# COMPLEXITIES OF SINTER DIAGENESIS

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**SUMMARY** - Diagenesis of hot spring rocks (sinters) is complex. $^{14}C$ AMS dating of five sinters revealed that the rates of silica phase changes (opal-A to quartz) are not controlled by time alone. Sinters may reach the diagenetic end-member of quartz in several hundred years, or they may require thousands of years. Other sinters initially formed as opal-A may remain opal-A for many thousands of years. Sinters may record two distinct hot-spring discharge cycles into a single deposit, leading to misinterpretation of the reconstruction and timing of fluid discharge events. Multiple pulses of thermal fluids also complicate evaluation of the paleohydrology and may create a mineralogic-morphologic disjunct within the sinter. Generally, an increase in density and a decrease in porosity accompanies sinter diagenesis and silica phase mineralogical maturation. However, when a sinter is overprinted with acidic steam condensate dissolution commonly occurs increasing secondary porosity. Therefore, the porosity of a sinter can not be used as an indicator of mineralogical maturation. These problems highlight the complexities of interpreting sinter diagenesis and post-depositional events.

## 1. INTRODUCTION

Siliceous sinters are terrestrial hot-spring deposits that typically form when fluids over-saturated with silica cool to temperatures below 100 ºC and deposit silica (Fourner and Rowe, 1966). The silica initially deposits as non-crystalline opal-A from discharging alkali chloride springs. With time and little or no burial, the sinters undergo diagenesis which involves a series of phase transformations from non-crystalline opal-A and opal-A-CT, to para-crystalline opal-CT ± opal-C and eventually to micro-crystalline quartz (Herdianita et al., 2000; Lynne et al., 2005). As the silica precipitates it entombs many biotic and abiotic components present within hot-spring channels or pools. Therefore, sinters preserve environmentally significant components (e.g., microbes, plants, pollen) which remain in the rock record over time. Hydrothermal surface environments were likely to have been present on the Earth billions of years ago so understanding the paleo-environmental record preserved within sinters may reveal insights into settings for early life on Earth.

## 2. SINTER DIAGENESIS AND TIME

Diagenesis is any process whereby a change in texture or mineralogy of a rock occurs at low temperatures and pressures. Herdianita et al. (2000), estimated that complete sinter diagenesis required at least tens of thousands of years for opal-A to reach the end-member of quartz. However, the duration required for opal-A to transform to quartz is highly variable among individual sinter deposits (Table 1).

Herdianita et al. (2000), Campbell et al. (2001), Rodgers et al. (2004), and Lynne et al. (2007) recognised more than one diagenetic pathway accompanying the opal-A to quartz transformation. The varying micromorphologic-mineralogic pathways are due to a variety of post-depositional events that influence micro-scale geochemical conditions and diagenetic rates. Time alone does not control sinter diagenesis (Table 1).

**Table 1: Sinter mineralogy and $^{14}C$ AMS dates**

| Location | Silica phase | Age (years) | Reference |
|---|---|---|---|
| Tahunaatara, TVZ | Opal-CT | 14,500 | Campbell et al., 2004; Campbell unpublished data |
| Steamboat Springs, Nevada | Opal-A | 6500 | Lynne et al., 2008 |
| Opal Mound, Utah | Opal-A | 1600 | Lynne et al., 2005 |
| Steamboat Springs, Nevada | quartz | 11,500 | Lynne et al., 2008 |
| Opal Mound, Utah | quartz | 1900 | Lynne et al., 2005 |
| Sinter Island, TVZ | quartz | 456 | Campbell and Lynne, 2006 |

## 3. FRAGMENTAL SINTERS AND DATING

Fragmental sinters are commonly preserved in the rock record but may be problematic when used for dating, as they may consist of sinter fragments originally formed from different hot-spring discharge cycles. Hot-springs do not always discharge continuously, and may flow intermittently or cease altogether. During times of reduced flow, sinter terraces often become dry and brecciate. Once the spring flow recommences, the brecciated fragments become incorporated into the newly-forming sinter. Thus, a sinter deposit may be formed from two distinct discharge cycles (Figure 1).

Many hot-springs are situated in tectonically active areas where fracturing is common. The opening of micro-fractures within a sinter provides conduits whereby sinter fragments resting on the surface may be washed downward into open fractures, and become deposited within stratigraphically, lower and older deposits (Figure 1).

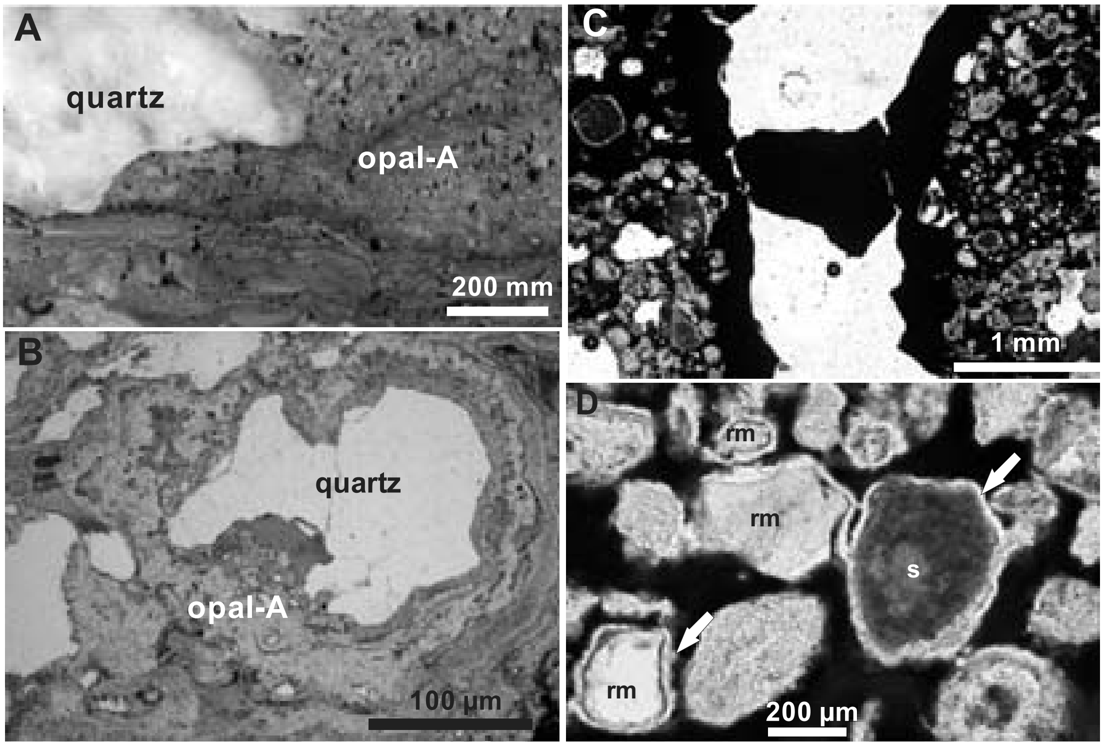

Figure 1: Mixed mineralogies and inclusions within a sinter deposit from Steamboat Springs, Nevada, USA. (A-B) 11,500 BP quartz sinter fragment incorporated within a 6500 BP opal-A sinter. (C) Fracture within sinter horizon with fragment infill from above. (D) Sinter fragments (s) and remnant mineral grains (rm) formed prior to becoming cemented in iron-rich silica.

## 4. MULTIPLE PULSES OF THERMAL FLUID

The varying nature of hot-spring flow is recorded within sinters. Figure 2 reveals multiple influxes of thermal fluid in a sinter from Steamboat Springs, Nevada, USA. Here, X-ray diffraction analysis detected opal-CT, yet scanning electron microscopy revealed opal-A. Careful examination showed small patches of opal-CT underneath the temporally and mineralogically younger opal-A (Figure 2A, 2C). The products of other pulses of thermal fluid also infill voids (Figure 2B), while other samples have an iron-rich matrix cementing iron-poor sinter fragments, suggesting two distinct flow cycles (Figure 2D).

Lynne et al. (2005) reported that a second influx of thermal fluids also occurred at the Opal Mound sinter deposit, Utah, USA. Here, fractures within a 1900 BP deposit, allowed pathways for a later pulse of fluids. This process added heat, thermal water, and silica to the existing deposit, accelerating diagenesis to quartz. Fracturing also opened flow paths to the surface where a temporally younger, 1600 BP, opal-A sinter formed. Clearly, the timing and distribution of discharge events complicates both the dating and mineralogical maturation of individual sinters.

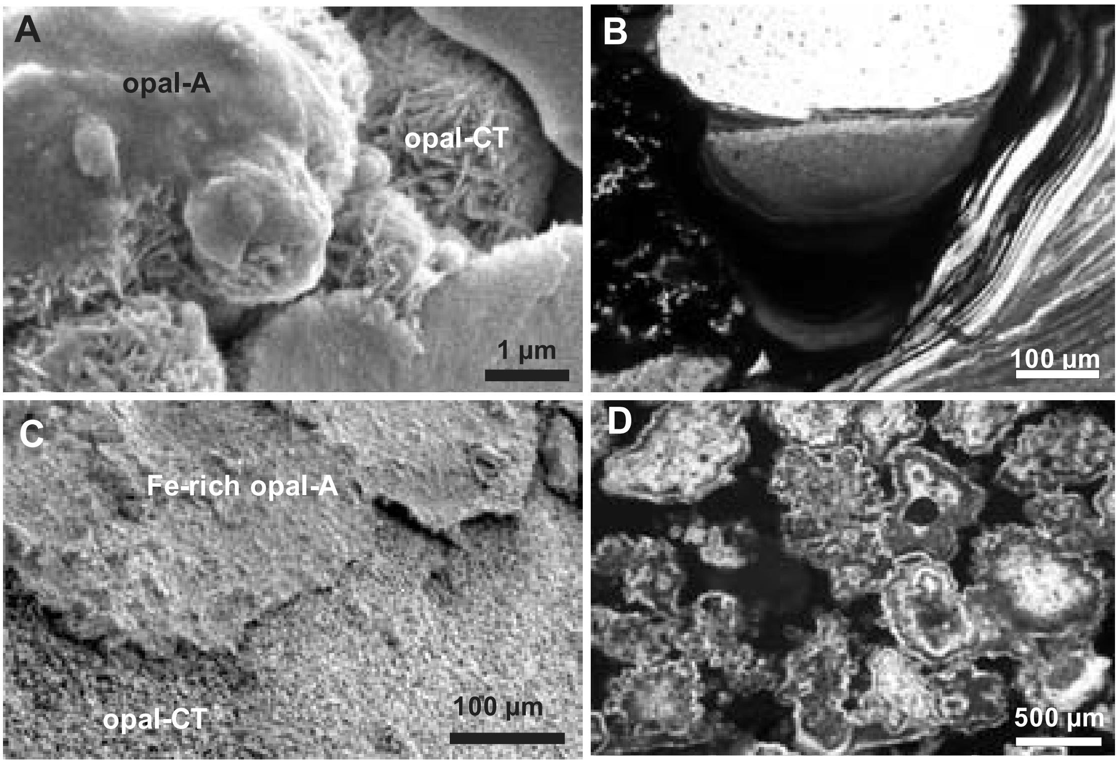

Figure 2: Evidence of multiple pulses of fluid. (A) Opal-A coating opal-CT. (B) Geopetal infill structure. (C) Iron-rich opal-A coating iron-poor opal-CT. (D) Iron-rich matrix surrounding iron-poor sinter fragments.

## 5. DENSITY AND POROSITY CHANGES ACCOMPANYING DIAGENESIS

Herdianita et al. (2000) reported that density increases and porosity decreases with diagenesis. Figure 3 shows the density and porosity trends for samples from Steamboat Springs and reveals that while density increases with diagenesis, porosity does not. At Steamboat Springs secondary porosity is created via dissolution through acidic steam condensate, yielding high porosity values in the mineralogically more mature silica phases (opal-CT to quartz). This resulted in minimal changes in the porosity values that accompanied diagenesis. Therefore, the trend reported by Herdianita et al. (2000) does not necessarily apply to all sinters.

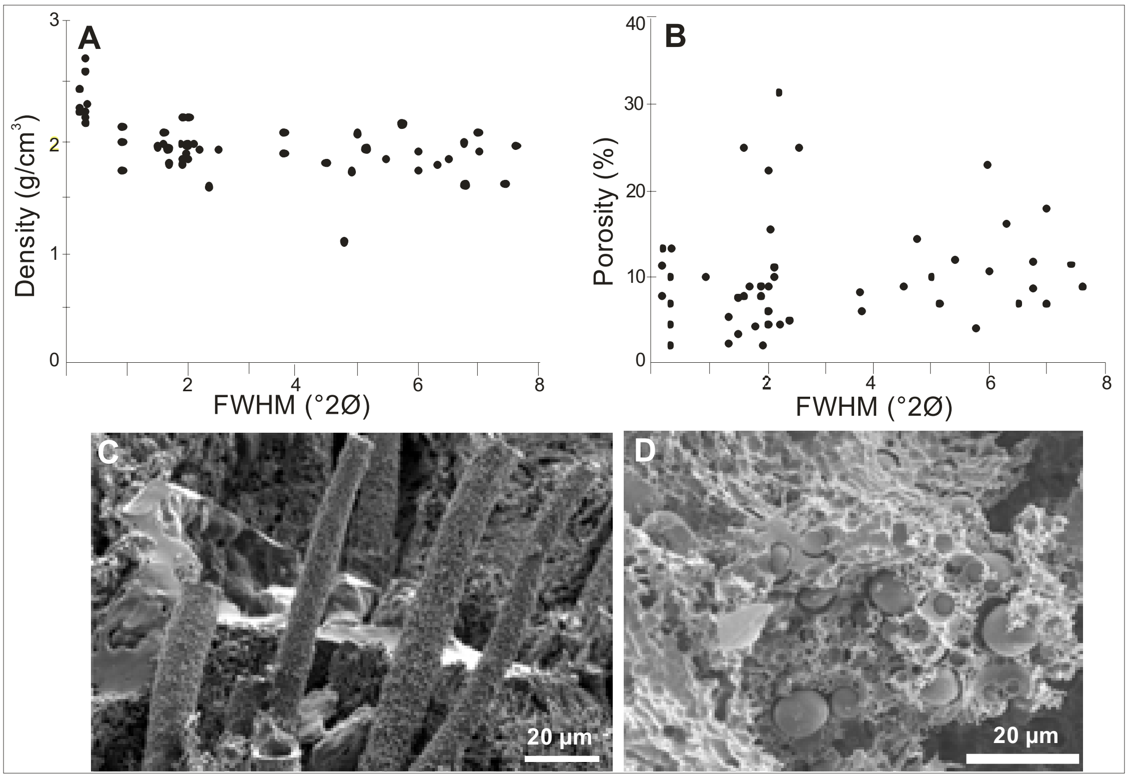


Figure 3: Density and porosity trends accompanying sinter diagenesis at Steamboat Springs, USA. (A) Density increases with silica phase maturation. (B) Porosity does not decrease with silica phase maturation. (C) Dissolution of filaments shown as etched surfaces, Steamboat Springs, USA. (D) Pitted sinter horizon, Sinter Island, NZ. Full Width at Half Maximum (FWHM) is the measure of silica phase crystallinity.

## 6. SUMMARY

Sinter diagenesis is not a simple process. While universal trends are apparent, sinter at each location must be examined to understand fully the processes controlling diagenesis. Numerous post-depositional events influence the morphology and mineralogy, diagenetic rates, and porosity values. Multiple discharge events are common in geothermal systems but if they remain unrecognised, lead to misinterpretation of the relative timing of thermal events, paleohydrologic setting and its temporal context.

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## 8. ACKNOWLEDGEMENTS

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