RELATIVE AGES OF THE BORAX LAKE AND MICKEY GEOTHERMAL SYSTEMS, ALVORD BASIN, OREGON USA: PRELIMINARY EVIDENCE FROM SILICA PHASE TRANSITIONS.

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SUMMARY – We investigated the mineralogy of sinter and travertine deposits associated with the Borax Lake and Mickey geothermal systems in the Alvord Basin, southeast Oregon. Together, the two areas comprise approximately 235 spring vents, located on the edge of the Great Basin, where geothermal systems arising from extensional tectonics and high crustal heat flow are common.

Both the Mickey and Borax Lake systems demonstrate sodium-bicarbonate-chloride-type waters. Surface temperature in both systems range between 24 and 98°C and standard geothermometers indicate reservoir temperatures of 200 – 250°C. Despite the similarity in fluid chemistries, mineral precipitates vary significantly between the two systems. The Borax Lake system is dominated by calcite with minor amounts of amorphous silica (opal-A) and rare microcrystalline quartz. The Mickey system is more diverse and includes: quartz, opal-A, opal-CT, microcrystalline quartz, hematite, and minor calcite. Using silica phase transformations as an indicator of relative age, we suggest that the occurrence of opal-A, opal-CT and quartz at Mickey indicates the system is older than the Borax Lake system.

1. INTRODUCTION

Silica sinter is the result of silica deposition in the geothermal environment. Initial deposition is of noncrystalline opal-A, which over time transforms to paracrystalline opal-CT ± opal-C and eventually to microcrystalline quartz (Herdianita *et al.*, 2000). In additional to the phase transformations, this process also results in observable changes in silica morphology: from opal-A microspheres to opal-CT and opal-C lepispheres through to equant microcrystalline quartz (Herdianita *et al.*, 2000; Campbell *et al.*, 2001). Herdianita *et al.* (2000) reported that the process of silica transformation required approximately 40,000 in undisturbed systems, however external factors such as excess organic matter or post depositional alteration, can accelerate the process. Hence, it is theoretically possible to use the silica phase transformation process as an indication of relative ages when comparing geothermal springs and/or systems.

The Alvord Basin, Oregon USA, contains three active geothermal systems: Borax Lake, Mickey and Alvord. Although investigated in the early 1980's as a possible site for geothermal energy production, both the Mickey and Borax Lake systems are protected and have remained undisturbed. As a result the systems have also remained relatively unstudied and there are many questions that remain unanswered, such as the relative ages of the systems. Our current study is part of a larger research program of the geothermal springs in the Alvord Basin (Fairley *et al.*, 2003; Fairley and Hinds, 2004; Koski and Wood, 2004). We have concentrated on the water chemistry and precipitate mineralogy of the Mickey and Borax systems (Colter *et al.*, 2004; Garringer *et al.*, 2004; Link *et al.*, 2004; Fairley and Nicholson, submitted; Nicholson *et al.*, submitted). As an indirect result of this work, we have begun to see distinct difference between the two systems. In particular the precipitate mineralogy is significantly different, resulting in preservation of different microbial textures. Our basic goal is to determine the relative age of the systems, which will have important implications on fault dynamics. This is a preliminary attempt at characterisation of diagenetic transformations and sinter textures in the two systems.

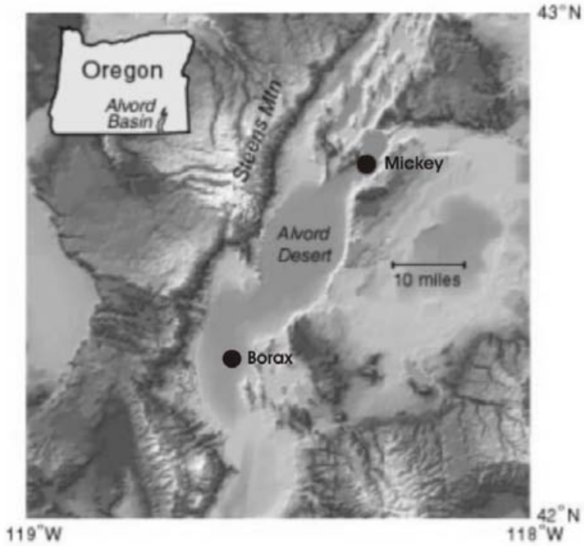

Figure 1. Map showing the relative locations of the Mickey and Borax Lake geothermal systems within the Alvord Basin, SE Oregon, USA.

2. GEOLOGY

The Alvord Basin is a north-northeast-trending graben in the continental USA Basin and Range Province, southeastern Oregon. Bounded on the east by the Sheepshead and Trout Creek Mountains and on the west by tilted faultblock mountains of the Steens and Pueblo Ranges (2975 m elevation), the north-central portion of the valley (roughly 250km^2) is covered by a large playa known as the Alvord Desert. The basement in the area consists of Permian and Triassic metamorphic rocks, dominated by quartzite, greywacke, greenstone, schists, argillite and minor marble. Cretaceous intrusions of gneissic granodiorite and quartz diorite cut the older metamorphic rocks, which are overlain by Miocene and younger volcanic rocks successively comprising rhyolite and dacite flows and tuffs, andesite and basalt flows, and finally minor siliceous flows and tuffs. Finally, the basin is filled with Plio-Pleistocene and Holocene alluvium.

The area experienced regional extension during the Cenozoic resulting high crustal heat flow and the observed thermal activity (Brown and Peterson, 1980; Cummings *et al*., 1993). Field and geophysical data suggest that each hot spring grouping is associated with faulting (Koski and Wood, 2004). Faults in the Alvord Basin are generally vertical or steeply dipping normal faults, striking north to northeast, and cut sequences of Miocene-age volcanics, including basalt, rhyolite, and tuff. Secondary faults are also steeply dipping and trend northwest. Studies of Alvord Basin geology have established that faulting is active along the western boundary of the basin based on geomorphic evidence and reports by residents of earthquakes in the 1920s and 1940s (Williams and Compton, 1953; Hemphill-Haley, 1987).

Within the Alvord Basin there are three main groupings of thermal springs: Borax Lake, Mickey and Alvord hot springs (Figure 1). The Borax Lake area consists of about 178 springs, aligned along the trace of a northeast-striking normal fault. Spring temperatures at Borax Lake range from 23.9 to 95.5^{o}C (average 62.1^{o}C), and pH ranges from 5.8 to 8.6 (average 7.3). Mickey Hot Springs, located 45 km to the northeast of Borax Lake, includes about 57 spring vents organized in discrete pods, ranging in temperature from 33.7 to 97.7^{o}C (average 79.1^{o}C) and pH ranging from 5.6 to 9.3 (average 7.7). In general all the waters are sodium-bicarbonate-chloride-type with a significant proportion of sulfate and are also high in As (1-6 mgL^{-1}) and B (10-27 mgL^{-1}). Waters from different springs within each thermal area exhibit remarkably coherent chemical characteristics. Oxygen and hydrogen isotope compositions are similar for waters in all three thermal areas and are consistent with meteoric water that has undergone O-isotopic exchange during water-rock interaction. Values of sulfate δ^{34}S and bicarbonate δ^{13}C show a very narrow range both within and among the two thermal areas (Cummings *et al*., 1993; Koski and Wood, 2004).

3. METHOD

Samples were taken from springs in both the Mickey and Borax Lake systems. Sample locations were chosen to accurately represent the range of features and fluid characteristics in each system (i.e. differing temperature, pH and precipitates). In total 17 discrete springs were sampled: 9 spring from Borax Lake and 8 spring samples from Mickey. A minimum of 50gm of sample was taken from each spring to allow for multiple analyses. Samples were prepared in a test-tube by dispersing the supplied crushed rock powders in a solution of distilled water containing a de-flocculent. The test-tube was then placed in an ultrasonic bath, followed by centrifuging and then mounted on a glass slide. The air dried X-ray diffraction (XRD) profiles were collected using a Philips PW 1050/25 diffractometer run at 20mA and 40kV using CuKα radiation between 2^{o} and 80^{o}. Selected XRD profiles are shown in Figure 2a (Mickey) and Figure 2b (Borax).

In addition to XRD analyses, selected sinter and travertine samples were analysed using scanning electron microscopy (SEM) at the University of Idaho. Samples were mounted on aluminium stubs and sputter coated with carbon. Selected SEM photos are shown in Figure 3 (both Borax and Mickey).

4 XRD AND SEM RESULTS

Whole rock XRD analyses of the samples from the Borax Lake system yielded variable results (Table 1; Figure 2). Eight of the nine springs sampled from the Borax Lake system were dominated by calcite, as evidenced by the formation of surficial calcite travertine deposits. Four of the spring samples contained feldspar and halloysite. Opal A and trace amounts of microcrystalline quartz were identified in five samples. In addition, a boron-bearing carbonate phase was also identified (possibly kutnahorite) in three samples.

The whole rock spectra from the Mickey system also have a varied mineral assemblage (Table 1; Figure 2). Six of the samples contained a feldspar, possible plagioclase, the samples also contained a mixture of calcite, quartz and hematite. In addition to quartz, many of the samples contain opal-A and opal-CT. Only one sample from the Mickey system contained halloysite.

TABLE 1

Sample	Minerals Identified by XRD
Borax Lake geothermal system	
B0050	Calcite
B0360	Calcite, carbonate*, feldspar (plagioclase?), trace quartz
B0810	Calcite, opal-A
B1210	Calcite, carbonate*, plagioclase, opal-A
B7	Smectite, halloysite
Flowing	Calcite
B1390	Calcite
B1430	Feldspar, quartz, clay†, opal-A, halloysite
Mickey geothermal system	
M0130A	Opal-A/CT
M0130B	Opal-A/CT, plagioclase
M0280	Plagioclase, clay†, quartz, calcite?
M0340	Feldspar, clay†, quartz, calcite?
M0480	Halloysite, hematite, poorly crystalline kaolinite
M0540	Plagioclase, trace clay†, quartz, trace calcite
ML	Feldspar, trace clay†, calcite
LM	Illite

*possibly kutnahorite. † smectite and/or illite-smectite

Spring waters are expelled in the vents at 24-96^{o}C at the Borax Lake system. The higher temperature springs (65-96^{o}C) precipitate travertine mounds with minor amounts of opal-A and para or microcrystalline quartz (Figure 3d,e,f). In addition fine needles of aragonite are present in travertine associated with higher temperature vents. The calcite takes a variety of forms, in places it occurs as ridged crystalline networks in which crystal form and cleavage are easily visible. At lower temperatures calcite occurs as both crystalline and microcrystalline coatings on organic matter, and rare calcite spherules.

The Mickey system is slightly warmer than the Borax system with spring temperatures in the range of 33-98^{o}C. All the springs sampled from Mickey are precipitating silica and only one was dominated by calcite. Higher temperature springs contain opal-A and opal-CT, whereas some of the cooler springs were dominated by microcrystalline quartz (Figure 3a,b,c). The opal

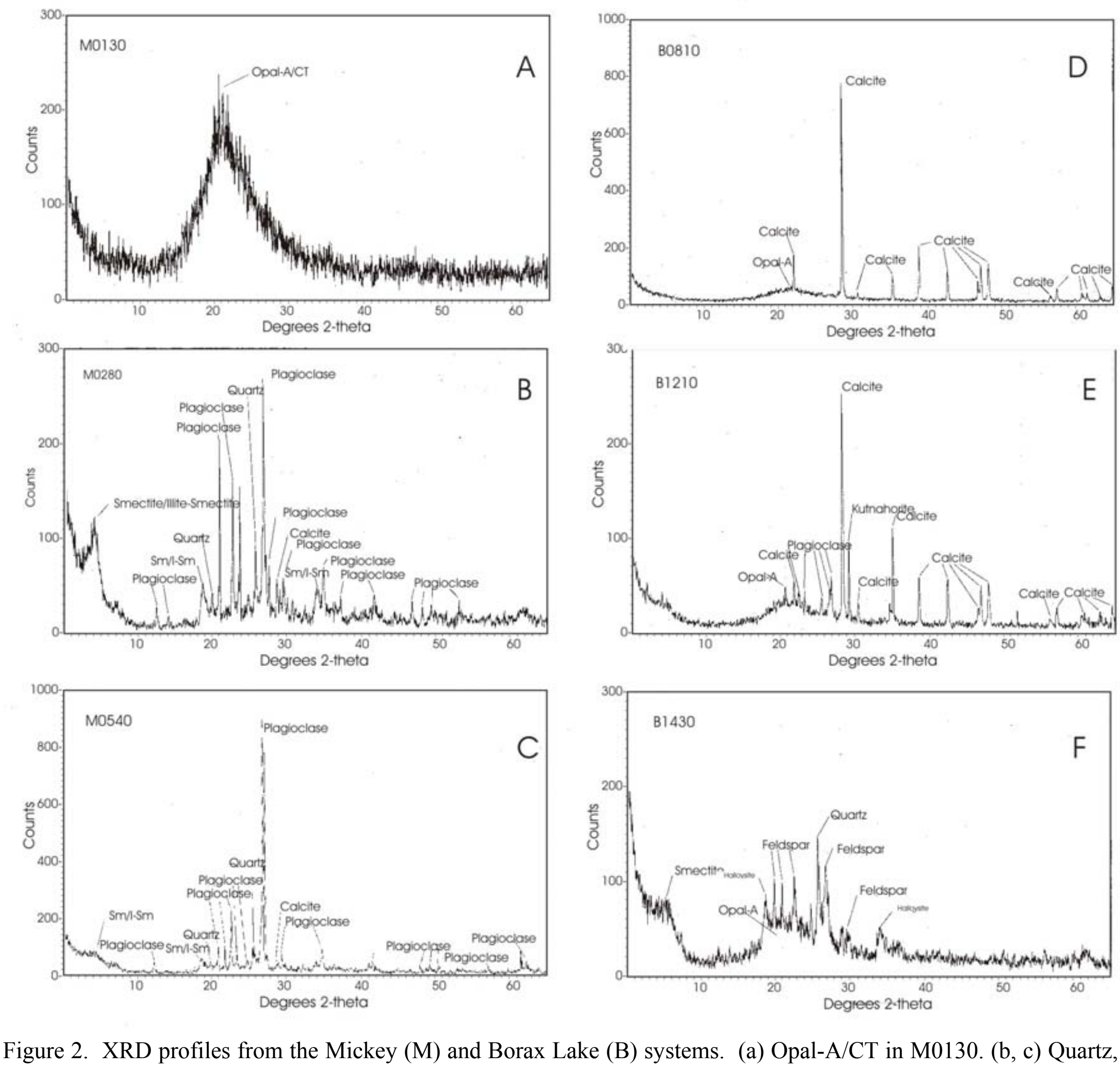

Figure 2. XRD profiles from the Mickey (M) and Borax Lake (B) systems. (a) Opal-A/CT in M0130. (b, c) Quartz, plagioclase, smectite/illite/smectite, and calcite in M0280 and M0540 respectively. (d) Opal-A and calcite in B0810. (e) Opal-A, calcite, plagioclase and kutnahorite(?) in B1210. (f) Opal-A, smectite, feldspar and hallyosite in B1430.

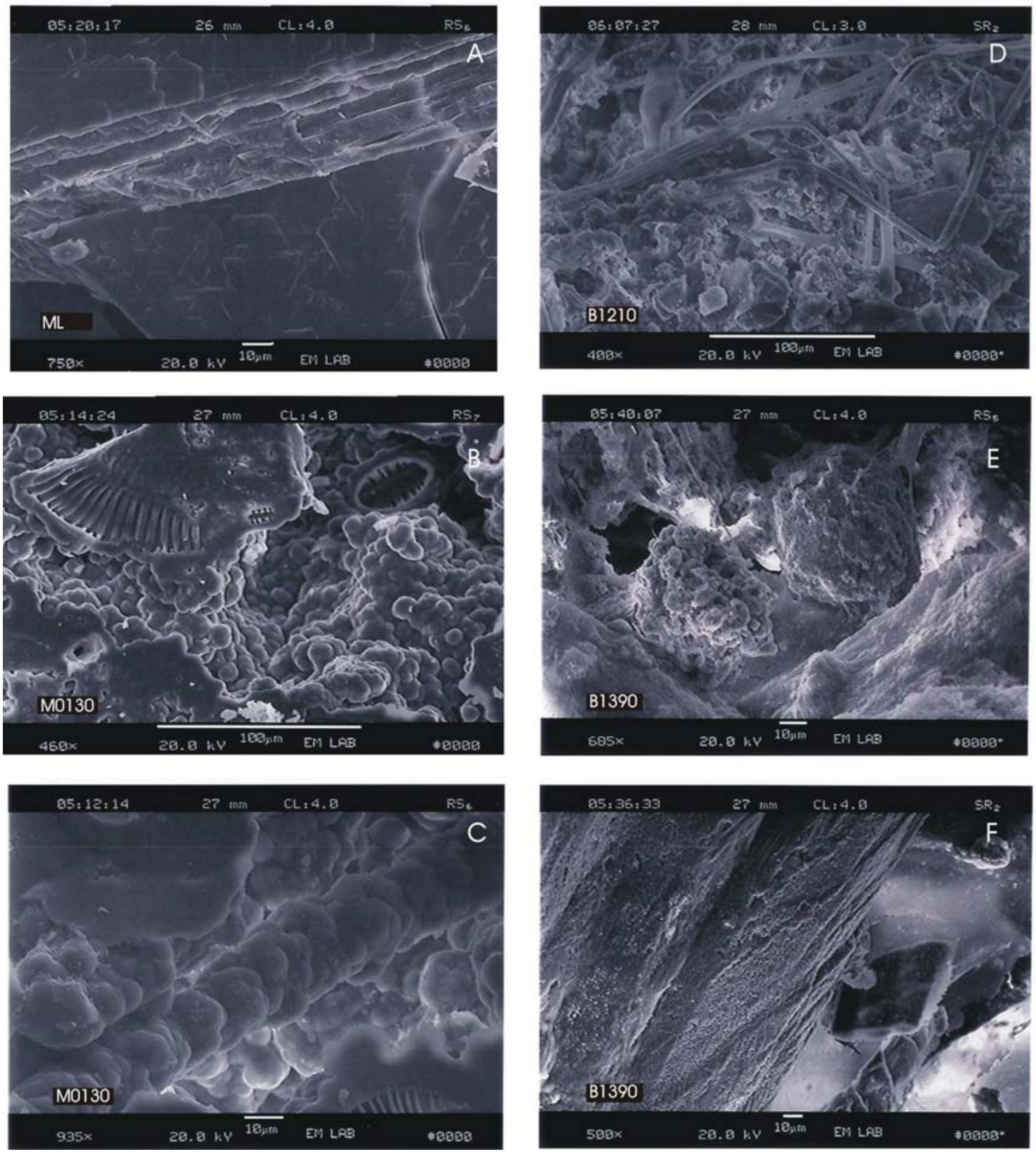

Figure 3. SEM photomicrographs of samples from the Mickey (M) and Borax Lake (B) systems. (a) Calcite showing cleavage in ML. (b) Opal-A microspheres and both oblique and cross-sectional views of preserved cyanobacteria in M0130. (c) Opal-A/CT filament moulds with cyanobacteria in M0130. (d) Tubular filament moulds and palisade fabric in B1210. (e) Aragonite needle, opal-A spheres and palisade fabric in B1390. (f) Lightly silicified palisade fabric with course grained crystalline calcite in B1390.

commonly forms bubble mats (lenticular voids) and as silica diagenesis proceeds opal obscures all microbiotic activity with the exception of microbially secreted exopolymeric substance and cyanobacteria sheaths. In samples from the cooler springs, microbial activity is almost entirely obscured as opal transforms to microcrystalline quartz.

5. DISCUSSION

Chemically both the Mickey and Borax Lake systems are similar however our preliminary study of precipitate mineralogy shows the systems are distinctly. Opal-A is present in samples from both the Borax Lake and Mickey system. Opal-A is amorphous and generates broad low intensity profiles. It is found in higher abundance in the Borax Lake system than at Mickey. Opal-CT has sharper peaks that are often of higher intensity. Opal-CT is found in the Mickey system but not at Borax. Both systems contain some amount of microcrystalline quartz, but it is more common in Mickey. In summary the Mickey system in dominated by microcrystalline quartz, crystalline quartz and opal-CT, whereas the Borax Lake system in dominated by calcite, opal-A and rare microcrystalline quartz.

Recent sinter studies suggest that age dating of sinter deposits is possible using the phase transition from opal to quartz (Herdianita *et al*., 2000; Campbell *et al*., 2001; Lynne and Campbell, 2003). Silica phase transformations in geothermal systems follows the predictable sequence found in petrified wood and diagenesis of siliceous marine sediments where amorphous opal-A transforms into paracrystalline opal-CT through to microcrystalline quartz. In systems not affected by external factors, such as other minerals and excessive microbiological activity, the transformation from opal-A through to microcrystalline quartz takes between 30,000 to 40,000 years (Herdianita *et al*., 2000). Hence samples such as those from Mickey have been dated at upwards of 40,000 years (Herdianita *et al*., 2000). Samples similar to those found in the Borax Lake system, that contain opal-A without opal-CT nor quartz, from the Taupo geothermal area in New Zealand have been dated to around 3500 years (Lynne and Campbell, 2003). Although the systems are much different, the basic principals are applicable: the samples with opal-CT and microcrystalline quartz are much older than the samples containing only opal-A.

Both the Mickey and Borax Lake systems contain microbiological activity, which may affect the silica phase transformation. Hot spring microbial communities comprise a wide range of diverse biotic components, most of which quickly become obscured by early silicification. Due to the low maximum temperature tolerance of microbes, they are generally only found a few millimetres above the spring waters. However, cyanobacterial sheaths and courser filamentous palisade microfacies are often preferentially preserved. Our preliminary comparison of organic preservation between the Alvord Basin and systems studied in New Zealand (Lynne and Campbell, 2004) suggests microbe preservation in the systems is broadly similar and that neither Mickey nor Borax exhibit excess microbial activity. Hence, our interpretation of these results suggests that the springs sampled from the Borax system are younger than the Mickey hot springs samples.

Fault-controlled palaeo-geothermal systems were responsible for the numerous small, but widespread, ore bodies known to exist in the Alvord Basin including: schwatzite (mercury tetrahedrite) and cinnabar. Other, less abundant minerals associated with hydrothermal deposits in the Alvord Basin include hematite, pyrite, arsenopyrite, and galena; secondary minerals include malachite, azurite, chrysocolla, cuprite, and various iron oxides (Williams and Compton, 1953).

Despite the apparent chemical similarities between Mickey and Borax, the precipitate mineralogy is controlled almost exclusively by fault hydraulics. The Borax Lake system is controlled by a single normal fault, which experiences limited activity. We suggest that the Borax Lake fault has not been active for a long period of time, possibly less than 4000 years. The Mickey system is also fault controlled but the faulting involves active conjugate faulting and the presence of opal-CT and microcrystalline quartz suggests the system is older and longer lived, possibly as old as 30,000 years. Although the system is relatively old, movement on the fault is active allowing system migration and boiling to occur near surface resulting in slightly higher surface temperatures than are found in the Borax Lake system. Although there are currently no working claims in the Alvord Basin, the strong connection between ore emplacement, fault dynamics and geothermal activity suggest the Alvord Basin geothermal systems would provide a good opportunity for future studies on the impact of hydrothermal fluid transport on ore emplacement.

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