POST-DEPOSITIONAL ALTERATION OF SILICEOUS SINTER NEAR OLD FAITHFUL GEYSER, YELLOWSTONE NATIONAL PARK, USA

Bridget Lynne[1,2], Gary Smith[2], Henry Heasler[3], Cheryl Jaworowski[3], Isaac Smith[2], Duncan Foley[4] and Dyah Sahdarani[1]

[1]University of Auckland, Department of Engineering Science, 70 Symonds St, Auckland, New Zealand

[2] Geothermal Scientific Investigations Ltd, 11 Kyle Rd, Albany, Auckland, New Zealand

[3] Yellowstone National Park, WY 82190; Independent Geologists Box 1238, Powell, WY 82435, USA

[4] Department of Geosciences, Pacific Lutheran University, Tacoma, WA 98466, USA

b.lynne@auckaland.ac.nz

Keywords: *Yellowstone National Park; Siliceous Sinter; Shallow Hydrology, Hydrothermal Alteration, Ground Penetrating Radar, Scanning Electron Microscopy, Computerised Tomography, X-Ray Diffraction.*

ABSTRACT

Siliceous sinters are hot spring rocks that form as opal-A silica precipitates and accumulates from discharging alkali chloride hot springs, as the water cools to <100 °C. In a thermal setting it is common for hydrothermal conditions to change over time. Such changes are recorded in the sinter as alteration over-prints. The shallow subsurface conditions underneath the siliceous sinter terrace surrounding Old Faithful Geyser, Yellowstone National Park, USA, was investigated for evidence of post-depositional alteration. A subsidence bowl was observed on the sinter terrace to the east, while no subsidence was visible on the sinter terrace to the west of Old Faithful Geyser. However, both areas displayed localised sites of steam discharging through the sinter terrace. To investigate the shallow subsurface conditions we used the multi-technique approach of Ground Penetrating Radar, Scanning Electron Microscopy, Computerized Tomography and X-Ray Diffraction. Our results revealed the presence of acidic steam condensate zones in the shallow subsurface, beneath the sinter terrace in both areas, providing evidence that the boundary of the hydrothermally-altered ground extends beyond that which is visible at the surface. Identifying these zones is important as this type of hydrothermal alteration weakens the sinter, providing ideal conditions for subsidence. The combination of these non-invasive techniques has proven successful in mapping potential subsidence sites and in tracking shallow heat migration pathways.

1. INTRODUCTION

1.1 Siliceous sinter

Hot spring rocks referred to as siliceous sinter are common in geothermal systems where alkali chloride waters discharge at the surface after equilibrating with the underlying rocks at temperatures >175 °C. As the silica-rich hydrothermal fluid discharges, it cools to temperatures <100 °C and the silica carried in solution precipitates and accumulates to form sinters (Fournier and Rowe, 1966). Therefore, siliceous sinters provide evidence of a geothermal reservoir at depth. Initially silica deposits as opal-A and subsequently undergoes diagenesis which involves a series of silica phase changes from opal-A to opal-A/CT to opal-CT +/- opal-C and eventually to quartz (Herdianita et al., 2000; Lynne et al., 2007). Time is not the only factor driving diagenesis. Site-specific, post-depositional conditions such as steam over-printing, dissolution or multiple pulses of hydrothermal fluid also influence sinter diagenesis (Lynne et al., 2005, 2008).

1.2 Hydrothermal conditions change over time

Geothermal systems and particularly surface hydrothermal activity can change over time. For example, hot spring flow rates/temperatures can increase or decrease and shallow subsurface heat flow can migrate or cease altogether. Also, there may be significant heat in the shallow subsurface even when there is no evidence of heat at the surface. These changing conditions are preserved as hydrothermal alteration signatures in siliceous sinters. Spatial and temporal alteration sequences captured within sinters can reveal the changing conditions of surface hydrothermal activity at any given site.

Subsidence at a variety of scales is a common feature in geothermal areas. Subsidence at the surface may result from changes in the deeper reservoir (Allis et al., 2009) or from changes in the shallow subsurface (Mackenzie, 2012). Subsidence may result from exploitation of a geothermal reservoir (Bromley et al., 2015) or it can occur naturally at specific sites where there is no hydrothermal fluid extraction (Powell, 2011). Surface features can change from discharging alkali chloride surface manifestations to acid sulfate features such as steaming ground and fumaroles, which reflect a lowering of the water table (Moore et al., 2004). This change favors the formation of acidic steam condensate in the shallow subsurface, creating a new low pH environment. This alteration process often compromises the structural integrity of the rocks. For example, kaolinite clay may form as an alteration product or dissolution may take place which is observed as pitted or etched surfaces. These processes weaken rock units increasing their susceptibility to collapse or subside.

Our study uses a multi-technique approach to investigate two areas near Old Faithful Geyser, Yellowstone National Park, USA, where hydrothermal alteration of a sinter is currently taking place (Areas A and B; Fig. 1) and where a sinter terrace has collapsed (Area B, Fig. 1). Ground Penetrating Radar (GPR) was used to examine the shallow surface conditions. Due to the protected status of the Old Faithful Geyser area, no invasive techniques were permitted making the non-invasive method of GPR an ideal method for this study. Sinter samples taken at selected sites along GPR transects were analysed with Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD) and Computerised Tomography (CT) scanning. These techniques were used to assess if there has been any post-depositional overprinting which may be responsible for the hydrothermal alteration and subsidence observed at the surface.

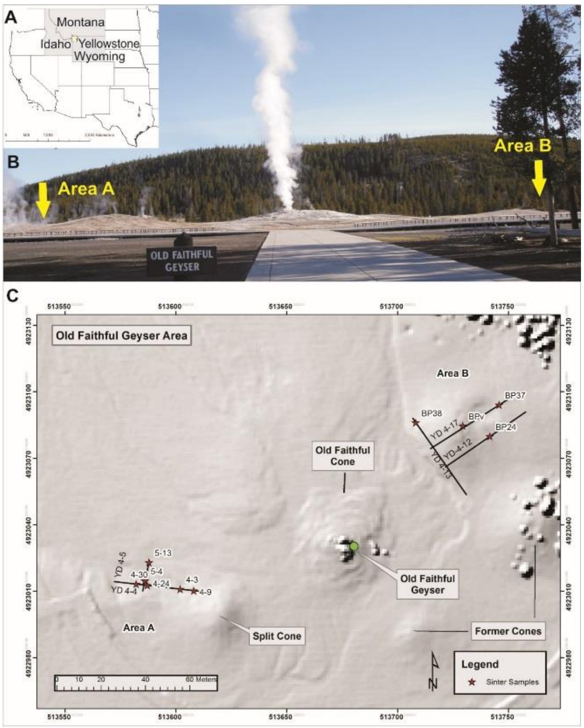

Figure 1: Location maps. (A) Location of Yellowstone National Park, USA. (B) Two study sites (Area A and B) in the Old Faithful Geyser area. (C) Location of GPR transect lines.

2. METHODS

2.1 Ground Penetrating Radar (GPR)

GPR was used to image the shallow subsurface (<5 m). GPR detects changes in properties of the shallow subsurface (e.g., mineralogy, density, porosity etc). A monostatic GSSI 200 MHz ground-coupled antenna with a GSSI SIR 4000 controller was used to collect GPR data. Typically, unaltered opal-A sinter, opal-A sinter experiencing mild alteration via dissolution and opal-A sinter undergoing intensive alteration image as strong, moderate and weak amplitude reflectors, respectively (Dougherty and Lynne, 2010; Lynne and Sim, 2012; Lynne and Smith, 2013; Lynne et al., 2017).

GPR profiles YD4-4 and YD4-5 in Area A (Fig. 1) are 39 m and 13 m long respectively, are perpendicular to each other and are located over sinter terraces and hydrothermally-altered ground (Fig. 2A). GPR transects YD4-12, YD4-17 and YD4-13 were collected in Area B (Fig. 1) over and beside an area of visible subsidence (Fig. 3A). YD4-12 is a 45m long GPR transect located outside the subsidence area. YD4-17 is a 48m long profile that runs through the center of the subsidence area. YD4-13 (Fig. 4A) runs perpendicular to YD4-12 and YD4-17 and is located outside the subsidence area.

2.2 Scanning Electron Microscopy (SEM), Computerised Tomography (CT) and X-Ray Diffraction (XRD)

SEM was used to identify post-depositional hydrothermal alteration signatures preserved in the sinter samples. CT scans documented density differences between the various sinter samples. XRD was undertaken to determine the mineralogy of each sample.

3. RESULTS

3.1 Area A

Two GPR transects perpendicular to each other were collected in Area A over sinter terraces and zones of hydrothermally altered ground (Fig. 2). On both GPR profiles, distinct zones of strong and weak amplitude reflectors were observed. The weak reflectors correlate to zones of hydrothermally-altered ground while the strong amplitude reflectors occur over unaltered sinter terraces (Fig. 2D-E). In places on both YD4-4 and YD4-5, weak amplitude reflections occur underneath strong amplitude reflections (sample sites 9 and 13). SEM observations (Fig. 2D-E) revealed strong amplitude reflection zones occur where the sinter consists of unaltered opal-A spheres (samples 3, 9 and 13) while weak amplitude reflections correlate to highly-altered sinter (samples 24, 30 and 4). XRD results revealed samples 3, 9 and 13 consisted of opal-A sinter while samples 30 and 4 were kaolinite clay. Sample 24 was not analyzed by XRD due to inadequate sample size. CT scan results show the altered sinter to have a significantly lower density than the unaltered sinter (Fig. 2C).

3.2 Area B

GPR transect YD4-17 crosses the rim of the visible subsidence area/dissolution pit at 18 and 37 m (Fig. 3). GPR imaging along YD4-17 revealed: (i) dominantly strong amplitude reflections from 0 to 12 m; (ii) weak reflections between 18-25 m and 30-35 m; (iii) dominantly moderate reflections at all other sites (Fig. 3B). Sinter sample BP 37 was analyzed from the edge of the subsidence area at the 37 m mark. CT scan results indicate the density of sample BP 37 was dominantly low with minor areas of moderate density (Fig. 3D). SEM observations show the sinter is undergoing moderate dissolution between individual opal-A spheres (Fig. 3E).

GPR imaging along YD4-12 shows: (i) dominantly strong amplitude reflections between 0-15 m; (ii) dominantly weak reflections between 15-32 m; (iii) moderate reflections between 32-45m (Fig. 3C). SEM images of sample BP 24 located at the 24 m mark of transect YD4-12 reveals aggressive post-depositional alteration of the sinter. This is shown by the extensive pitting and etched sinter surfaces, as well as the acceleration of diagenesis of opal-A spheres towards quartz crystals (Fig. 3F). Our SEM and CT data reveals intensive hydrothermal alteration processes are recorded in the sinter at the surface. Our GPR data show this alteration extends to approximately 3 m depth between 15 and 32 m along YD4-12. Therefore, alteration in the shallow subsurface is interpreted to extend beyond the dissolution pit area visible at the surface. XRD results showed samples BP37 and BPv were opal-A sinter while sample BP24 consists of opal-A + diagenetic quartz sinter.

GPR transect YD4-13 runs directly over a sinter outcrop (Fig. 4A-B). GPR imaging revealed most of the shallow subsurface consists of strong and moderate amplitude reflections to a depth of 5 m (Fig. 4C). This suggests minimal alteration of the sinter in the subsurface. SEM observations of sinter sample BP38 revealed minor dissolution of a filamentous sinter (Fig. 4D). CT scans of sample BP 38 show the sinter to be of moderate density with rare patches of low density (Fig. 4E). XRD analysis of sinter sample BP 38 revealed opal-A.

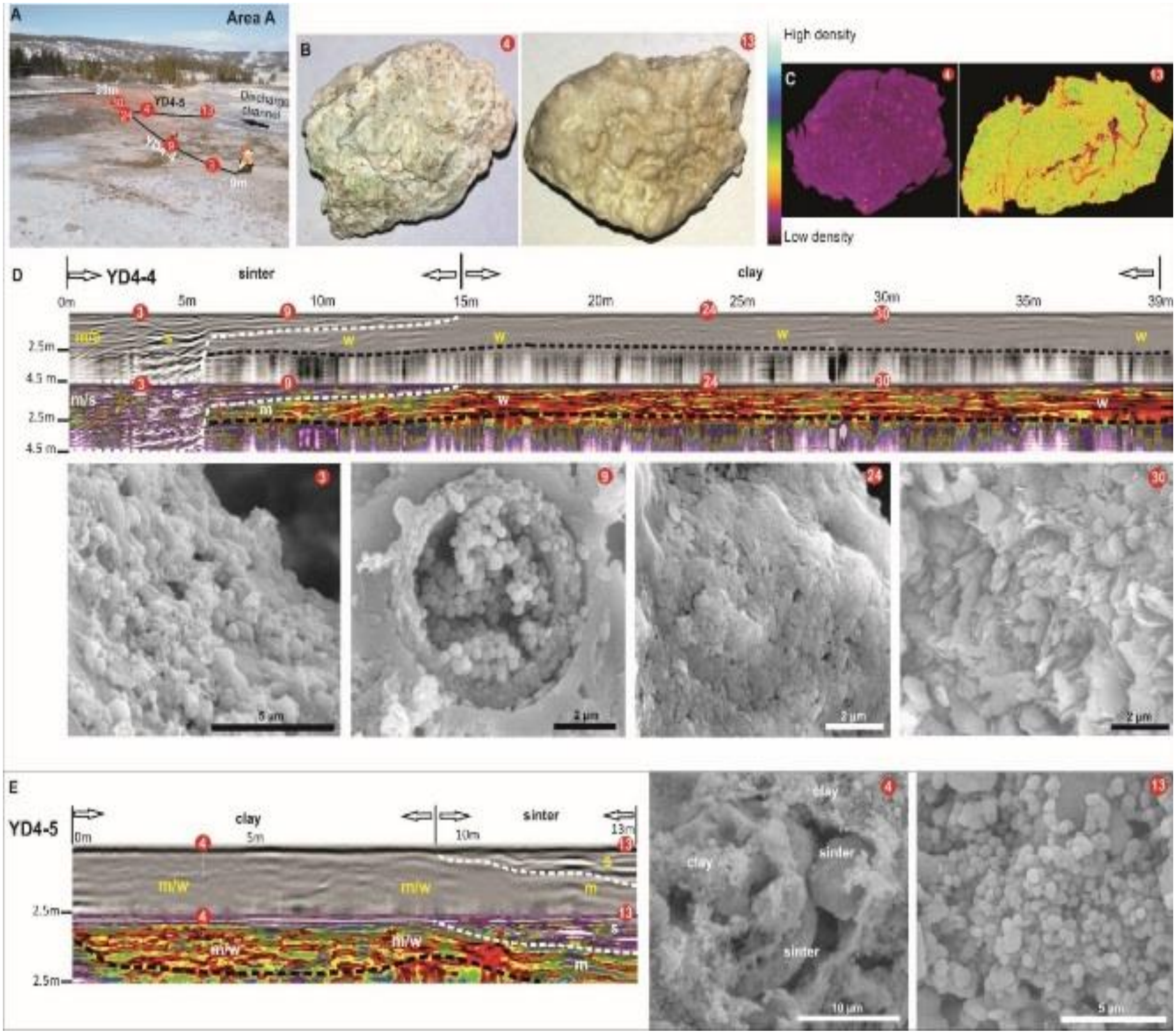

Figure 2: Area A (numbers in red circles = sample number and location along GPR profile). (A) Overview of Area A. White areas are sinter terraces and pink areas are hydrothermally-altered zones. (B) Hydrothermally-altered sinter sample 4 and unaltered sinter sample 13. (C) CT scans. Highly-altered sinter sample 4 is low density. Unaltered sinter sample 13 is moderate density. (D-E) GPR transects YD4-4 and YD4-5 show distinct zones of strong and weak amplitude reflections (s = strong, m = moderate, w = weak amplitude reflections). SEM images of samples collected along transect lines. Sinter samples 3, 9 and 13 show well-formed opal-A spheres. Samples 24 and 30 reveal clay. Sample 4 shows clay overlying sinter fragments. Attenuation below black dotted line.

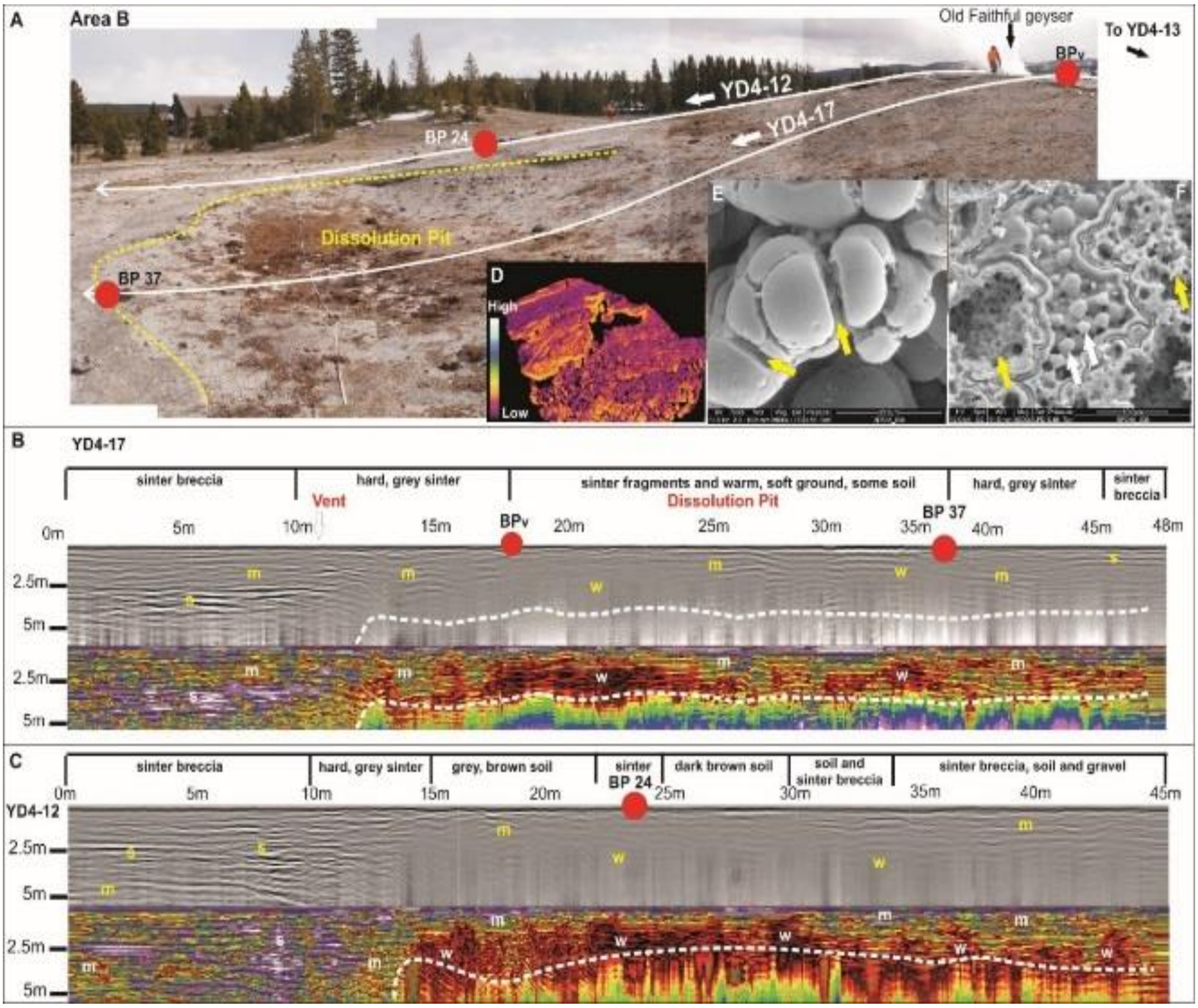

Figure 3: Area B (numbers in red circles = sample number and location along GPR profile). (A) Overview of dissolution pit and location of GPR transects YD4-12 and YD4-17. (B) GPR data collected along profile YD4-17 (s = strong, m = moderate, w = weak amplitude reflections). (C) GPR data collected along profile YD4-12 (s = strong, m = moderate, w = weak amplitude reflections). (D) CT scan of sinter sample BP37 shows a moderate-low density sample. (E) SEM image of sinter sample BP37 with moderate dissolution between individual opal-A spheres within a cluster of botryoidal opal-A (yellow arrows). (F) SEM image of sinter sample BP24. Aggressive dissolution textures (yellow arrows) and early formation of quartz directly from opal-A spheres (white arrows).

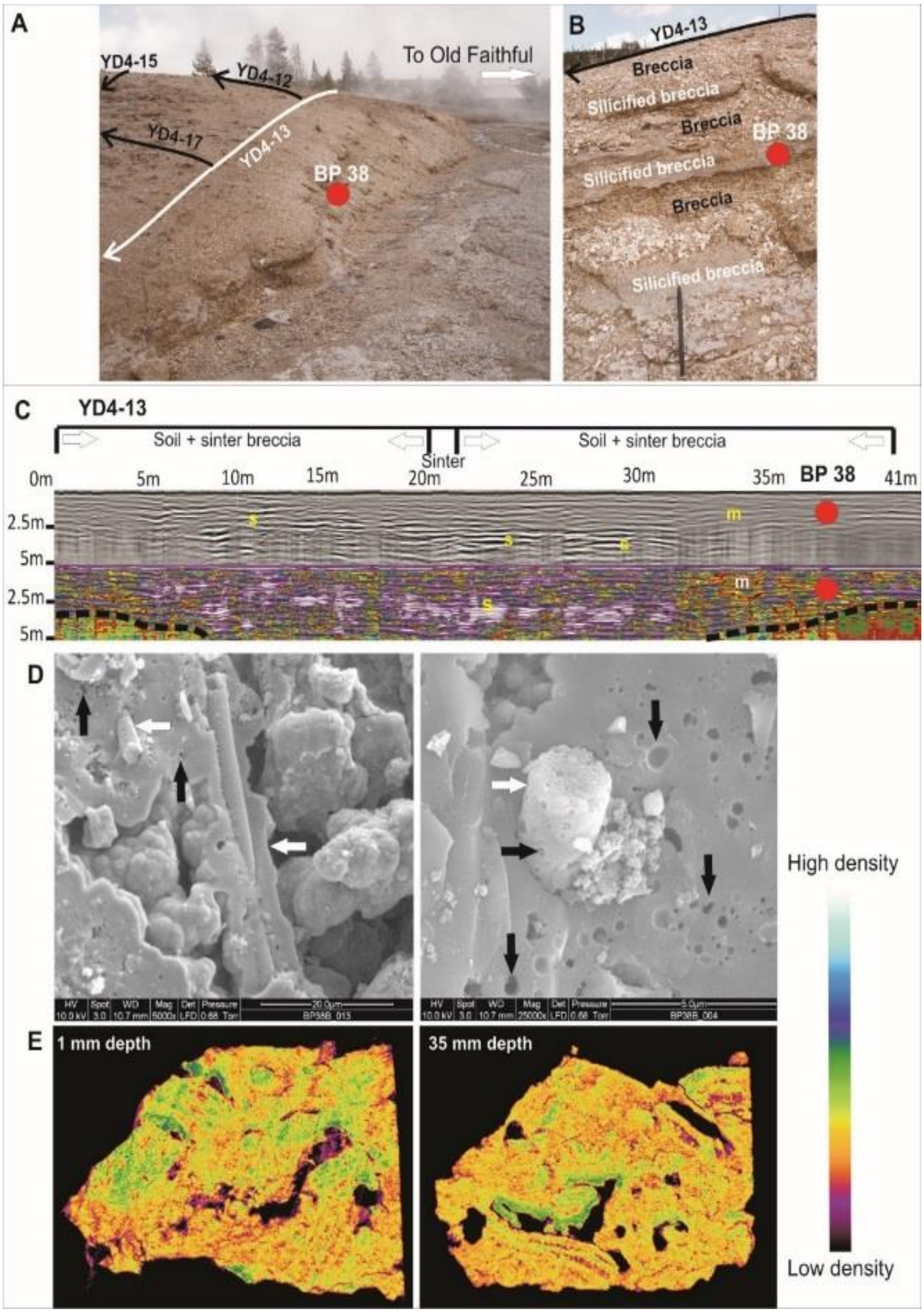

Figure 4: Area B outside dissolution pit. (A-B) Location of GPR transect YD4-13 over sinter outcrop and sinter sample site BP 38. (C) GPR profile YD4-13 (s = strong, m = moderate amplitude reflections). Loss of attenuation below black dotted line. (D) SEM images of sinter sample BP 38 reveals mild dissolution shown by pitting of surface (black arrows) within a filamentous sinter (white arrows). (E) CT scans of sinter sample BP 38 at 1 mm and 35 mm depth of penetration into the sample. Sinter is of moderate density with rare patches of low density. Black areas are voids.

4. DISCUSSION

Our multi-technique approach of GPR, SEM, CT scanning and XRD revealed hydrothermal alteration is taking place in the shallow subsurface in areas around Old Faithful Geyser, Yellowstone National Park. Specifically, at some sites in both Areas A and B hydrothermal conditions have changed over time, from discharging alkali chloride water which formed the sinter, to acidic steam condensate conditions.

GPR, SEM, CT scanning and XRD techniques documented significant differences between unaltered opal-A sinter and hydrothermally-altered opal-A sinter. SEM observations, XRD analyses and CT scans confirm post-depositional hydrothermal alteration of opal-A sinter has taken place where weak amplitude GPR reflections were recorded, while strong amplitude GPR reflections correlated to unaltered opal-A sinter (Fig. 5).

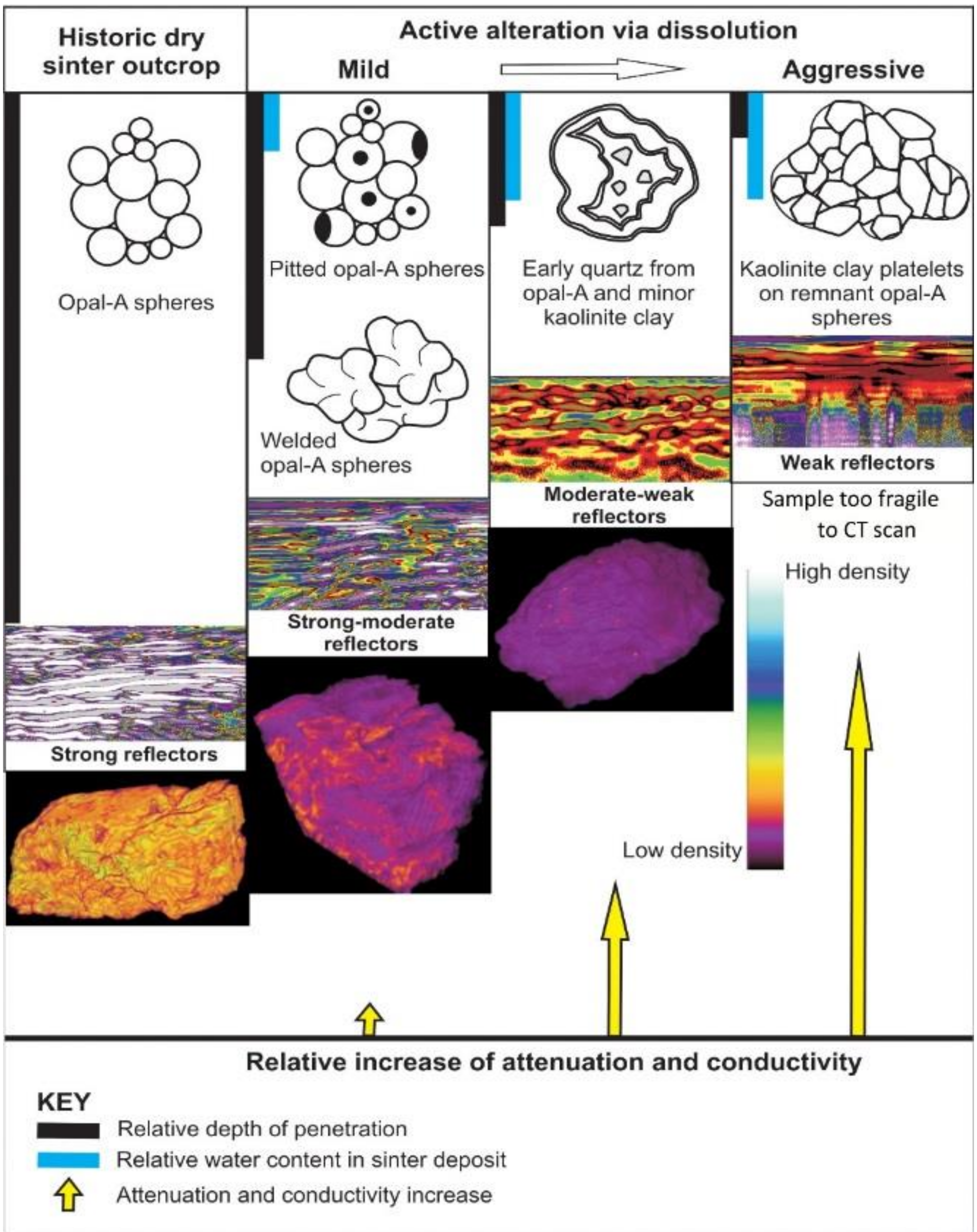

Figure 5: Summary of sinter morphology, mineralogy and density and how it relates to the GPR reflections.

Three alteration processes observed in the sinter in Areas A and B are typical of an acidic steam condensate environment: (1) The presence of kaolinite indicates a pH of 2-3 and temperatures <120 ºC; (2) Etched and pitted sinter surfaces are a typical dissolution texture in sinters occurring when the sinter is over-printed by acidic steam condensate (Campbell and Lynne, 2006); (3) The acceleration of opal-A directly to quartz. This process has been documented by Lynne et al. (2006) as the product of steam over-printing opal-A sinter where steam provided the necessary heat and fluid to accelerate sinter diagenesis. Our findings support a post-sinter formation increase in heat in the shallow subsurface in Areas A and B where any of these mineralogical - morphological changes were observed. Wherever these changes were noted, weak amplitude reflections were recorded by GPR.

Our GPR results indicate the area of alteration is far greater than that observed at the surface as weak amplitude reflections (i.e., hydrothermally-altered zones) occur underneath strong amplitude reflections (i.e., unaltered sinter). Therefore, zones of increased heat in the shallow subsurface extend beyond that which is visible at the surface. The three types of hydrothermal alteration observed in our study will compromise the integrity of a sinter and weaken it. A weakened sinter is more likely to subside. This non-invasive, multi-technique approach has proven successful in determining potential zones of subsidence in the Old Faithful Geyser area.

ACKNOWLEDGEMENTS

We would like to acknowledge the following funding sources: Expeditions Council of the National Geographic Society project EC0714-15, National Park Foundation Grant 9086, National Park Service Research Permit YELL-2014-SCI-5612. We would like to thank Pacific Lutheran University, Geothermal Scientific Investigations Ltd, and the Geothermal Institute at the University of Auckland for leverage in-kind. We would like to thank the following support personnel involved in making the acquisition of this data possible through a collaboration of resources and expertise: Dennis Lojko (Law Enforcement Ranger, Yellowstone National Park), Mary-Ellen Hackett (Law Enforcement Ranger, Yellowstone National Park), Michael Nichols (National Geographic Magazine) and Martin Gamache (National Geographic Magazine). We would also like to express our gratitude to the Indonesian Endowment Fund for Education who provided the research grant to conduct the XRD analyses.

REFERENCES

Allis, R., Bromley, C., and Currie, S.: Update on subsidence at the Wairakei-Tauhara geothermal system, New Zealand. *Geothermics* 38. pp. 169-180. (2009).

Bromley, C.J., Currie, S., Jolly, S., and Mannington, W.: Subsidence: an update on New Zealand geothermal deformation observations and mechanisms. *Proc. World Geothermal Congress 2015,* Melbourne, Australia. 9 p. (2015).

Dougherty A.J., and Lynne, B.Y. "A novel geophysical approach to imaging sinter deposits and other subsurface geothermal features utilizing ground penetrating radar." *Geothermal Resource Council Transactions 34, USA.* pp. 857-862. (2010).

Campbell, K.A., and Lynne, B.Y.: Diagenesis and dissolution at Sinter Island (456 years BP), Taupo Volcanic Zone: Silica stars and the birth of quartz. *Proc. 28th New Zealand Geothermal Workshop, New Zealand.* 7 p. (2006).

Fournier, R.O., and Rowe, J.J.: The deposition of silica in hot springs. *Bulletin of Volcanology* 29. pp. 585-587. (1966).

Herdianita, N.R., Browne, P.R.L., Rodgers, K.A., and Campbell, K.A.: Mineralogical and textural changes accompanying ageing of silica sinter. *Mineralium Deposita* 35. pp. 48-62. (2000).

Lynne, B.Y., and Sim, C.Y.: The successful application of Ground Penetrating Radar to image the opal-A to quartz diagenetic sequence in trace element-rich and trace element-poor sinters. *Proc. 36th New Zealand Geothermal Workshop, New Zealand.* 6 p. (2012).

Lynne, B.Y., and Smith, G.J.: A new investigative approach to understanding heat migration pathways within the shallow subsurface at Orakei Korako, New Zealand. *Geothermal Resource Council Transactions* 37, *USA.* pp. 289-294. (2013).

Lynne, B.Y., Campbell, K.A., Moore, J., and Browne, P.R.L.: Diagenesis of 1900-year-old siliceous sinter (opal-A to quartz) at Opal Mound, Roosevelt Hot Springs, Utah, USA. *Sedimentary Geology 119.* pp. 249–278. (2005).

Lynne, B.Y., Campbell, K.A., Perry, R.S., Browne, P.R.L., and Moore, J.N.: Acceleration of sinter diagenesis in an active fumarole, Taupo Volcanic Zone, New Zealand. *Geology 34.* pp. 749-752. (2006).

Lynne, B.Y. Campbell, K.A., James, B., Browne, P.R.L., and Moore, J.N.: Tracking crystallinity in siliceous hot-spring deposits. *American Journal of Science* 307. pp. 612-641. (2007).

Lynne, B.Y., Campbell, K.A., Moore, J.N., and Browne, P.R.L.: Origin and evolution of the Steamboat Springs siliceous sinter deposit, Nevada, USA. *Sedimentary Geology* 210. pp. 111-131. (2008).

Lynne, B.Y., Heasler, H., Jaworowski, C., Foley, D., Smith, I.J., Smith, G.J., and Sahdarani, D.: Using ground penetrating radar, scanning electron microscopy and thermal infrared imagery to document near-surface hydrological changes in the Old Faithful Geyser area, Yellowstone National Park, USA. *Geothermics 68.* pp. 33-53. (2017).

Mackenzie, H.T.: Determining the origin of localised subsidence features in the Kawerau Geothermal Field, Bay of Plenty, New Zealand. *MSc thesis, Canterbury University.* 286 p. (2012).

Moore, J. N., Christenson, B., Browne, P. R. L., and Lutz, S. J.: The mineralogic consequences and behavior of descending acid-sulfate waters: an example from the Karaha-Telaga Bodas geothermal system, Indonesia. *Canadian Mineralogist* 42. pp. 1483-1499. (2004).

Powell, T.: Natural subsidence at the Rotokawa Geothermal Field and implications for permeability development. *Proc. 33rd New Zealand Geothermal Workshop, New Zealand.* 4 p. (2011).

Weres, O., and Apps, J.A.: Prediction of chemical problems in the reinjection of geothermal brines. In: Marasimhan, T.N. (Ed.), Recent Trends in Hydrogeology. *Geological Society of America, Special Paper* 189. pp. 407-426. (1982).

Williams, L.A., and Crerar, D.A.: Silica diagenesis, II: general mechanisms. *Journal of Sedimentary Petrology* 55. pp. 312–321. (1985).