

NEWBERRY CRATER LAKES, OREGON: PAULINA LAKE

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INTRODUCTION

For two lakes separated only by a narrow ridge of obsidian, Paulina and East Lake could not be more different. The chemical and physical differences that distinguish these two bodies also inform a steady state model for Paulina Lake that requires extensive injection from a currently unidentified source, which we propose is a hydrothermal vent. Major and trace element concentrations, in tandem with water properties like conductivity and alkalinity, prove an area of high temperatures in deep water may be the location of a lake-bottom vent. A pluton emplaced around 4,200 years ago beneath the surface of Newberry's caldera may divide these two lakes (Jensen & Chitwood, 2000).

In this study, temperature and conductivity data were collected with a TLC meter on site in Paulina Lake and to a lesser extent in East Lake. Alkalinity and pH data were determined by titration at Wesleyan University. Major and trace element (TE) data was compiled from IC (Ion Chromatography) and ICP-MS (Inductively Coupled Plasma Mass Spectroscopy) runs at Colgate University. Graphical and statistical analysis was performed in Microsoft Excel™.

RESEARCH RESULTS

Temperature and Conductivity Analysis

For typical lakes, water temperatures in the hypolimnion (depths below the thermocline) are 4-5°C (Boehrer & Schultze, 2008). Furthermore, temperature increases with depth are evidence of hydrothermal activity (Christenson et al., 2015), and by mapping

these profiles on the lake, we expect a vent source for this heated water to be located around the north-west edge of PL (Fig. 1); this prediction is further supported by records of minimal ice coverage in this area through winter months (Morgan et al., 1997; Varekamp et al., 2012).

Conductivity data were gathered simultaneously with temperature depth profiles. This enabled us to model water conductivity trends with depth at different locations (Fig. 2), as well as the lake's conductive properties with distance from the vent. Conductivities are consistent for most depth profiles in PL, except within 200 m of the proposed vent location; within that distance, we found a greater range of conductivity values than were recorded farther from the vent (Fig. 2).

Water from EL has a lower average conductivity than PL by half (averaging 0.37 compared to 0.53 mS/cm). PL waters must therefore have higher concentrations of total dissolved solids (Boehrer & Schultze, 2008).

Alkalinity and pH

Alkalinity, unaffected by pH or CO₂ levels, documents the concentration of neutralizing bases in the water. Most alkalinity profiles in PL varied minimally with depth, maintaining concentrations between 6.55 and 6.85 mmol/L. Two profiles decreased more markedly than the others; the more extreme of the two decreased to 4.9 mmol/L (Fig. 3).

pH decreases with depth, indicating greater acidity closer to the lake bottom (Fig. 3a). There is a significant drop in pH levels closer to the vent. At 50 m depth, pH levels increase with distance from the

proposed vent.

Alkalinity profiles in EL and PL indicate consistently higher concentrations in PL; on average, PL water alkalinities (6.7 mmol/L) are two and a half times those of EL (2.7 mmol/L). East Lake waters have alkalinities equivalent to those in seawater (Varekamp et al., 2012). East Lake is less basic than Paulina (average pH 8.17), whereas EL values are more neutral (average pH 7.14) (Fig. 3).

Major Elements

Cation concentrations in Paulina exhibit similar trends with depth and distance. Cations Mg^{2+} , Si, and SiO_2 (aq) have curved depth relationships; concentrations decrease from the surface to 40 m, and increase in waters below 40 m. Bicarbonate concentrations in PL decrease with depth similar to alkalinity (Fig. 3). However, Ca^{2+} , Na^+ , and K^+ have minor increased concentrations with depth, and none of the cation concentrations change significantly over distance. Chloride in groundwaters is usually low, and typical high-temperature waters contain at least several hundred parts per million concentrations (Mariner et al., 1981); chloride concentrations in Paulina are far below high-temperature concentrations, which suggests lower temperature water-rock alteration (Mariner et al., 1981).

Concentrations of Ca^{2+} and K^+ remain mostly constant between PL and EL (Fig. 4). Paulina has double or more the cation concentrations of East for K^+ and Mg^{2+} , and nearly the same concentrations of Ca^{2+} , consistent with previous studies (Varekamp et al., 2012). EL has over thirty times PL concentrations for SO_4^- (Fig. 4). East Lake's HCO_3^- concentration is much lower than in PL, which explains EL's lower pH (Fig. 3). The two lakes' bicarbonate concentration trends with depth are broadly similar.

Trace Elements

Within Paulin Lake there are slight variations in trace element (TE) concentrations, primarily in Al, As, Sr, Zr, Cu, Co, Cr, Rb, Se, Nb, V, Ni, Ga, Ba, and Zn. Concentrations nearly double below the hypolimnion for Al, As, and Sr (Fig. 5c-d).

East and Paulina have opposite TE patterns in deep waters (Fig. 5c-d), but different TE concentrations in shallower depths. In particular, EL has higher concentrations of Nb, Al, and Sr (Fig. a-b). Compared to EL, Paulina has 150% As concentrations and almost 500% the concentrations of Ba.

NEWBERRY SYSTEM COMPARISONS

Newberry Hot Springs

Paulina's hot springs are small ponds of lake water dug into the northeastern shoreline. Some springs are pools of captured lake water, whereas some others are more separated from the shoreline. We observed regular gaseous input into these pools.

Samples from five of the hot springs have high temperatures (32-52°C) and decreased pH levels (6.29-7.14) with respect to PL (8.05-8.32). Similarly, when compared to PL, the hot springs' cation concentrations are quadruple the values of Si and SiO_2 , and nearly double the concentrations of Na^+ , K^+ , and Ca^{2+} . Bicarbonate concentrations in the springs are also elevated compared to PL. The only cation that is not significantly more concentrated in the springs compared to the PL was Mg^{2+} , and anions Cl^- and SO_4^{2-} have similar concentrations in the lake and springs (Fig. 4).

Trace elements are more similar between the PL and its springs. The lake has higher concentrations in Al, Sr, and Zr, but mostly similar concentrations within the other series. Iron was removed from this graph because its concentrations were much higher than all other species, but as with the other TEs, Fe concentrations in PL were negligibly higher than in the springs (PL had only 60 ppb more than the springs' average).

Direct comparison of the two bodies indicates that Paulina spring has nearly four times the levels of Mg^{2+} , double the Ca^{2+} , and almost sixteen times the Si as East spring (Fig. 4). Only SO_4^{2-} is more concentrated in East springs. In fact, East spring exhibits no significant increase in cation or anion concentrations with respect to East Lake; conversely, Paulina springs have higher concentrations than

Paulina Lake in Ca^{2+} , Na^+ , K^+ , Si , and double the Cl^- and SO_4^{2-} (Fig. 4).

Steady State Water Budget

Paulina Lake maintains its water level throughout the year (Philips & Van Denburgh, 1968; Johnson, et al., 1985; Morgan et al., 1997), leading us to conclude that for matters of cation and trace element inflow, we should approach the lake as a steady state system, with equivalent input and output. On the basis of this conclusion, the total movement of particles in and out of PL were calculated using the following equation (Varekamp et al., 2012; “General Guidelines for creating a water budget”, 2010):

$$Q_{(sp)} = [Q_e + Q_{cr} + Q_{so}] - [Q_p + Q_{si}]$$

where Q_e is the evaporative rate of the system (2,190 ac-ft/yr averages from 4 years), Q_{cr} is the volume of outflow from Paulina Creek (14,206 ac-ft/yr averaged from 27 years), Q_{so} is an estimated seepage from PL into the basement (3,800 ac-ft/yr averaged from 4 years), Q_p is the average precipitation volume for the Newberry basin (18,800 ac-ft/yr averaged from 12 years), and Q_{si} is the estimated surface inflow seepage, not including any groundwater transport from East Lake (1,150 ac-ft/yr averaged from 12 years). Newberry’s hydrologic system averages were compiled from several sources (Philips & Van Denburgh, 1968; Morgan et al., 1997; Sammel & Craig, 1983) to yield these values.

To maintain the steady state assumption throughout the year, the equation must include additional input, $Q_{(sp)}$, distinct from precipitation, snowmelt, or seepage. If average seepage from EL is to be 1,666 ac-ft/yr (Sammel & Craig, 1983), still require an unexplained 2,200 ac-ft/yr water input to maintain steady state. Without seepage from EL, the hydrothermal vent must inject Paulina Lake with nearly 3,866 ac-ft/yr.

DISCUSSION

Paulina Lake’s Hydrothermal System

We conclude that there is no significant groundwater flow from EL into PL, and that the 3,866 ac-ft/yr input that Paulina requires to maintain a steady state level

is introduced into the lake via a hydrothermal vent. Our chemical analysis of Paulina Lake supports this conclusion:

Water temperatures increase significantly in deep waters (>40 m) and in a confined area in the north-west corner of the lake.

Decreased pH around the vent implies that hydrothermal waters must be affecting the system, reducing deep water pH values to around 8. Because pH levels are nearly identical over a kilometer from the north-west site, it is likely that increased acidity is confined to depths immediately around the vent.

Paulina Lake has decreasing conductivities with proximity to our proposed north-western vent.

Metals with increased concentrations in PL including Cu, Ni, Cr, and Zn (Todd and Mays, 1980) may be the reason that all conductivities are so high in PL (Fig. 5).

Arsenic (As), rubidium (Rb), strontium (Sr), barium (Ba), and chromium (Cr) are significantly concentrated in Paulina’s hypolimnion (Fig. 5).

The gas vents heating Paulina springs do not inject any trace elements, which differentiates the type of thermal activity between Paulina’s hydrothermal input from that of the gaseous springs (Mariner et al., 1981). If PL was only being heated by the gaseous vents, then we would not expect to see any elevated concentrations of TE.

While Paulina Lake exhibit elevated TE concentration in deep waters, we conclude that element fluxes in and out of PL are for the most part equivalent to each other; trace elements are not *highly* concentrated on the bottom of the lake, and so even with the concentration trends that we observe with depth, the lake must be moderately well mixed. The degree of lake mixing is the extent that heat is transferred from the epilimnion, above the thermocline, to the hypolimnion, below the thermocline (Boehrer & Schultze, 2008); water circulation mobilizes particles from the bottom of the lake into shallower depths, reducing bathymetric concentrations. Temperature and conductivity patterns with depth further suggest that Paulina’s degree of mixing is subject to the heat

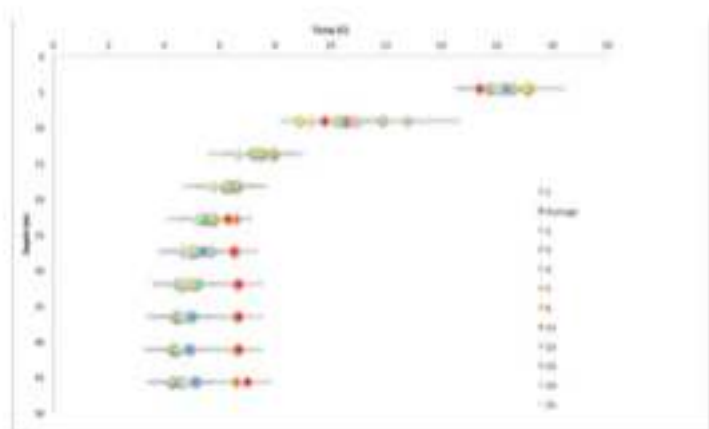


Figure 1. Temperature-depth profile for Paulina Lake, with noted averages for each depth. Profiles with significant increases in temperature below the thermocline are highlighted in red, orange, and yellow. Error bars are 1σ

Map image shows proposed vent location.

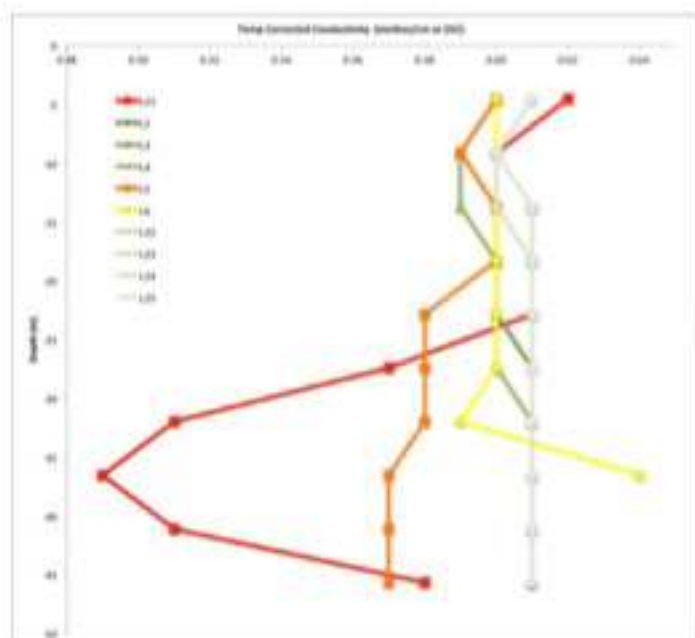
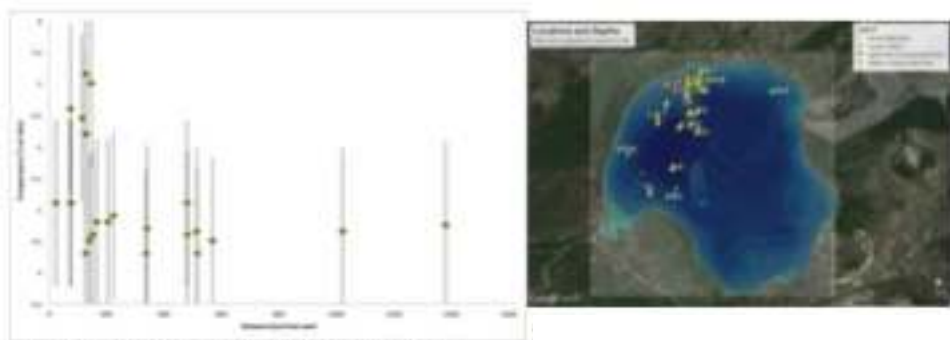


Figure 2. Compiled conductivity data with depth at various locations on PL.

Figure 3a. East and Paulina Lake pH profiles. Error bars are 1□.

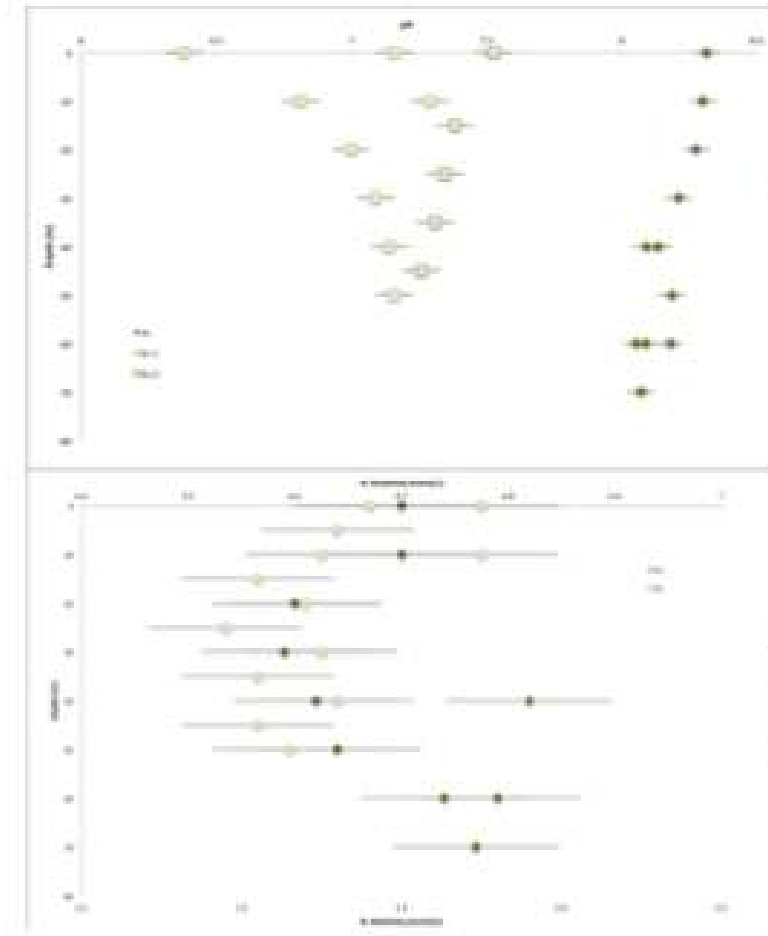


Figure 3b. Alkalinity profiles of EL and PL. Please note the different scales used for each dataset; EL data corresponds to the lower x axis, while PL data corresponds to the top x axis.

Error bars are 1□.

of its hydrothermal input, which reduces the density of hypolimnetic waters and promotes mixing (Boehrer & Schultze, 2008). Seasonal fluctuations, especially those caused by melting ice, also alter PL's degree of mixing by adding a significant volume of meteoric water that dilutes the concentrations of hydrothermally sourced elements in the lake (Varekamp et al., 2012).

Therefore, the hydrothermal system in PL has to be the primary source of foreign trace elements and major ions, especially in contrast with the concentrations found in EL (Fig. 4, 5). Paulina's hydrothermal system is also the source of higher conductivities and alkalinities, as well as increased bathymetric temperatures.

Newberry's Lakes: Separate Systems

Comparison of elemental concentrations for both lakes and their spring areas indicates that each lake and its spring has an internally consistent

relationship; Paulina springs have higher TE and cation concentrations than PL waters, and in the same manner East springs are more concentrated than EL waters (Varekamp et al., 2012; Fig. 4). Yet between the two lake-spring systems, there are several significant differences:

Nearly all major elements are more concentrated in Paulina Lake than in EL (Fig. 4). Trace elements in EL are greater only in shallow waters.

While SO_4^{2-} is consistently more concentrated in EL than PL, as well as in East spring compared to Paulina springs, there is almost no difference in SO_4^{2-} concentrations between East and its spring, nor between Paulina Lake and its springs.

Bicarbonate concentrations do not change significantly between EL and its spring, whereas Paulina springs are 125% more concentrated in HCO_3^- than PL.

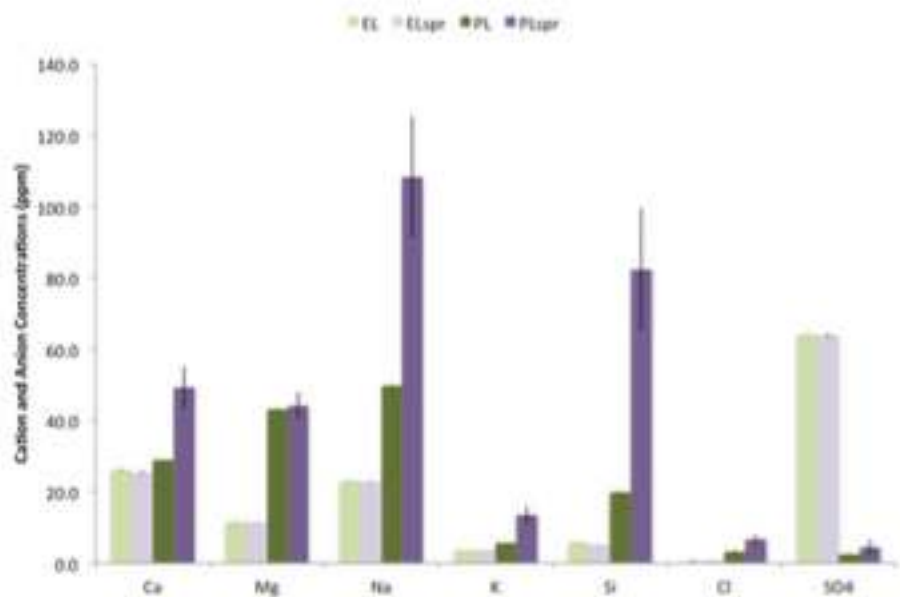


Figure 4. Side by side comparison of cation and anion properties for both regimes. Error bars are 1σ.

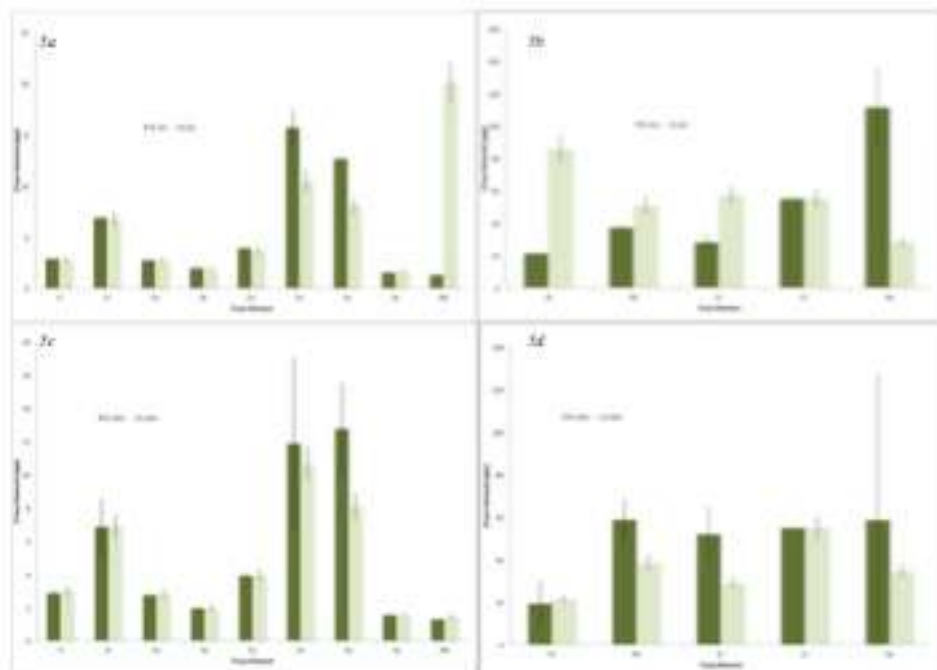


Figure 5. a-d Trace element concentrations between East and Paulina Lakes. Error bars are 1σ.

Both hot spring areas have equal or greater cation and anion concentrations with respect to their lake, and yet trace elements are more concentrated in the lake bodies themselves.

Active crater lakes are those that exhibit continuous degassing during inter-eruptive periods, whereas inactive lakes are not connected to a magma reservoir; they exhibit no significant gaseous output and no hydrothermal activity (Christenson et al., 2015). Of such volcanic systems, those fed by gaseous vents are by far the most active and chemically altered (Fournier et al., 2003). Both East and Paulina have shallow areas around their shores with significant thermal alteration, and their hot springs produce gaseous CO₂ at a near-constant rate (Varekamp et al., 2012). These springs are likely submerged gas vents, and their elevated Mg²⁺ concentrations and moderate temperatures (averaging 43°C) are consistent with low-temperature water-rock alteration (Mariner et al., 1981).

If PL experiences porous transport from the higher-elevated EL, we would expect to see all cations concentrated uniformly in the two lakes. Rather, concentrations of some cations are similar between the bodies, while others are more concentrated in PL (Varekamp et al., 2012); this may suggest that PL and EL have the same fundamental elemental concentrations, a result of both mostly being sourced by meteoric water (Johnson et al., 1985; Morgan et al., 1997; Mariner et al., 1981) and their common gaseous input from the caldera floor. The differences between the two lakes, therefore, must be the result of Paulina Lake experiencing hydrothermal injection, but East Lake lacking that input.

The chemical distinctions between gaseous input and Paulina's hydrothermal vent indicate that Newberry Caldera is host to two venting regimes. Caldera basement rocks are mainly rhyolitic lavas (Higgins & Waters, 1967), and yet they do not appear to allow for porous water transport from EL to PL. The events forming East and Paulina Lake are not well understood, although the positioning of the Interlake Obsidian Flow suggests that these two lakes may have once been one, prior to a plutonic intrusion that

raised and separated East from Paulina, as suggested by ongoing caldera floor uplift (Varekamp et al., 2012; Jensen & Chitwood, 2000). An igneous intrusion would also explain the lack of groundwater transport from the higher-elevated EL; while porous transport should occur in a rhyolite basement, it would be inhibited by granites and confined to upper layers of more porous material, as suggested by Sammel (1981).

The Significance of Hydrothermal Lakes

Beyond their novel interest, hydrothermal lakes provide insight into understanding many of the inexplicable features on planets such as Mars. With new evidence of an historic abundance of water on Mars, coupled with its long dead volcanic bodies (located in the Tharsis Region on the northern hemisphere), there is a genuine chance that Mars was once a home to many volcanic lakes.

Detailing the chemical signatures of hydrothermal environments on Earth can provide planetary scientists with the context to investigate craters on martian volcanoes. Trace element concentrations in dry lake beds could provide evidence for the existence of hydrothermal lakes. Sediments high in Si and Mg-Fe carbonates (which evidence water-rock interaction) have already been discovered on Mars (Ruff et al., 2014). Vast calderas may have housed massive volumes of water, and brought microbial life to the red planet.

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