (IR) camera which is sensitive within the 8-14 µm wavelength band with an accuracy of ±2°C. The emissivity value used was 0.85, the background temperature was adjusted to ambient air temperature and 100% transmission value.

3. RESULTS

3.1 Downhole temperature measurements

0.5, 1.0 and 1.5 m deep downhole temperature data were collected at 29 sites to establish the ground temperatures in the shallow subsurface (Fig. 2). In the study area temperatures ranged between 13 to 100 °C at 0.5 m depth, 15 to 100 °C at 1.0 m depth and 16 to 100 °C at 1.5 m depth.

3.2 Mapping shifting fluid migration pathways using sinter analysis, downhole temperature measurements, infrared imaging and GPR.

Downhole temperature measurements, infrared imaging, GPR and sinter analyses were performed at nine sites at Orakei Korako in 2012 (Figs. 2 and 3) and offer a new investigative method for establishing heat flow migration pathways in the shallow subsurface. At Orakei Korako the nine sites could be divided into 2 categories: (1) Thermal activity in the shallow subsurface with no evidence of steam overprinting in the sinter at the surface and (2) Significant thermal activity in the shallow subsurface and evidence of steam overprinting the sinter at the surface.

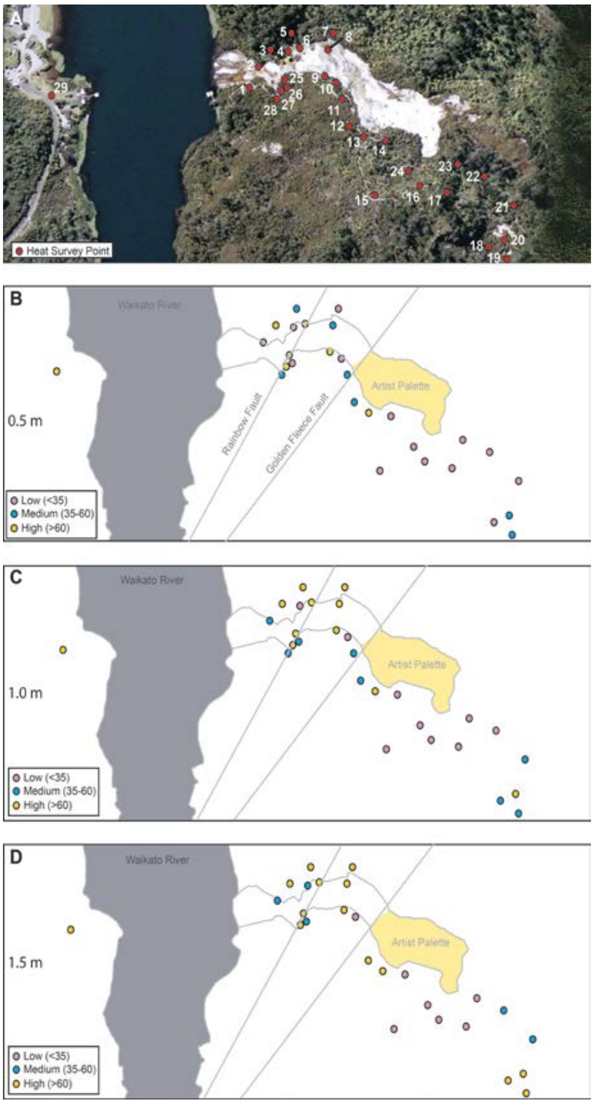

Figure 2: Downhole temperature measurement sites for the Orakei Korako survey in 2012. (A) Location map of subsurface temperature data collected in June and July 2012. (B) Measured temperatures at 0.5 m depth. (C) Measured temperatures at 1.0 m depth. (D) Measured temperatures at 1.5 m depth. Measured temperatures are separated into low-temperature <35 °C (pink dots), mid-temperature, 35-60 °C (blue dots) and high-temperature, >60 °C (yellow dots).

Figure 3: Map showing location of the 29 GPR transects collected at Orakei Korako. Orange line indicates direction of GPR profile

3.2.1 Heat in the shallow subsurface with no evidence of heat overprinting in the sinter at the surface

Case study 1: Site G24

Site G24 is located adjacent to Soda Fountain (Figs. 3 and 4). This hot spring contains near-neutral, alkali chloride water with a temperature around 100 ˚C. It discharges into a well-constrained channel. Intermittently the discharge channel overflows and thermal water flows over the surrounding area building up a sinter apron (Fig. 4A). Sinter was collected from the apron beside the discharge channel at the 2 m mark on the GPR transect line (arrow on Fig. 4A). XRD analysis of the sinter showed it to consist of opal-A silica with a FWHM value of 7.5 °2θ. SEM examination of the sinter revealed an unaltered, newly-forming, sinter with two generations of opal-A spheres where the older spheres are 2.0 µm in diameter and the younger opal-A spheres are 0.5 µm diameter (Fig. 4C-E).

Infrared imaging of the ground surface showed minor areas of elevated temperature (20-25 ˚C: Fig. 4B). A downhole temperature measurement of 52 °C at 1 m depth was collected on the edge of the sinter apron (T-profile on Fig. 4A-B).

A 4 m long GPR profile (Fig. 4F) was taken over the sinter apron (Fig. 4A-B). Strong-amplitude, horizontal reflections captured directly over the sinter outcrop indicate unaltered sinter persists to a depth of around 1.0 m. Below this depth the reflections weaken and may indicate steam alteration overprint of a sinter deposit or a transition from sinter to another lithologic unit.

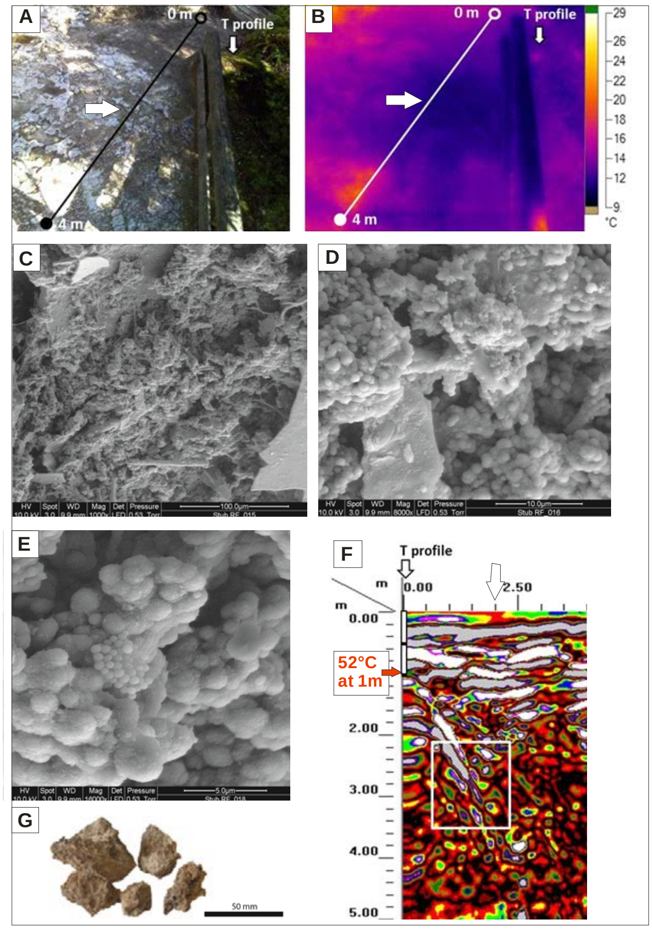

Figure 4: Site G24. (A) Site photograph shows 4 m GPR transect line (G24) located over sinter apron by Soda Fountain. T-profile = site of downhole temperature measurement. Arrow = location of sinter sample at the 2 m mark along the GPR transect line. (B) Infrared photograph. (C-E) SEM images. (C) Overview of unaltered opal-A sinter. (D-E) Well-formed, opal-A spheres with diameters of ~ 2 µm as well as newly-formed, younger opal-A spheres with diameters of ~ 0.5 nm. (F) Strong-amplitude reflections (white and gray areas) dominate the upper 1.2 m of the GPR reflection profile while an abrupt change to medium- (yellow and green areas) and low-amplitude reflections (red and black areas) are visible below 1 m depth. Downhole temperature measurement revealed 52 °C at 1 m depth. (Box = bow-tie effect from EM waves. (G) Hand specimen photograph of sinter samples.

Case study 2: Site G8

Site G8 is located on the western side of the boardwalk near Fred and Maggie's hot spring (Fig. 3). Fred and Maggie's pool discharges ~99 ˚C, near-neutral, alkali chloride water. Site G8 is located approximately 50 m from the pool, where water is discharging intermittently. Currently, low-temperature (<35 ˚C) microbial mats occupy the site, indicating intermittent, low-temperature, thermal fluid flows over the sinter today (Fig. 5A). The sinter under the living microbial mats was examined (sinter site is shown by the triangle on Fig. 5A) and revealed the preservation of microbes typical of those that inhabit mid-temperature (35-59 ˚C) discharging hot spring water (Fig. 5B). Therefore hot spring discharge over this area has decreased in temperature with time. The sinter consists of opal-A silica with a FWHM value of 7.6 °2θ. SEM examination reveals an unaltered, opal-A sinter with at least two generations of opal-A sphere deposition (Fig. 5C-D). The older spheres form botryoidal clusters with sphere diameters <1.5 µm, while newly-formed opal-A spheres (<0.5 µm in diameter) have deposited on top of the earlier formed spheres (Fig. 5C-D). The newly-depositing spheres are precipitating from the present-day, intermittent hot spring flow.

The downhole temperature measurements were 39, 70 and 92 ˚C at 0.5, 1.0 and 1.5 m respectively (T-profile site shown on Fig. 5A, E). Infrared imaging shows the surface temperature of the sinter terrace to be slightly elevated in isolated areas and ranged from 15 to 30 ˚C (Fig. 5F).

The GPR profile shows bands of near-horizontal, moderate- to weak-amplitude reflections with at least four near-vertical, low-amplitude, weak reflection areas (black vertical columns indicated by yellow arrows on Fig. 5E). The near-vertical, weak reflection areas may represent paths of ascending steam given the measured temperature at 1.5 m depth in one of these zones was 92 °C.

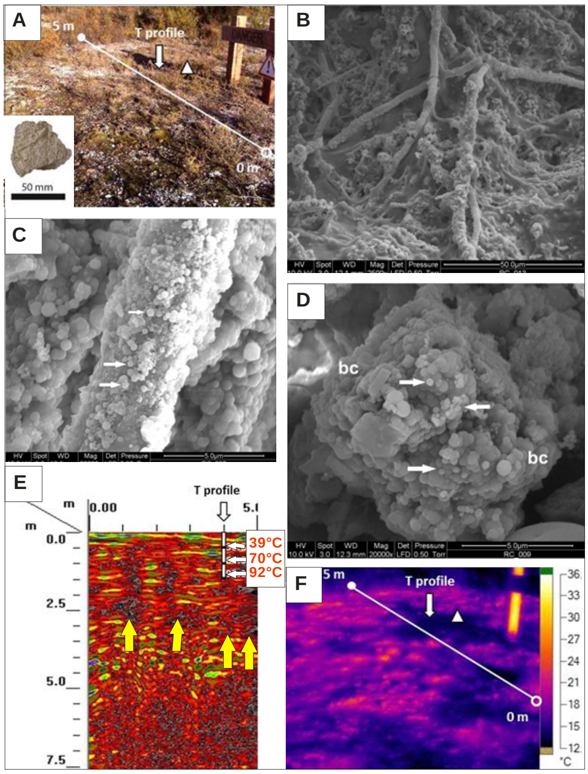

Figure 5: Site G8. (A) Site photograph. Black, low-temperature (<35 ˚C) microbial mats on surface of sinter. 5 m long GPR transect location shown. T-profile indicates the downhole temperature measurement site and the location of the sinter sample collected is shown by the triangle. Insert: Hand specimen photograph of sinter sample. (B-D) SEM images of sinter. (B) Mid-temperature (35-59 ˚C) sized filaments display diameters of ~4 µm. (C) A second generation of opal-A spheres with diameters <0.5 µm (arrows) rest on the surface of a mid-temperature sized filament. (D) Primary botryoidal clusters (bc) of opal-A spheres and newly-deposited, opal-A spheres (arrows) indicating second pulse of thermal fluid. (E) 5 m GPR transect shows both moderate-amplitude (green and yellow areas) and low-amplitude reflections (red and black areas) dominate the uppermost 5 m. Vertical zones of weak-amplitude

reflections (arrows) indicate zones of intense alteration and suggest ascending steam. The downhole temperature measurements were 39, 70 and 92 ˚C at 0.5, 1.0 and 1.5 m depth, respectively, clearly indicating high temperatures in the shallow subsurface. (F) Infrared image of sinter terrace at site G8.

3.2.2 Significant heat in the shallow subsurface and evidence of heat overprinting the sinter at the surface

Case study 1: Site G9

Site G9 is on the western side of Wairiri Geyser (Fig. 3). The location of the measured downhole temperatures (T-profile) and the sinter sample site (triangle) is shown on Figure 6A-B. The measured ground temperature was 100 °C at 0.5 m below the boardwalk (Fig. 6A). The infrared image of the site shows the surface temperature in the broader area to range between 20 and >50 ˚C (Fig. 6B).

SEM imaging of the sinter revealed numerous dissolution pits typically formed when sinter is overprinted with acidic steam condensate (Fig. 6C-D). The sinter sample removed from the ground surface where the temperature measured 50 ˚C, consisted of opal-CT silica (intermediate maturity), with a FWHM value of 0.9 ˚2Ɵ. Within dissolution pits and cavities of the sinter early opal-CT bladed lepispheres were present (see arrows on Fig. 6D).

The GPR profile shows areas of strong-amplitude reflections (white and gray areas) as well as large areas of moderate- (green and yellow areas) and weak-amplitude reflections (red and black areas) inferring spatially patchy steam overprinting up to 1 m below the ground surface.

A sinter sample collected from a site that correlates to weak-amplitude GPR reflections, shows abundant dissolution textures suggesting long-term overprinting by acidic steam condensate. A measured temperature of 100 ˚C at 0.5 m depth was recorded immediately below the sinter sample site. The dissolution of the sinter, the elevated ground temperature at 0.5 m depth and the widespread low-amplitude reflections in the GPR image suggest significant sustained steam flow in the shallow subsurface (<1 m depth).

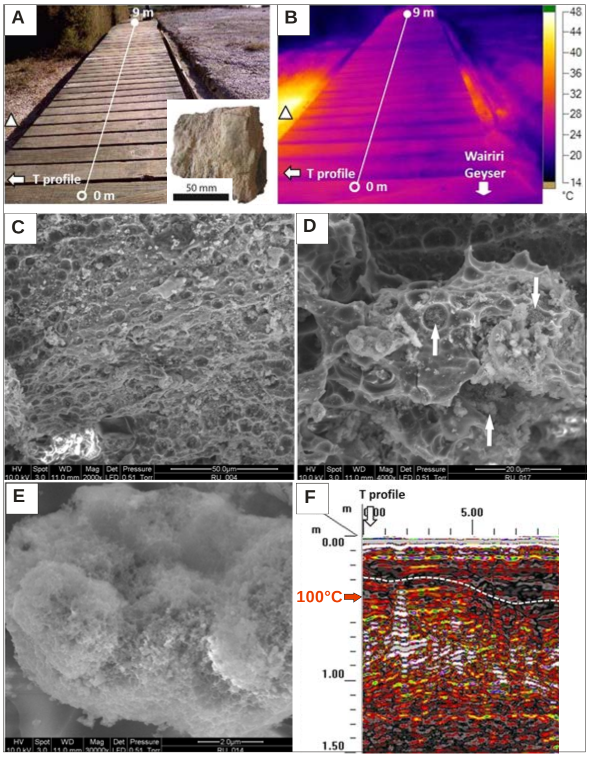

Figure 6: Site G9. (A) Site G9 with 9 m long GPR profile shown along boardwalk, downhole temperature measurement site (T-profile) and sinter site (triangle) shown. Insert: Hand specimen photograph of sinter. (B) Infrared image of site G9 shows a temperature at the surface of > 48 ˚C where the sinter sample was collected. (C-E) SEM images of sinter. (C-D) Dissolution pits within sinter surface (arrows). (E) Opal-CT morphology shows an early opal-CT formation where the individual blades of typical opal-CT lepispheres are not yet fully formed. (F) GPR transect of site G9 shows low-amplitude signals in most of the area (red/black zones) with minor moderate amplitude areas (green/yellow zones) and strong amplitude areas (grey/white zones) which likely represent areas of minimal alteration. Dotted line represents ground surface below boardwalk.

Case study 2: Site G23

Site G23 (Fig. 3) is located along the boardwalk immediately before Soda Fountain (Fig. 7A). Downhole temperature measurements on the right side of the boardwalk (T-profile on Fig. 7A) revealed a temperature of 80.1 °C at 1.5 m depth below the boardwalk. Infrared imaging of the site showed occasional areas of elevated temperature to the right of the path (20 to 40 ˚C; Fig. 7B). A sinter sample (Fig. 7C) was collected from the surface next to the downhole temperature measurement site (triangle on Fig. 7A-B). The sinter consisted of opal-A/CT silica with a FWHM value of 2.7 ˚2Ɵ.

The GPR profile imaged strong-amplitude reflections (grey/white areas on Fig. 7D) inferring unaltered ground, surrounded by moderate- (yellow/green areas on Fig. 7D) and low-amplitude reflections (red/black areas on Fig. 7D) indicative of altered ground. The 80 ˚C downhole temperature measurement correspond to an area of medium- to low-amplitude reflections suggesting localised zones within the subsurface of steam alteration.

The sinter shows evidence of overprinting by acidic steam condensate by: (i) the abundance of kaolinite clay platelets over previously formed smooth, botryoidal opal-A spheres (Fig. 8A-B; note kaolinite determined by Electron Dispersion Spectroscopy on SEM), and (ii) numerous dissolution textures (Fig. 8C-D).

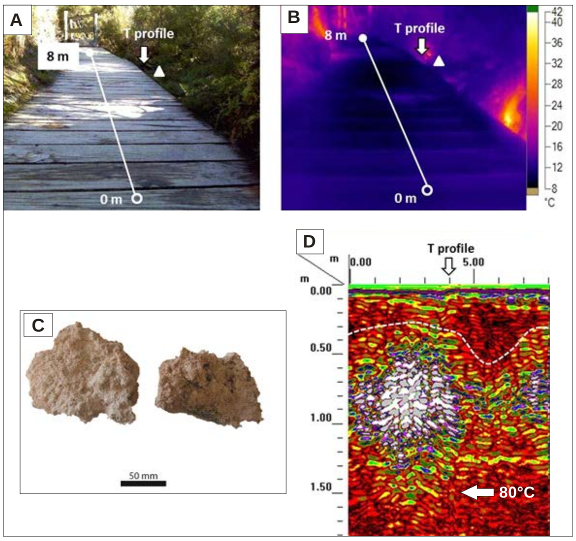

Figure 7: 8m GPR transect (G23) collected on boardwalk immediately before Soda Fountain. (A) Site photograph. Sinter collected beside boardwalk (triangle). Downhole temperature measurements (80.1 ˚C at 1.5 m depth) recorded where the T-profile arrow is shown. (B) Infrared image captured isolated zones of above ambient temperature along the right side of the boardwalk (20 to 40 ˚C). (C) Hand specimen photograph of sinter sample. (D) Dotted line shows ground surface under boardwalk. GPR profile, with strong-amplitude reflections between 0 m and 4 m of transect (grey/white area) surrounded by moderate- to low-amplitude reflections. The reflection profile suggests minimal alteration of the subsurface between 1 m and 4 m of transect with progressively greater alteration outside this zone.

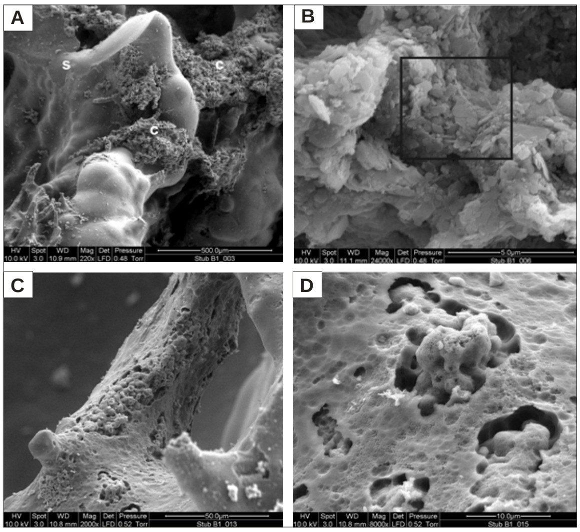

Figure 8: SEM images of sinter sample from the surface at site G23. (A) Overview of sinter shows smooth botryoidal opal-A spheres (s) and clay platelets (c). (B) Increased magnification of clay platelets. Boxed areas indicates EDS site confirming kaolinite clay platelets. (C-D) Dissolution textures. The dissolution is spatially patchy and consists of pitted surfaces within the previously formed smooth sinter surface.

4. CONCLUSION

The multi-technique approach of sinter examination, downhole temperature measurements, Ground Penetrating Radar and infrared imaging offers a new perspective for characterisation of sinter deposits at shallow depths and changes due to flow migration pathways within the top few metres below the ground surface. Specifically the combination of these techniques enables:

(i) Mapping subsurface sinter textural changes where there is no evidence of changes at the surface

(ii) Appraisal of fluid pathways in the subsurface

Repeated surveys using this multi-technique approach allows the tracking of extinct and modern fluid pathways within the shallow subsurface. This is important for the evaluation of:

- whether a geothermal system's boundary is shifting over time
- if a system is heating up or cooling down

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