Sinter architecture and Ground Penetrating Radar: A new and innovative dual technique for understanding paleo-flow hot spring settings and their application for early geothermal exploration

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Abstract
Siliceous sinters (hot spring rocks) are common in geothermal areas where alkali chloride reservoir water discharges at the surface and deposits amorphous silica (opal-A) to form sinters. The amount of silica in hot spring water is not accounted for by the solubility of opal-A, but is controlled by the solubility of quartz at depth. For example, 210°C alkali chloride reservoir water in equilibrium with quartz at depth becomes saturated with respect to opal-A when the water temperature decreases to 100°C. As hot spring water discharges, it cools to < 100°C facilitating the precipitation of opal-A. The opal-A entombs everything it comes into contact with silicifying all biotic and abiotic components present in hot spring water such as microbes, pollens and sinter surfaces. The silicification results in the preservation of a variety of textural fabrics reflecting specific hot spring settings such as: (1) near-vent, high temperature pools (>60°C); (2) mid-slope, mid-temperature (35-60°C) pools; (3) low-temperature (<35°C) distal-apron settings.

Sinters remain preserved at the surface for thousands of years after hot spring flow has ceased. Also, the deeper hot reservoir fluid can exist at depth long after hot spring activity has stopped. Therefore, sinters provide valuable records of paleo-biologic, paleo-hydrologic and paleo-environmental conditions in extinct hot spring settings and infer a reservoir temperature of > 210°C. The recognition of temperature significant sinter textures enables the locations of high versus low temperature hot spring sites to be identified. There are many examples around the world where geothermal power plants successfully operate with no present-day discharging hot springs, but sinters in the area indicating historic hot spring flow.

Sinters undergo silica phase-changes from opal-A to opal-A/CT to opal-CT to opal-C to quartz. The transformation rates of opal-A to quartz differ between locations. Therefore, mineralogical maturation alone cannot be used as an indicator of the age of a sinter and Accelerator Mass Spectroscopy ^{14}C dating is required to determine the timing of fluid flow to the surface. Regardless of the silica phase and age, textural preservation usually persists.

To date, the study of sinters has been limited to outcrops and cores. Ground Penetrating Radar (GPR) images a continuous cross-sectional view of the shallow subsurface. Our results show GPR was successful in: (1) imaging through opal-A to quartz sinters to a depth > 10 meters; (2) identifying the spatial extent and thickness of completely buried and partially exposed sinters; (3) distinguishing between altered versus unaltered sinters; (4) imaging vent directionality; (5) mapping vent to distal apron areas. GPR has demonstrated promising results as a non-invasive, cost-effective method for imaging a range of geothermal features in the shallow subsurface.

The new and innovative combination of techniques that includes GPR imaging of sinters, ^{14}C sinter dating and sinter textural mapping greatly assists in the initial stages of geothermal exploration. This provides useful information about reservoir temperatures, timing of hot spring flow, volume and distribution of flow, flow migration pathways, as well as identifying high versus low temperature sinter textures which allows reconstruction of paleo-flow hot spring settings.

Keywords: Sinter, GPR, geothermal exploration, hydrothermal alteration, sinter textures and dating.

Depósitos de sínter y Geo-radar: Una nueva e innovadora técnica dual para comprender paleo-flujos en ambientes de manantiales termales y su aplicación en las primeras etapas de la exploración geotérmica

Resumen

Los depósitos de sínter silícico son comunes en zonas geotérmicas donde yacimientos de aguas cloruradas alcalinas descargan en superficie y depositan sílice amorfa (ópalo-A) para formar sínter. La cantidad de sílice en las aguas termales no depende de la solubilidad del ópalo-A, sino que es controlada por la solubilidad del cuarzo a profundidad. Por ejemplo, agua clorurada alcalina de un yacimiento a 210°C de temperatura en la que el cuarzo se encuentra en equilibrio a profundidad, se vuelve saturada con respecto al ópalo-A cuando la temperatura desciende a 100°C. Conforme se descarga el agua de los manantiales, se enfría a < 100°C facilitando la precipitación de ópalo-A. El ópalo-A engloba todo con lo que entra en contacto, silicificando todos los componentes bióticos y abióticos presentes en las aguas termales, como microbios, pólenes y superficies de sínter. La silicificación da como resultado la preservación de diversas fábricas texturales, que reflejan entornos específicos de los manantiales tales como: (1) albercas de alta temperatura, cercanas a la fuente (>60°C); (2) albercas de temperatura intermedia (35-60°C) ubicadas en una distancia intermedia de la fuente; (3) entornos distantes de la fuente, de baja temperatura (<35°C).

El sínter permanece preservado en superficie durante miles de años después de que el flujo de los manantiales terminó. Además, el fluido caliente más profundo del yacimiento puede subsistir a profundidad mucho tiempo después de que termina la actividad de los manantiales termales. Por consiguiente, el sínter proporciona valiosos datos sobre las condiciones paleo-biológicas, paleo-hidrológicas y paleo-ambientales en áreas de manantiales termales extintos y permite inferir temperaturas de yacimiento > 210°C. El reconocimiento de texturas de sínter significativas, asociadas a la temperatura, permite diferenciar el emplazamiento de áreas de manantiales termales de alta temperatura de los de baja temperatura. Hay muchos ejemplos en el mundo donde plantas geotermoeléctricas operan exitosamente, sin observarse descargas actuales de manantiales termales pero donde hay sínter, lo que indica un flujo histórico de esos manantiales.

El sínter sufre cambios de fase silícica desde ópalo-A a ópalo-A/CT, a ópalo-CT, a ópalo-C, a cuarzo. Las velocidades de transformación desde ópalo-A a cuarzo difieren de uno a otro sitio. Por lo tanto, no puede utilizarse únicamente la madurez mineralógica como indicador de la edad del sínter, sino que se requiere una datación de ^{14}C mediante Espectroscopía de Aceleración de Masas para determinar la edad en la que los fluidos eran descargados en superficie. Pero independientemente de la fase de sílice y de su edad, la textura suele preservarse.

Hasta la fecha, el estudio de sínter se ha limitado a muestras de superficie y de núcleo. El Geo-radar (GPR: *Ground Penetrating Radar*) toma imágenes de una sección transversal continua del subsuelo poco profundo. Nuestros resultados muestran que esta técnica resultó exitosa para: (1) captar imágenes

de sínter desde ópalo-A hasta cuarzo a profundidades > 10 metros; (2) identificar la extensión espacial y el espesor de sínters completamente enterrados o parcialmente expuestos; (3) distinguir entre sínter alterado e inalterado; (4) tomar imágenes de la dirección de los conductos; (5) cartografiar conductos hasta zonas distales. El GPR ha demostrado resultados prometedores como método no invasivo y rentable para tomar imágenes de una gama de manifestaciones termales en el subsuelo somero.

La nueva e innovadora combinación de técnicas que incluyen imágenes GPR de sínter, datación de sínter por ^{14}C y el mapeo textural del sínter, ayuda enormemente en las primeras etapas de exploración geotérmica. Esto proporciona información útil sobre las temperaturas del yacimiento, la edad, volumen, distribución y vías de migración del flujo de los manantiales termales, así como en la diferenciación de texturas de sínter de alta y baja temperatura, lo que permite la reconstrucción del paleo-flujo en ambientes de manantiales termales.

Palabras clave: Sínter, GPR, geo-radar, exploración geotérmica, alteración hidrotermal, texturas y edad del sínter.

1. Introduction

This paper presents new techniques useful in the reconnaissance stage of geothermal exploration and how this information can be extracted from historic geothermal surface features to assist in our understanding of heat and mass flow. Since geothermal systems may exist at depth even when there is no evidence of present-day thermal activity at the surface, it is important to be able to recognise the surface remnants of past discharging hot springs such as siliceous sinter, travertine or silica residue.

Alkali chloride water is the fluid type we use for geothermal power generation. Therefore identifying surface locations of discharging alkali chloride fluids provides us with important information on the deep reservoir fluid composition and the hydrology of a geothermal system. As discharging alkali chloride hot springs cool to temperatures less than 100°C, the silica carried in solution deposits and accumulates to form rocks known as siliceous sinters (Fournier and Rowe, 1966; Weres and Apps, 1982; Fournier, 1985; Williams and Crerar, 1985). As the silica accumulates, distinctive sinter textures are formed depending on the environmental conditions of the hot spring such as water temperature, pH, flow rate, or water depth. These environmentally significant textures are preserved long after hot spring discharge ceases, and are also preserved during the five step opal-A to quartz diagenetic transformation (Lynne et al., 2005, 2007, 2008). Therefore, sinters provide a record of alkali chloride hot spring paleo-flows, while their textural characteristics enable the mapping of broad temperature gradients from high-temperature vent to low-temperature distal-apron areas. ^{14}C Accelerated Mass Spectroscopy (AMS) dating of plant-rich sinters further contributes to our understanding of the timing of discharging alkali chloride hot springs and fluid flow migration pathways. One example, where there are no discharging hot springs but there is an extensive sinter sheet dated 1630-1920 years old, is at the Blundell power plant, Utah, USA (Lynne et al. 2005). Here there is a 26 MW power plant that was commissioned in 1984 (Blackett and Ross, 1992).

As geologists, in the initial stages of exploration we are limited to the examination of rock outcrops. However, often much of the outcrop is below the surface and inaccessible. One technique successfully used to image the shallow subsurface (< 50 m) of many geologic settings is Ground

Penetrating Radar (GPR) as reported by Jol, 2009. GPR imaging provides information on buried rock formations such as the identification of stratigraphic boundary depths and/or changes in rock properties such as density, porosity or mineralogy. GPR has not been previously used in geothermal environments but we applied GPR to our sinter sites to map the lateral and vertical extent of siliceous sinters (Dougherty and Lynne, 2010). This enables the volume of a sinter deposit to be calculated. As sinter can only form from discharging alkali chloride fluids, the reservoir fluid we seek for our geothermal power generation, understanding the volume of sinter provides information on the mass flow from the reservoir to the surface. GPR also provided information on hot spring vent directionality and connectivity (Dougherty and Lynne, 2011). New work is underway examining the silica accumulation rate of sinters which relates to the total fluid discharged in any given area.

The combination of sinter textural identification, volume of sinter formed, the sinter accumulation rate and sinter dating reveals information about the timing of mass flow to the surface, the total mass of fluids discharged, paleo-flow migration pathways, as well as paleo-flow temperature gradients. These new techniques can be used in the early stages of geothermal exploration to provide insights into heat and mass flow from a geothermal reservoir.

2. Methods

2.1 Silica phases

X-Ray Powder Diffraction (XRPD) is the principal technique used to determine the type of silica phase present, as well as to compare the degree of lattice order/disorder among samples. XRPD analysis of samples was undertaken with a Phillips diffraction goniometer fitted with a graphite monochromator, with acquisition controlled by Sietronics (1993) VisXRD software, and subsequent processing achieved using Diffraction Technology Traces V6 software. The XRPD comprises a Phillips PW1130 high voltage (HV) generator fitted with a copper (Cu) anode X-ray tube; the PW1050/25 goniometer uses a PW 1752 curved graphite crystal monochromator and a PW1965 proportional detector. The goniometer has been modified for computer control by the fitting of a Sietronics Sieray 112 stepper motor and control unit. Dry, untreated samples were ground in a mortar and pestle and pressed into an aluminium holder and scanned at 0.6° 2Ø/min, with a step size of 0.01°, from 10 to 40 °2Ø, and operating conditions of 40 kV and 20 mA, using CuKα radiation ($\lambda\alpha 1$ = 1.54051 Å ; $\lambda\alpha 2$ =1.5443 Å).

2.2 Sinter textures

The morphology of the sinter samples were examined using Scanning Electron Microscopy (SEM). Each sample was mounted on an aluminium stub, sputter-coated with gold–palladium for 2 minutes (2–10 nm coating thickness), and examined with a Phillips SEM XL30S field emission gun, at an accelerating voltage of 10–20 keV, and a working distance of 5 mm. Fresh (hydrated) to lightly silicified microbial mat samples were investigated by SEM using a Gatan Alto Cryo Transfer System. Modern field samples were collected in 50% spring water and 50% ethanol (95%), and stored in refrigeration, were subsequently frozen rapidly in liquid nitrogen slush to minimize ice-crystal formation. Structural water was sublimated at -95°C to reveal the intact, three-dimensional network of the mat. The samples were then cooled to < -135°C and coated for one minute with gold-palladium under vacuum. They were imaged at 5 keV accelerating voltage at -180°C.

2.3 Ground Penetrating Radar

Sinter outcrops were imaged using Ground Penetrating Radar (GPR). We used a GSSI (Geophysical Survey System Inc., USA) SIR-2000 GPR system with a 200 MHz transceiver. Both the 200 and 400 MHz frequency antennas were used with variable settings to determine the best acquisition parameters at each site. The range settings varied from 100 to 300 nanoseconds depending on individual features and depth to attenuation. All transects and grid lines were run at least twice, once with a highest range setting possible to penetrate the entire sequence to depth of signal attenuation and then again at a lower range setting to acquire greater detail in the shallow subsurface. GPR data processing and analysis was performed using RADAN 6.5 Software. While more advanced processing is available, such as running FIR (Finite Impulse Response) filter, bandpass filters designed to pass the signal and reject noise of certain frequencies, as well as filtering phantom hyperbola and minor antenna ringing, it was decided that the minimally processed data be presented. Surface elevation data were collected using a Sokkia Electronic Total Station. Topographic corrections, normalization, stacking and depth conversions were achieved using the appropriate steps embedded in RADAN. A dielectric constant of 6-7 was used to convert travel-time to depth and elevation was confirmed using cored samples. The geophysical records were ground-matched to determine the nature of each reflection and the intermittent sedimentary layers using a vibracore or pulse-auger coring system and outcrop mapping of scarp exposures where possible. To ground-truth our GPR images, samples were collected in the field and their mineralogical, textural and physical properties were established using XRPD analysis, scanning electron microscopy, density and porosity measurement as well as standard sedimentological observation techniques.

3. Results

3.1 Hot spring rocks: Siliceous sinter, travertine and silica residue

It is necessary to be able to distinguish between the different types of hot spring rocks such as siliceous sinter, travertine and silica residue (Fig. 1). Siliceous sinters are the most important hot spring rock type for geothermal exploration as they indicate a direct link to a deeper alkali chloride geothermal reservoir and form close to the hot up-flow zone of a geothermal system. Travertine is a calcium carbonate hot spring rock formed by the deposition and accumulation of carbonate deposited from discharging bicarbonate-rich thermal fluids. Geothermal hydrological models report travertine occurs either (i) on the cooler margins of a geothermal field where a magmatic intrusion is the heat source or (ii) where deep circulating fluids heat up through the natural thermal gradient and dissolve carbonate rocks such as limestone during their ascent. The carbonate is then deposited at the surface from the discharging bicarbonate water.

Unlike siliceous sinter and travertine, silica residue forms not by mineral deposition from thermal fluid but by dissolution via acidic steam condensate of volcanic rocks such as ignimbrites. The silica is dissolved from the silica-rich rocks and re-deposited at the surface to create a thin silica-rich veneer.

3.2 Siliceous Sinter Architecture

Walter (1976) developed a general framework illustrating the relationship between hot spring water temperature, microbial communities and sinter textures. Cady and Farmer (1996) produced a model that summarizes major biofacies, lithofacies and taphofacies trends along a thermal gradient in modern hot spring settings where each distinctive texture inferred a specific location on the vent to distal-apron flow path. Their model was based on hot springs at Yellowstone National Park but similar trends have been observed around the world (Walter, 1976; Lowe et al., 2001; Lynne and Campbell, 2003).

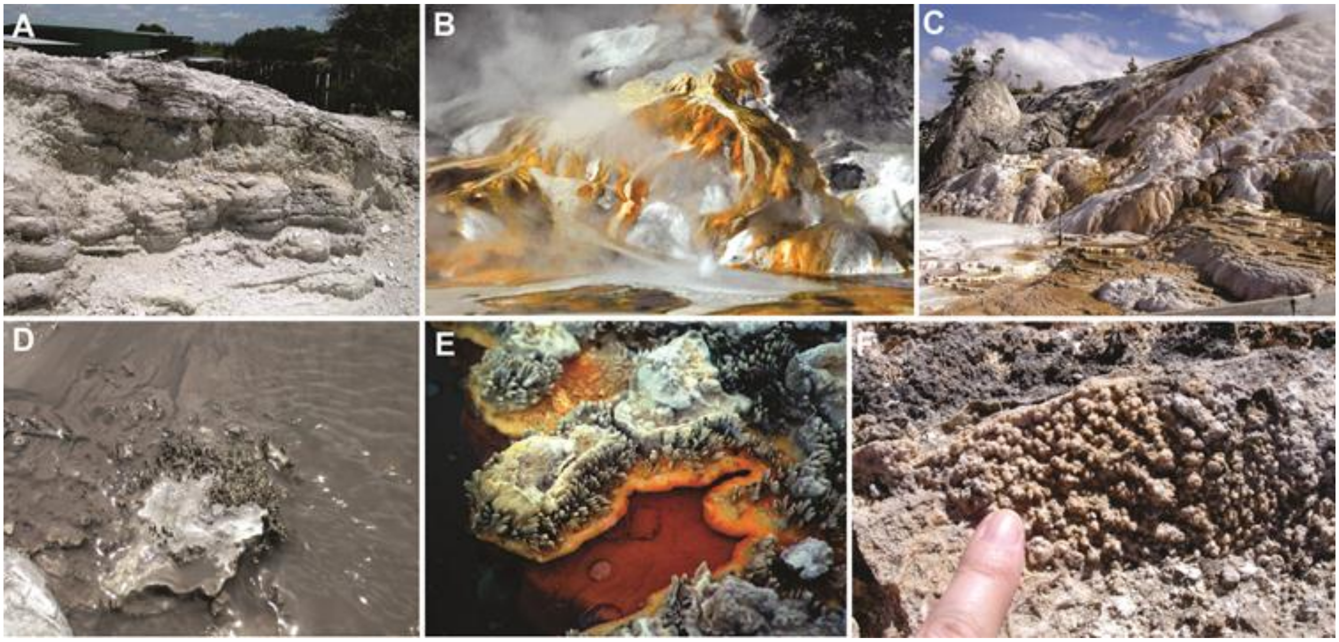

Fig. 1. Geothermal surface activity and associated surface rock deposits. (A) Outcrop of ignimbrite undergoing alteration via acidic steam condensate producing silica residue. (B) Discharging alkali chloride hot springs forming sinter (white rock) with coloured microbial mats living in the warm water. (C) Discharging bicarbonate hot springs forming travertine (white rock). Coloured microbial mats inhabit the warm water. (D) Silica residue. (E) Siliceous sinter. (F). Travertine.

Thermal settings are represented by a variety of sinter textures. For example, sinter architecture differs for high-, mid- and low-temperature pools and discharge channels. Splash zones, deep pool floors, shallow terracettes, fast flowing channels, and turbulent high temperature vents are examples of environmental conditions that produce distinctive sinter textures (Lynne, 2010; Lynne, 2012).

Sinters undergo a 5-step series of silica phase transformations from opal-A to opal-A/CT to opal-CT to opal-C and eventually to quartz (Lynne et al., 2005, 2007, 2008). Over time, and during these silica phase changes, environmentally-significant textures within sinters are preserved (Walter et al., 1996; Trewin, 1994; Rice et al., 1995; Lynne et al., 2005; 2008). Therefore sinter architecture provides a tool whereby former thermal fluid flow pathways can be identified from ancient sinter deposits. The recognition of these textures enables the mapping of hot spring paleo-flow conditions (i.e., temperature, flow rate) and the identification of former hot up-flow zones (i.e., high temperature vents) in areas where hot springs no longer discharge.

3.2.1 High temperature texture (>90 °C)

Spicular, nodular and columnar textures commonly form in high temperature (>90°C), near-vent environments and are referred to as geyserite. These textures form in the splash zone of eruptive hot springs, pools and geysers, where the sinter surface is intermittently wet and dry (White et al., 1964; Renaut and Jones, 2000). Geyserite architecture consists of stacked, convex laminations within each column, nodule or spicule (Fig. 2). The characteristic convex laminations distinguish it from other similar textures.

Fig. 2. Typical high-temperature, eruptive hot spring and associated sinter. (A) >90°C eruptive alkali chloride hot spring surrounded by opal-A sinter. (B) Plan view of opal-A sinter reveals nodular clusters characteristic of geyserite sinter. (C) Cross-sectional view of quartzose geyserite clearly shows multiple stacks of convex laminations that define geyserite texture.

3.2.2 Mid-temperature texture

Mid-temperature hot springs and discharge channels (35-59 °C) flowing over mid-slope settings are inhabited by thin, sheathed filamentous cyanobacteria. The filamentous cyanobacterium *Leptolyngbya* (previously called *Phormidium)* thrives in mid-temperature alkali chloride waters (cf. Walter, 1976; Lowe et al., 2001) and consists of microbes with finely filamentous, <5 µm exterior diameters (Hinman and Lindstrom, 1996; Campbell et al., 2001; Lynne and Campbell, 2003). As these microbes photosynthesize, released gas accumulates within the mat and forms bubbles. The microbial mat surrounding the bubbles is silicified to produce macro-scale sinter textures of multiple curved laminations with oval or lenticular voids (Fig. 3). Void dimensions indicate where you are in the discharge channel. Oval voids parallel to the bedding plane form on pool floors. Flattened oval voids form in discharge channels and elongated voids indicate fast flowing water.

Fig. 3. Mid-temperature, alkali-chloride, hot spring microbial mats and associated sinter texture. (A) Living microbial mat (bubblemat) showing trapped oxygen bubbles in gel-like mat. (B) Partially silicified bubblemat. (C) 11,493 ± 70 year old, quartzose, bubblemat sinter with oval voids preserved where oxygen was once trapped (arrows).

3.2.3 Low-temperature palisade textures (<35 °C)

Low-temperature alkali chloride hot-springs commonly support the cyanobacterium *Calothrix* and form sinters that contain coarsely filamentous, sheathed cyanobacteria (Cassie, 1989; Cady and Farmer, 1996). These microbes consist of an inner tubular filament mould or trichome of porous cellular material, and thick outer sheaths, with a total exterior diameter of >8 μm. Often the trichome decays and secondary silica fills the void. Silica infill consists of silica that is not laminated. Sinter architecture consists of closely-packed, vertically-stacked, micro-pillar structures referred to as palisade texture (Fig. 4). Environmental conditions favourable for palisade textures are low-temperature, shallow fluid flowing over micro-terracettes of previously formed sinter. Palisade textures are visible at the macro-scale with lamination thicknesses (commonly < 5 mm thick) controlled by water depth.

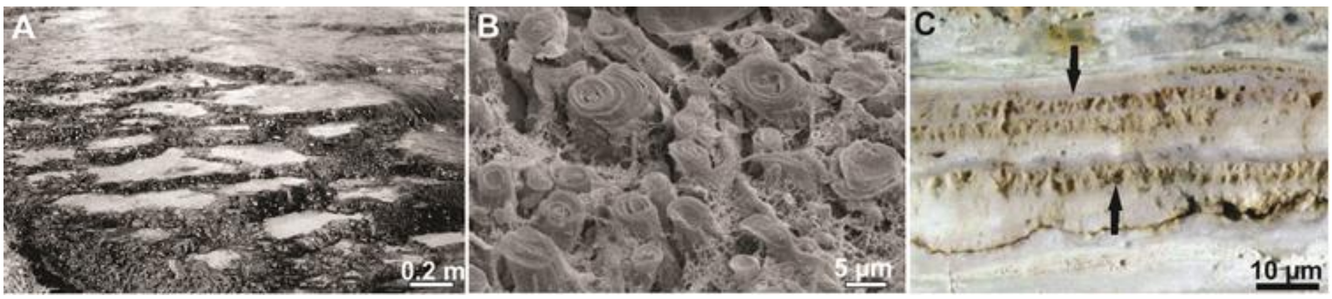

Fig. 4. Low-temperature (<35°C), alkali chloride hot spring setting and associated sinter texture. (A) Shallow, terracette setting typical of low-temperature, hot spring discharge area where slow flowing water ponds in micro-terracettes and black microbial mats live in the hot spring water. (B) Vertically-aligned microbes from black mat shown in (A). (C) 1920 ± 160 year old palisade texture (arrows) within quartzose sinter indicating sites of preserved low-temperature microbes from a similar hot spring setting shown in (A).

3.3. Sinter dating

^{14}C Accelerator Mass Spectroscopy (AMS) was used to date entombed plant material in sinter samples from New Zealand and the USA. Sinter dating provides a temporal context for the spatial distribution of sinters and hot spring paleo-flow paths. Dating also distinguishes those sinters that may be sufficiently young to be related to a potentially exploitable geothermal resource at depth, from those that are less likely to be associated with a useable resource based on age. It is important to note that the age of the sinter may not be related to its silica phase (Fig. 5). For example, quartzose sinter from Steamboat Spring, Nevada, has been dated at ~11,500 years old (Lynne et al., 2008), while quartzose sinter from Opal Mound, Utah is only 1920 years old (Lynne et al., 2005).

Sinter dating enables fluid flow migration trends to be identified on both a local and regional scale. The timing of discharging fluids can be related to the geology and structure of the area. The identification of geologic and structural controls to fluid flow such as the location of faults, the timing of fault movements, topography or stratigraphy, enhances our understanding of the deeper geothermal system.

3.4. Ground Penetrating Radar

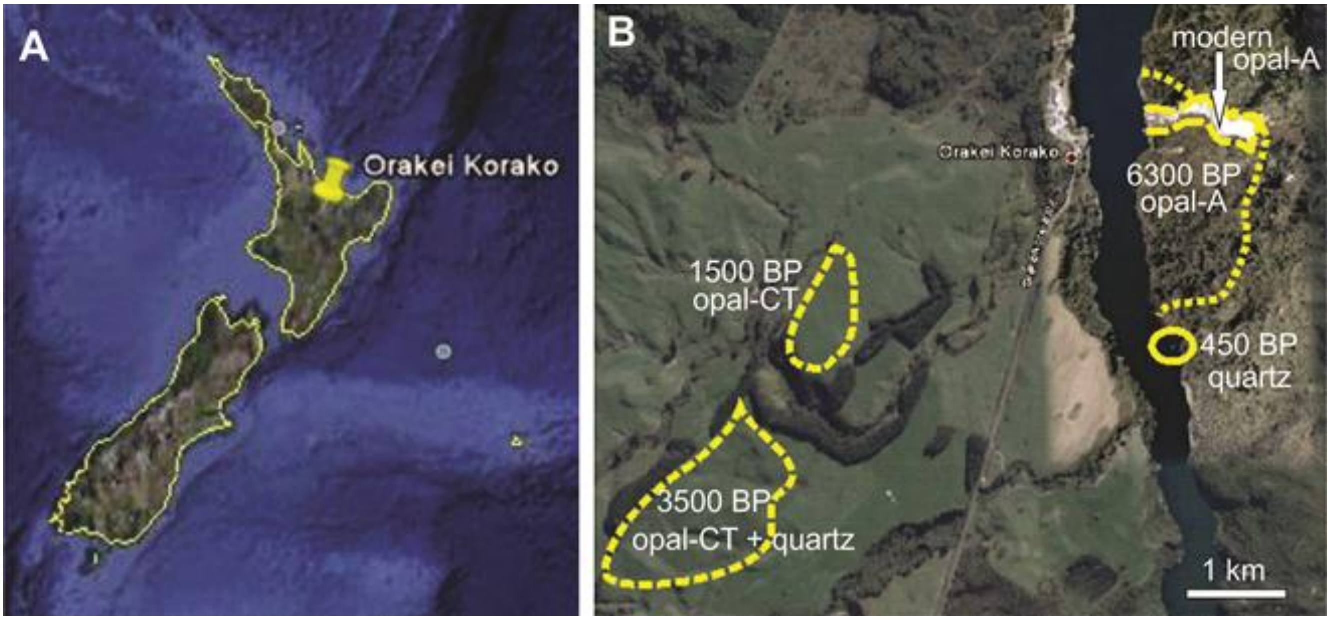

Fig. 5. Tracking alkali chloride hot spring migration pathways over time via sinter dating. (A) Location of Orakei Korako within New Zealand. (B) Sinter deposits in the Orakei Korako area outlined in yellow. ^{14}C AMS dates and silica phase shown for each sinter deposit.

The use of GPR in our sinter exploration work removes the restriction of only working with an outcrop and enabled the volume of a sinter to be better estimated. For example at Opal Mound, Utah, USA a 1920 year old outcrop is exposed with dimensions of 15 m wide x 50 m long x 2 m thick. This calculates to a volume of 1500 m^3. However, our GPR imaging revealed a large amount of sinter was buried. To verify that the GPR signature was sinter, we cored into the subsurface to confirm the presence of sinter. Based on the GPR image we predicted the depth of the sinter sheet and the coring hit sinter within several centimeters of our predicted depth. Using information obtained from both our GPR and outcrop information, the spatial extent of the sinter was shown to be >50 m long x >100 m wide, with a thickness of over 10 m. Therefore the volume of the sinter at this site was actually >50,000 m^3, an order of magnitude greater than estimated by outcrop.

Another example where we imaged the extent of a buried sinter using GPR was at Horohoro, New Zealand (Fig. 6). At Horohoro, a 2 m^2 area of sinter was observed in outcrop. However, by using GPR we were able to determine the lateral and vertical extent of the buried sinter to be at least 40 m^2.

In the Waipahihi Stream area, New Zealand, historic photographs taken around the early 1900's show the presence of an expansive sinter sheet. At this time the area was a well-known tourist location. However, today the extinct sinter terrace is buried. We used GPR to map the area shown in the historic photographs which allowed us to image the buried sinter. Coring established the exact depth of the sinter and it was located within five centimeters of the depth we predicted from our GPR image.

Further GPR work in thermal areas showed that we can establish directionality and connectivity between hot spring vents, subsurface connectivity of fractures (to within 15 m depth) and identify locations of ground altered via acidic steam condensate.

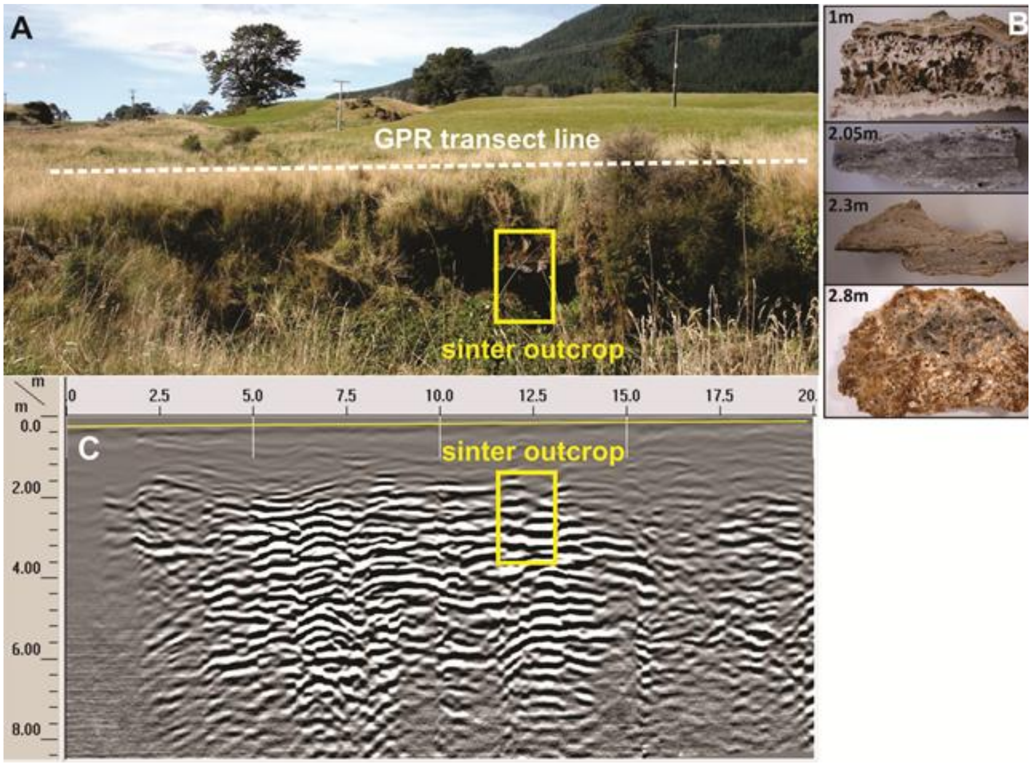

Fig. 6 Sinter area, Horohoro, New Zealand. (A) Sinter outcrop (yellow boxed area) in 4 m thick scarp. (B) Photographs of sinter in outcrop at various depths. (C) GPR image taken along the scarp directly above and to both sides of the sinter outcrop (yellow boxed area) reveals sinter is present laterally over a distance of ~ 18 m and is ~ 6 m thick. The sinter is shown as strong black and white reflections in the GPR image.

3.5 Growth of sinter deposits

Geochemical modelling of silica deposition rates and the growth of hydrothermal sinter deposits has been examined (Boudreau and Lynne, *in press*) using measured silica concentrations, temperature, flow rate and dimensions of currently discharging hot springs in New Zealand. Weather conditions such as ambient air temperature, humidity, wind, and evaporation rate have also been measured for each feature. From this data, Bordreau and Lynne (*in press*) model the growth of high-temperature eruptive hot springs such as geysers. This work is based on the silica content of the fluid, hydrodynamics of the discharging hot springs and weather conditions. The specific sinter texture that forms in these environments consists of a series of peaks and depressions (see Fig. 2). The silica modelling work takes into account the textures of this environment and provides explanations for abiotic growth of such distinctive textures. Future work will include extending the rate of silica accumulation modelling to mid- and low-temperature hot spring settings.

4. Conclusion

It is important to recognize the different types of hot spring rocks (sinter, travertine, silica residue) as each deposit forms through a different process with each process providing different information about the geothermal system. The identification of siliceous sinters is important for early geothermal exploration as they form from discharging alkali chloride hot springs and provide evidence at the surface of a deeper potentially exploitable geothermal reservoir. Long after hot spring discharge ceases, sinter textures are preserved and the geothermal system may remain at depth. Therefore, sinters may be the only evidence at the surface of a hidden geothermal resource. The recognition and mapping of preserved environmentally-significant textures in ancient sinters reveals hot spring paleo-flow conditions and temperature gradient profiles from high-temperature vents to low-temperature, distal-apron slopes. Sinter dating reveals the timing of discharging hot springs and enables the tracking of discharging fluids on a regional scale. The addition of Ground Penetrating Radar and understanding the accumulation rate of sinters further extends the sinter textural work to provide a better understanding of the total mass flow of alkali chloride fluids discharged from any given geothermal area. These simple techniques can be added to and compliment other standard geological and geochemical work usually undertaken in the early stages of any geothermal exploration project.

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