

Quaternary Borate Deposits as a Geothermal Exploration Tool in the Great Basin

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ABSTRACT

A close spatial relationship exists between Quaternary borate deposits and moderate to high temperature ($\geq 150^{\circ}\text{C}$) geothermal systems in the western portion of the Great Basin, USA. Similarly, a strong correlation exists between high concentrations of boron in groundwater and geothermal activity in the Great Basin. These relationships have special significance for geothermal exploration because in a number of cases, Quaternary surface borates occur without associated springs, and thus the borates can, and are, serving as a guide to locating otherwise blind geothermal systems.

Borate deposits typically form by the evaporative concentration of boron-enriched thermal spring waters in a closed basin whose topography prevents significant influx of relatively boron-poor clastic sediments and chemical constituents from outside the basin. The relatively high boron concentrations of geothermal waters may ultimately be due to the greater opportunity of hot waters, which have relatively deep circulation paths, to interact with and leach boron-bearing host rocks. Deep-seated magmas may also be a significant source of boron.

In southern California and western Nevada, the highest concentrations of boron are sometimes found in warm springs instead of hot springs. In some cases, this could be caused by remobilization of boron from older borate deposits by shallowly circulating groundwater, but in other cases, geothermometry data suggests such springs may actually consist of geothermal waters that have cooled significantly below their peak temperatures before reaching the surface.

Using borates as an exploration guide, and with key assistance from remote sensing techniques, three new geothermal targets have been identified in west-central Nevada at Rhodes, Teels, and Columbus Salt Marshes (playas). In each of these

playas, geothermometry data from springs and wells suggest the possible presence of geothermal reservoirs at depth.

Introduction

Awareness that hot springs and steam vents, especially in volcanic terrains, sometimes have high concentrations of boron has been known since at least 1790 when the production of boric acid and borate minerals from geothermal brines began at Larderello, Italy (Lund, 1996). The relationship between thermal springs and borate deposits became more evident during the late 1800s as numerous discoveries were made of borates in the spring “aprons” or discharge zones of active hot springs in the United States and Chile (Smith, 1985). From descriptions of Smith (1979) and Barker and Barker (1985) it seems clear that thermal springs were at times targeted as sites to explore for potentially mineable borate occurrences in the last century. Nevertheless, there is little evidence that borates, at least in recent times, have been used in a systematic manner to explore for geothermal systems. This paper reviews the relationship between Quaternary borate deposits and active geothermal systems in the Great Basin, investigates some of the complexities of the relationship, and discusses the value of borates as a geothermal exploration tool. New evidence is presented to suggest that three borate occurrences in west-central Nevada may be associated with previously unknown, concealed, potentially high-temperature geothermal systems.

Quaternary Borates and Boron in Geothermal Fluids

Quaternary borate deposits are found along the western side of the Great Basin in a 100-200-km-wide belt that roughly parallels the eastern margin of the Sierra Nevada batholith (Figure 1). In Nevada and Oregon, the correlation between borate deposits and geothermal systems is striking, with at least 7 and possibly as many as 10 out of 11 Quaternary borate deposits occurring in close proximity to moderate to high temperature geothermal systems (with estimated reservoir

temperatures $\geq 150^{\circ}\text{C}$) and all of them occurring in areas where B is elevated in groundwaters. In at least 3 of these areas, the associated geothermal systems are considered to be blind (Salt Wells, Fish Lake Valley, and Soda Lake). The relationship between borates and geothermal activity is somewhat obscured in southern California, where many older (Tertiary) borate deposits (Smith, 1985) are known, and where in one case the Owens River has transported boron for approximately 300 km from hot springs in the Long Valley caldera to the Searles Lake playa (Smith, 1976).

Geothermal fluids are known to contain high concentrations of certain elements including boron (Ellis and Mahon, 1977, p. 66; Ballantyne and Moore, 1988) compared to most groundwater. This relationship was documented statistically for Nevada by Coolbaugh et al. (2002) and is illustrated in Figure 2. Zehner et al. (2006) extended the analysis to the entire Great Basin (Figure 1) where only fluorine in groundwater correlates better than boron with geothermal activity (among the trace elements analyzed, and exclusive of major elements such as silica that are used in geothermometer calculations). The high boron concentrations of geothermal waters are likely due to the greater opportunity of hot waters, which have relatively deep circulation paths, to interact with and leach boron-bearing host rocks. Especially high boron concentrations have been documented for geothermal systems flowing through boron-rich sedimentary rocks (e.g., Aggarwal et al., 2003). That cooling magmas may contribute a portion of the boron budget to some

geothermal systems is suggested by the fact that geothermal systems heated by magmas or cooling intrusions tend to have higher B/Cl ratios than equivalent-temperature geothermal systems in amagmatic terrains (Arehart et al., 2003).

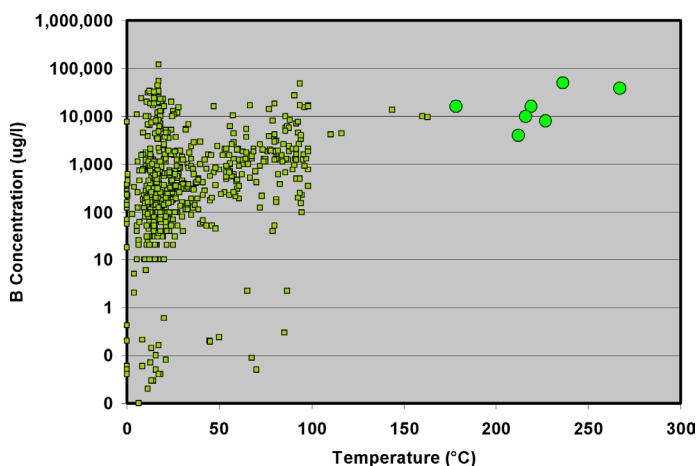


Figure 2. Boron concentrations in geothermal production fluids (green circles) lie near the upper limit of boron concentrations found in groundwater in the state of Nevada (green squares). Geothermal production data are from Nevada excepting one sample from Utah, and are from DeRocher and Shevenell (unpublished data). Groundwater data are from the United States Geological Survey NWIS database (<http://waterdata.usgs.gov/nwis>).

Models of Borate Genesis

The relatively high solubility of most borate minerals in water (Barker and Lefond, 1985) restricts their geological occurrence. They almost always occur in arid, lacustrine, playa-lake environments where surface waters experience high degrees of evaporation (Smith, 1985). Significant deposits have been found in Turkey, the western United States, Chile, and China (Harben and Dickson, 1985; Smith, 1985).

In contrast to many minerals formed from the evaporation of water, especially those associated with sea-water evaporation (Guilbert and Park, 1986), most economic borate deposits are associated with lacustrine lakes or playas. In particular, their formation appears favored when such lakes or playas occur in relatively small, closed basins where the influx of clastic and chemical sediments from outside the basin is limited (Barker and Lefond, 1985). Such circumstances facilitate the formation of relatively rich borate evaporites from high-boron thermal waters, by minimizing dilution from more regionally derived sediments and waters with lower boron concentrations.

Several categories of Holocene borate deposits can be distinguished by their depositional environments (Barker and Barker, 1985). They include: 1) spring aprons, 2) ephemeral saline lakes and playas, and 3) perennial saline lakes. Borate-rich spring aprons form adjacent to and immediately down-slope from thermal springs, while borates in ephemeral saline lakes and playas form by the evaporation of saline water from springs (Barker and Barker, 1985) or upwelling groundwater (Smith, 1985). The largest and richest borate deposits, including those at Furnace Creek, California, are described as having formed near

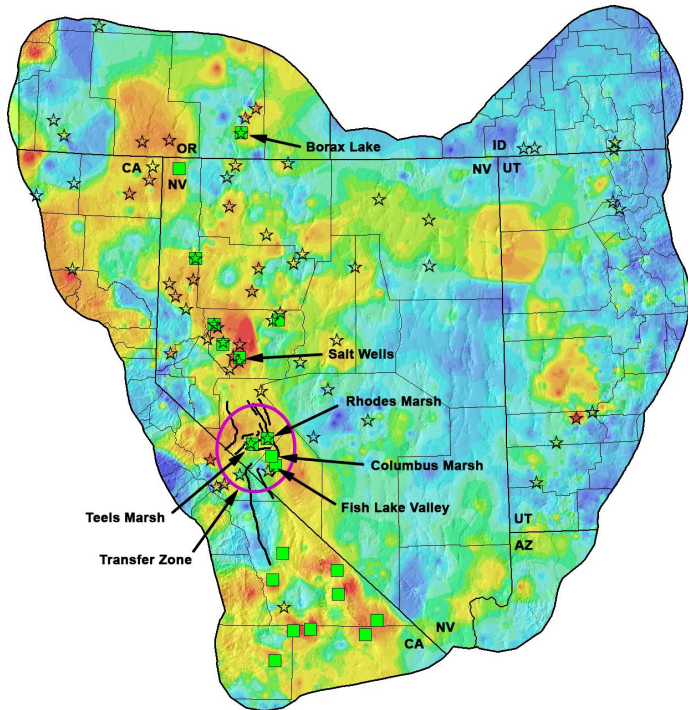


Figure 1. Quaternary borate deposits (green squares) in the Great Basin. Warmer background colors represent progressively higher boron concentrations in groundwater (from Zehner et al., 2006). Stars are geothermal systems with measured or estimated temperatures $\geq 150^{\circ}\text{C}$. Irregular black lines are faults in the right-stepping transfer zone of the Walker Lane, taken from Wesnousky (2005). Topographic shading is present in the background.

the bottoms of perennial, saline, lacustrine lakes, with the boron derived from thermal springs (Barker and Barker, 1985).

The distance that boron-charged waters travel before borates precipitate varies significantly from deposit to deposit. Spring apron deposits, by definition, lie near source springs, but saline lake and playa borate deposits can either be located nearby, as at Salt Wells (Coolbaugh et al., 2006) and Borax Lake, OR (Libbey, 1985), or, in an extreme case, they could lie hundreds of kilometers away, as is the case for the Searles Lake borate deposit whose boron is believed derived from hot springs near Mammoth, CA (Smith, 1976). The range of possible transport distances for each borate deposit can be assessed by studying the local and regional hydrological and geological conditions.

Warm Springs, Hot Springs, and Geothermometers

Some features of boron mobility in groundwater are not well understood. One such feature is an apparent inverse

relationship between the concentrations of boron in springs versus the temperature of such springs in southern California and west-central Nevada, as documented by Barker and Barker (1985, Figure 3). Their figure illustrates that many thermal springs in southern California have high boron concentrations, but on the average, warm springs have higher boron concentrations than hot springs, although there is significant “scatter” in the data. The current authors have chosen to take a closer look at this relationship.

A different relationship than that of Barker and Barker (1985) is suggested from a larger database of thermal springs and wells from the entire Great Basin (Reed et al., 1983; Boyd, 2002), where waters with high boron concentrations have, on the average, higher measured temperatures and higher geothermometer temperatures (Figure 3a-c) than warm springs. This relationship is clearer when only waters from western Nevada are considered (Figure 3d). A significant scatter in Figs. 3a-d might be attributed to differences in host-rock boron concentrations in different areas of the Great Basin. Although no de-

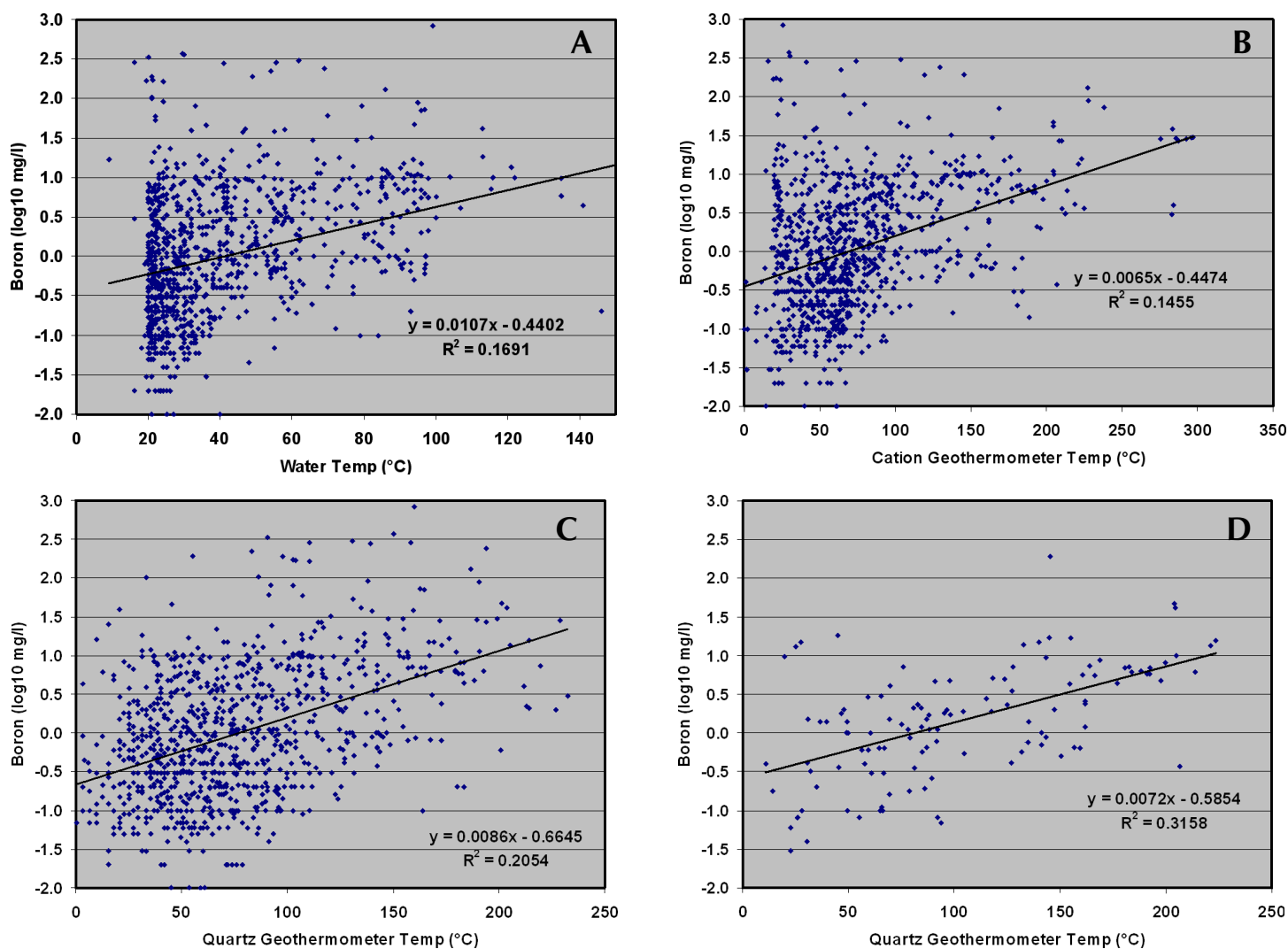


Figure 3. Boron concentrations in thermal springs and wells plotted against water temperature (a), Na-K-Ca-Mg geothermometer temperature (b), and quartz (no steam loss) geothermometer temperature (c and d). Data are from the Geo-Heat Center database (Reed et al., 1983; Boyd, 2002). Figures a-c cover the entire Great Basin whereas Figure d covers only the western half of Nevada (west of 117° long). References for geothermometer calculations are listed in the caption for Table 1.

finite answer can be provided at this time for the differences in trends of Figure 3 (herein) versus Figure 3 of Barker and Barker (1985), two possible explanations are offered. First, most of Barker and Barker's samples come from southern California, where many Tertiary borate deposits occur. Smith (1985) and Barker and Barker (1985) discuss evidence that some of these older deposits have been remobilized by groundwater to form younger borate deposits. Such remobilization would likely involve relatively shallow, and probably warm, groundwater since the older borate deposits are Tertiary in age and buried at relatively shallow depths. Secondly, geothermometry data suggests some warm springs with high boron concentrations may actually comprise geothermal waters that have significantly cooled below their peak temperatures before reaching the surface. This appears to be the case for a warm artesian well (22°C) at Rhodes Marsh, NV (one of the areas listed by Barker and Barker), where both the quartz and K-Na-Ca-Mg (cation) geothermometers predict reservoir temperatures on the order of 150-160°C (Table 1).

Another issue concerns the reliability of geothermometry estimates when spring and well waters are high in boron and other components commonly associated with evaporites. The Na-K-Ca and Mg-corrected Na-K-Ca geothermometers (Fournier and Truesdell, 1973; Fournier and Potter, 1979) are in-part empirically derived, and as such, assume certain constraints in average host-rock compositions. If unusually high concentrations of dissolved species typical of evaporite sequences are present, perhaps the geothermometer equations will not yield reliable estimates of geothermal reservoir tem-

peratures. To qualitatively evaluate this hypothesis, a spring and well database from the Geo-Heat Center (Reed et al., 1983; Boyd, 2002) was combined with data from the National Water Information System (NWIS) database (<http://waterdata.usgs.gov/nwis>), and a subset of 1,600 samples from playas in the Great Basin was extracted and geothermometers calculated. Of these samples, 300 contain $\geq 10,000$ mg/l Cl, while 340 samples contain $\geq 1,000$ mg/l SO_4 and 30 samples contain ≥ 50 ppm B. The large majority of these samples yielded geothermometer temperatures (cation and no-steam-loss quartz) less than 100°C, and those that yielded higher temperatures come almost exclusively from known geothermal areas. Another example is provided by the Ngawha geothermal system in northern New Zealand (Aggarwal et al., 2003), where boron, at ~ 800 mg/l, dominates the dissolved species of the geothermal fluid in terms of molar abundance. The quartz and cation geothermometer estimates of reservoir temperatures (220-230°C) are in close agreement with measured reservoir temperatures in wells (Thain, 1985). These data, while not definitive, clearly show that groundwater with high concentrations of B, SO_4 , and Cl in the Great Basin usually do not have high geothermometer temperatures, and when they do, it appears to indicate the presence of nearby geothermal activity.

Borate Playas and Geothermal Targets in Nevada

Of significance to geothermal exploration is the fact that many borate deposits in the western Great Basin form close to the point of initial surface discharge of thermal fluids. Examples include Salt Wells, NV (Coolbaugh et al., 2006), Borax Lake, OR (Libbey, 1985), Soda Lake NV (Papke, 1976), and Eagle Springs/Brady Hot Springs, NV (Benoit et al., 1982). This suggests that borate occurrences can help narrow the search for geothermal systems. Even more interesting is that in several cases, including Salt Wells, Soda Lake, and the Fish Lake Valley, the associated geothermal systems do not have obvious hot springs to reveal the presence of subsurface geothermal activity. At Salt Wells, ephemeral hot springs are present, but they are small, difficult to locate, and dry up during the summer (Coolbaugh et al., 2006). In contrast, upwelling groundwater can produce evaporite crusts at the surface without forming springs.

Borate minerals, especially borax and tincalconite (which are the borate minerals most often found on the immediate ground surface), are typically bright white in color and are difficult to distinguish visually from more common chloride and sulfate evaporites. For this reason it is likely that some occurrences of borate minerals have escaped notice in the Great Basin. For exploration for borates to be practical, it is essential to have an efficient means of identifying them in the field. Kratt et al. (2006) have developed such means using field spectroradiometers and remote sensing methods.

Table 1. Chemical analyses for rhodes and wells from Rhodes, Teels, and Columbus Marshes, Mineral and Esmeralda Counties, Nevada. Samples 5/35-22bbb and 2/36-8adb are from Vandenberg and Glancy (1970); sample WS8 is from Smith and Drever (1976). The remaining samples were analyzed at the Nevada Bureau of Mines and Geology as part of this study. HCO₃⁻ = alkalinity reported in equivalent mg/L HCO₃⁻. References for geothermometer equations are: quartz (no steam loss) and chalcedony (Fournier, 1977; Fournier, 1981); and Na-K-Ca-Mg (Fournier and Truesdell, 1973; Fournier and Potter, 1979). Ave Temp = average of quartz and Na-K-Ca-Mg geothermometers when Na-K-Ca-Mg temperature is $\geq 100^\circ\text{C}$. When Na-K-Ca-Mg temperature is $< 100^\circ\text{C}$, Ave Temp = average of chalcedony and Na-K-Ca-Mg geothermometers.

Sample Area		5/35-22bbb Rhodes well	RM-1 Rhodes well	RM-2 Rhodes well	WS8 Teels spring	TM1 Teels grndwater	2/36-8adb Columbus well	CM1 Columbus well	CM2 Columbus spring
East (meters)	UTM NAD83	404,920	405,957	406,475	381,470	383,753	413,030	412,537	411,670
North (meters)	UTM NAD83	4,237,650	4,237,276	4,237,602	4,230,770	4,229,870	4,211,440	4,218,748	4,211,601
Temp	°C	16.0	23.7	21.6	15.8	14.1	16.0	21.7	14.3
HCO ₃ ⁻	mg/L	485	201	1250	429	1450	248	250	91
B	mg/L	55.0	7.4	319.0		209.0		19.6	22.1
F ⁻	mg/L	32.0	18.7	54.5		10.3	2.3	9.9	12.0
Cl ⁻	mg/L	2110	170	361	227	5940	1680	1180	1308
NO ₃ ⁻²	mg/L		0.0	0.0		0.0	0.0	0.0	0.0
SO ₄ ⁻²	mg/L	1830	263	414	179	1020	254	456	185
Ca	mg/L	15.0	6.4	1.1	6.8	1.8	4.4	29.8	79.9
Fe	mg/L	0.040	0.214	0.263		0.605	0.270	0.313	0.211
K	mg/L	70.0	13.1	26.3	30.1	370.0	86.0	48.7	101.0
Li	mg/L		0.01	0.10		1.35		1.29	1.18
Mg	mg/L	2.2	0.0	0.0	0.1	0.1	0.1	8.3	10.9
Mn	mg/L		0.282	0.272		0.291		0.369	0.340
Na	mg/L	2550	329	1050	360	4630	1300	1000	811
SiO ₂	mg/L	121.0	78.9	152.7	70.3	121.9	47.0	65.7	65.5
Charge	Sum Cat	113.64	14.96	46.40	16.78	211.14	58.97	47.09	42.91
Charge	Sum An	107.29	14.55	42.16	17.17	213.18	56.89	47.41	42.89
Charge	Balance	1.06	1.03	1.10	0.98	0.99	1.04	0.99	1.00
Geothermom	Quartz	148.1	124.4	162.3	118.4	148.6	98.9	115.0	114.8
Geothermom	Chalced	122.7	96.4	138.6	89.8	123.2	68.8	86.1	85.9
Geothermom	T_NaKCaMg	146.3	146.6	155.3	192.3	262.8	210.5	86.8	137.2
Geothermom	T_SiO2	148.1	124.4	162.3	118.4	148.6	98.9	86.1	114.8
Qtz-NaKCaMg	Ave_Temp	147.2	135.5	158.8	155.3	205.7	154.7	86.5	126.0

To test the usefulness of surface borates as an exploration tool, three borate-bearing playas not known to be associated with geothermal activity were investigated at Rhodes, Teels, and Columbus Marshes (Figure 1), together with a nearby fourth borate-bearing playa at the Fish Lake Valley. All of these playas occur within a broad right-stepping transfer zone in the strike-slip Walker Lane fault zone in Esmeralda and Mineral Counties, Nevada (Wesnousky, 2005). At the Fish Lake Valley, a pull-apart structure within the transfer zone is believed responsible for providing the deep fracture permeability necessary for two geothermal systems to form (Stockli et al., 2003; Hulen et al., 2005). Inference of a link between Quaternary borate deposits and geothermal activity in the Fish Lake Valley is complicated by the existence of Tertiary borate mineralization within the catchment basin (Smith, 1985; Hulen et al., 2005), so it is not clear if the younger borates have formed by remobilization or weathering of older borates or as a consequence of on-going geothermal activity. In any case, the Fish Lake Valley is the only playa out of the four, so far as is known, that has seen deep drilling (oil, mineral, and geothermal drilling) or temperature gradient drilling. Oil drilling and mineral exploration drilling led to the discovery of hot water in the two otherwise blind geothermal systems (Edmiston and Benoit, 1984; Hulen et al., 2005) at Fish Lake.

A literature review by the authors uncovered published chemical analyses of cold and warm springs and wells in Rhodes, Teels, and Columbus Marshes (Vandenburg and Glancy, 1970; Smith and Drever, 1976). When geothermometer calculations were applied to these analyses, anomalous geothermometer temperatures were obtained for many of them (the two highest temperature results are shown in Table 1). With the help of a spectroradiometer and remote sensing analyses (Kratt et al., 2006), tinalconite and borax crusts were rapidly identified in the field. New samples of well, spring, and ground waters were analyzed and the resulting geothermometry has largely confirmed the initial geothermometer estimates of the older analyses (Table 1).

At Rhodes Marsh, a 22°C artesian well with adjacent crusts of tinalconite and borax (Figure 4a) yields reservoir temperature estimates of 155°C and 162°C respectively for the cation and quartz geothermometers (Table 1), suggesting the possible presence of a geothermal reservoir at depth. This well water contains relatively low levels of chloride and sulfate (361 mg/l and 414 mg/l respectively), suggesting minimal evaporation or interaction of the well water with playa brines, even though the measured boron concentration was 319 mg/l (Table 1).

At Teels Marsh, a cold spring sampled by Smith and Drever (1976) on the north side of the playa yielded a cation geothermometer estimate of 192°C and a quartz geothermometer of 118°C. The discrepancies between the two numbers might be caused by dilution of geothermal waters with descending shallow groundwaters from the adjacent Excelsior Mountains. The low chloride content (227 mg/l) suggests minimal prior evaporation or mixing with playa brines (Table 1). A sample of shallow groundwater from the borate-rich portion of the playa also yielded high geothermometer temperature estimates, but in this case, relatively high chloride and sulfate concentrations may indicate evaporation or mixing with playa brines (Table 1).



Figure 4. a) White tinalconite and borax crusts next to a 21.6°C artesian well on the southeast side of Rhodes Marsh. The water yields geothermometer temperatures of 162 and 155°C (quartz and cation respectively, Table 1, RM2) and contains 319 mg/l boron. b) Tinalconite and borax crusts surround a 14.3°C cold spring with 22 mg/l boron on the southwest side of Columbus Marsh. Quartz and cation geothermometers average 126°C (Table 1, CM2).

Near the south end of Columbus Marsh, analysis of a cold water spring surrounded by tinalconite crusts (Figure 4b) yielded cation and quartz-based geothermometer temperature estimates of 137°C and 115°C, respectively. On the north end of Columbus Marsh, a 30°C temperature was measured in a warm well 3 km northeast of a large area of old borate tailings (the well was not flowing and water samples were not obtained).

Discussion and Conclusions

Quaternary borate evaporite crusts can be a valuable guide in the exploration for blind geothermal systems in the Great Basin. Because borate crusts visually resemble more common chloride and sulfate evaporites, they are easy to miss and consequently, undiscovered occurrences are likely to exist. Kratt et al. (2006) report on the development of remote sensing tools to efficiently explore for surface borates.

In the playas at Rhodes, Teels, and Columbus Marshes in west-central Nevada, the presence of Quaternary borate crusts provides evidence of undiscovered moderate to high temperature ($\geq 150^{\circ}\text{C}$) geothermal systems. Anomalous geothermometer temperatures calculated from analyses of springs and wells in each of these valleys support the existence of possible subsurface geothermal activity. These valleys clearly warrant more detailed geothermal exploration. Similarly, a search for additional borate occurrences in the Great Basin could result in new geothermal discoveries elsewhere.

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