CARBON DYNAMICS IN EAST LAKE, NEWBERRY VOLCANO, OR

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INTRODUCTION

Twin Crater Lakes

Newberry Volcano is a large shield volcano in central Oregon. The average caldera wall height is 1000m with its highest point, Paulina Peak, reaching 2434m. Newberry caldera stretches ~5km North-South and ~7km East-West and is home to two lakes: Paulina Lake and East Lake (Williams, 1935; MacLeod and Sherrod, 1988). Paulina Lake, the larger of the two lakes, sits at a lower elevation than East Lake and has a steep subaqueous cliff (MacLeod and Sherrod, 1988). East Lake morphology resembles that of a drowned volcanic crater. Volcanic lakes typically have geothermal fluid or gas inputs that may include toxins or nutrients. The composition of lake sediments and water reflect these volcanic inputs providing insight into the volcanic system as a whole (Christenson et al., 2015). The two lakes at Newberry Volcano have very different sediment and water chemical compositions: Paulina Lake has iron and arsenic-rich sediment and East Lake has mercury-rich sediment and sulfate-rich waters.

East Lake

This study focuses on the carbon dynamics of East Lake, which has an active geothermal gas input (largely CO_2) observable through bubble trains that rise from the bottom, but dissolve 15-20m below the surface. Lake waters have ~130 ppm of HCO_3^-, with slightly higher values at depth and pH values ranging from 6.5 to 7. Some hot spring areas along the beaches have escaping CO_2 bubbles, but most of the surface water lacks bubble activity. East Lake is a productive

Figure 1. East Lake (lower left) and Paulina Lake, separated by a tuff cone and obsidian flow, with the Big Obsidian flow and the Newberry caldera rim in the background.

mesotrophic lake with phytoplankton (diatoms and various species of chrysophytes, cryptophytes, and chlorophytes; Johnson 1985) colorful cyanobacterial gelatinous spheres (Nostoc sp.) and large "phytobergs" of partially submerged, floating vascular aquatic plants.

Diffusive CO_2 loss to the atmosphere occurs at the surface because the internal PCO_2 is higher than the atmospheric values (~400 ppm of CO_2). Given the almost constant DIC over the last 5 years, the geothermal CO_2 input is largely balanced by this diffusive CO_2 loss and through photosynthetic processes. Photosynthesis and diffusive CO_2 loss impose a carbon isotope fractionation on the system, leading to a 13C enriched residual DIC. The $\delta^{13}C$ (DIC) shows a strong gradient with depth, with the

highest values at the surface (+4‰ to +5‰) and lower values at depth (-0.5 ‰). The slope of the $\delta^{13}C$ gradient has varied over the seasons, but the overall depth trend has remained consistent over the years.

METHODS

Water Profiles

Two water profiles were taken during the summer of 2015 (KELA 43.73286 N, 121.20525 W; EL7_3S2 43.73338N, 121.207221 W) starting at depths of 0m and 5m. A bulk water sample was collected at 10m vertical increments, using a Teflon van Dorne water sampler. Water samples were sub-sampled for $\delta^{13}C$ (DIC) determination (MS), alkalinity titration and pH measurements (Mettler 1012 Autotitrator), major and trace element analyses (ICP-OES; IC) and stable isotope composition (MS). The water samples were filtered through 0.45µm nylon syringe filters. Temperature, conductivity and dissolved oxygen were measured in the field using digital probes (YSI) down to 45m.

Sediment Cores

A percussion corer with a plastic barrel was used to extract sediment cores up to 1m long from several sites in the lake. Two cores (KCEL5, KCEL2) were extruded and sliced at 2 cm increments and placed on Styrofoam plates for air-drying. Bulk dry density was calculated from dry weight, slice volume, water mass, and a mean rock particle density. Samples were ground and analyzed for major and trace elements (XRF), mercury (DMA-80) and carbon and nitrogen (Flash Elemental Analyzer Series 1112). Biogenic silica (BSi) extractions were done in hot sodium hydroxide and analyzed by colorimetry (DeMaster, 1979).

CO_2 FLUX SURVEY AND ANALYSIS

CO_2 flux surveys were conducted on East Lake in the field from June 26th to July 2nd 2015 at approximately 40 different locations spread over the lake. We used a floating accumulation chamber (West Instruments). The increase in CO_2 concentration over time (30-60 seconds) was measured with a LICOR CO_2 analyzer and registered on a laptop. The increase

in CO_2 contents per second is used with the geometric data of the instrument to calculate a lake-derived CO_2 flux. Sub-samples of gas from the chamber and from ambient air were taken for $\delta^{13}C$ measurements. The measured fluxes were converted into a new data set that shared spatial and statistical (Fig. 3) characteristics of the 40 original flux data points using the statistical technique, Sequential Gaussian Simulation (SGS). The original data were declustered to create a variogram and SGS was subsequently performed (Mazot and Bernard, 2015). The data were back-transformed into 7234 new flux points that were used to configure a CO_2 flux map (Fig. 2).
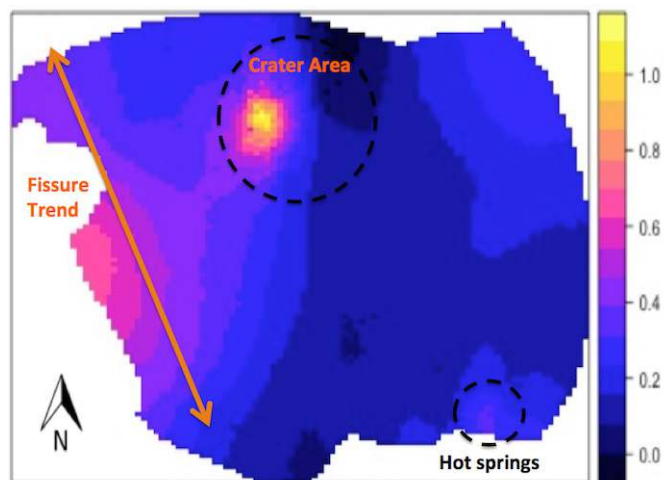

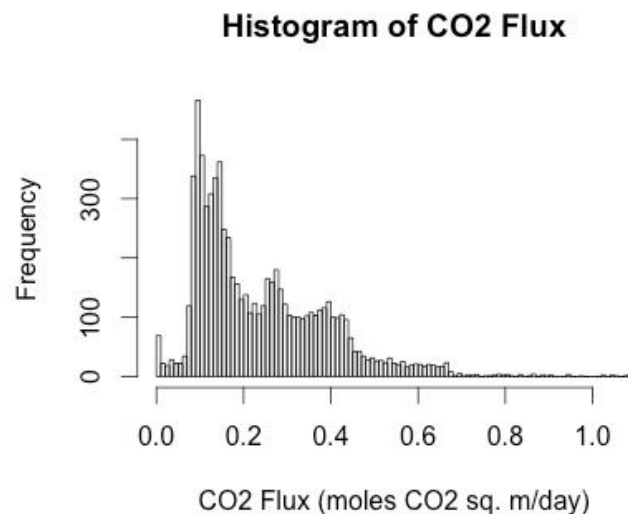*Figure 2. CO_2 flux map of East Lake (scale: moles CO_2 m^{-2} day^{-1}).*

Figure 3. Histogram of CO^2 flux in East Lake.

Biogenic Silica Analysis

Ground samples of cores KCEL5 and KCEL2 were used for BSi analyses. We used the timed-extraction method to distinguish between the dissolution of opal (BSi) and other silica phases (volcanic glass and crystals). For the NaOH digestion, 25mg of sediment is placed into NaOH at 80°C. Timed aliquots are extracted at 60, 90, 120, 200, and 230 minutes and diluted with water. The analyses of all samples used the molybdate-blue technique and absorbances were recorded. Using an appropriate calibration curve absorbances were then translated into Si concentrations.

RESULTS AND INTERPRETATION

East Lake CO_2 Flux

The estimated CO_2 flux off the surface of the lake, as obtained from the SGS algorithm, is 44.17 tons of CO_2/day. A map of the flux measurements (moles CO_2 m-2 day-1) show yellow-pink colors in areas of high CO_2 flux and blue in areas that have lower CO_2 fluxes (Fig. 2). The high CO_2 flux area corresponds with a trend of a NNW-SSE fissure crossing East Lake near the scoria vent area at its NW side. The frequency distribution of fluxes in East Lake is shown in Figure 3. The internal PCO_2 for East Lake in July 2015, the driving force for the CO_2 degassing process (PCO_2 atmosphere = 10-3.4 bar), was calculated at 10-1.5 bar. Cumulative calculations of the daily flux over the year have uncertainties (variable wind speed, water temperature, etc.) and we assume that no CO_2 escapes when the lake is frozen over during the winter months. The accumulated winter CO_2 may be released upon thawing in May. For comparison, Paulina Lake has no measurable CO_2 loss and its calculated internal PCO_2 (10-2.9 bar) is less than at East Lake.

Carbon and Nitrogen Distribution

Elemental analyses revealed that 8-12% of East Lake sediment consists of organic carbon. It is likely that the organic carbon in East Lake is predominantly derived from phytoplankton, cyanobacteria, and aqueous vegetation (phytobergs). The C/N, $\delta^{13}C$ and $\delta^{15}N$ values for these various producers were applied to a mixing model (Fig. 4). Figure 4 shows the mixing
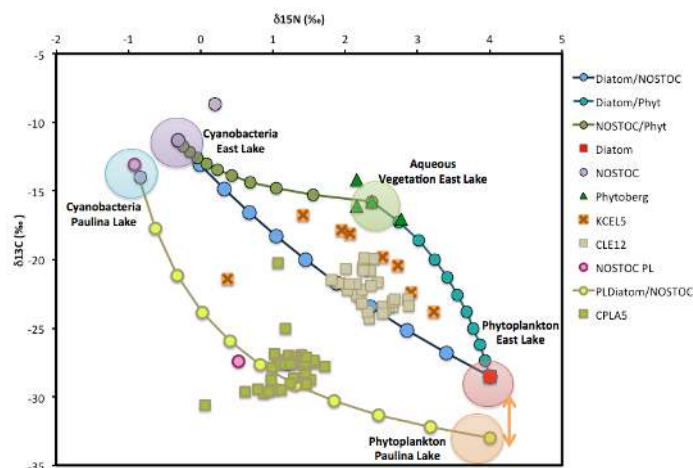

Figure 4. Mixing curves for organic matter in core samples based on $\delta^{13}C$ and $\delta^{15}N$ in East Lake sediment using three endmembers: aqueous vegetation (phytobergs), cyanobacteria, and phytoplankton. For comparison, sediment data of Paulina Lake (Lefkowitz, 2012) show lighter $\delta^{13}C$, as expected from the lighter $\delta^{13}C$ (DIC) and less input of phytobergs because they were not found in Paulina Lake.

curves for these three endmembers. The organic matter in samples from core KCEL5 consist of about 60-70% phytoplankton and roughly equal amounts of aqueous plants and cyanobacteria. The Paulina Lake mixing curve for phytoplankton and cyanobacteria is offset in $\delta^{13}C$ from the East Lake curve by ~5‰ (orange arrow), which is comparable to the offset in $\delta^{13}C$ (DIC) between the lakes.

Biogenic Silica

Diatoms are a type of phytoplankton whose frustules, or skeletons, are composed of opaline silica. Measuring biogenic silica in sediment is therefore a measure of the rate of organic productivity by diatoms in the lake. Core samples from KCEL5 had ~60 weight % of biogenic silica suggesting that at least half of the sediment is derived from organic processes by phytoplankton. Based on XRF data (not shown here) the remainder of the sediment is volcanic ash.

$\delta^{13}C$ (DIC)

The $\delta^{13}C$ (DIC) values in East Lake are unusually 13C enriched. The sign of slope of the $\delta^{13}C$ (DIC) gradient with depth has been consistent (Fig. 5), although the values vary with sampling month. The $\Delta\delta^{13}C$ (DIC) with depth is the largest late in the year (October 2015 = 4.8‰; August 2011= 3.9‰; June 2014= 2.6‰;

June 2015 1.2-2.1‰), and is presumably reset to 0‰ during the winter mixing period. We speculate that the combined fractionation effects of diffusional CO_2 loss and photosynthetic carbon sequestration are drivers for the evolving $\delta^{13}C$ (DIC) gradient over time. The carbon loss processes occur at the surface of the water, whereas the isotopically lighter geothermal CO_2 input occurs at the bottom. The absolute $\delta^{13}C$ (DIC) for the lake becomes lighter again during the winter CO_2 accumulation period, which occurs without surface loss, and the fractionation process repeats itself over the next summer.
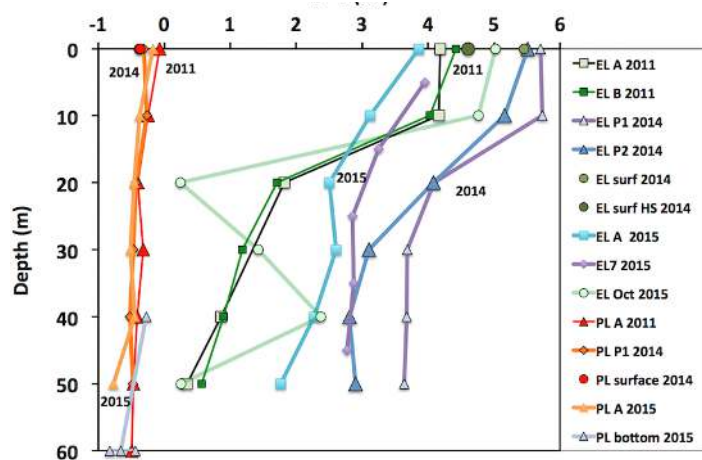

Figure 5. $\delta^{13}C$ (DIC) profiles in East Lake (green blue colors) from 2011-2015. For comparison, Paulina Lake (red-orange colors) has a very small, constant $\delta^{13}C$ (DIC) gradient over the same time period.

CONCLUSIONS

The volcanic CO_2 input at East Lake sets the stage for a variety of unique features at temporal and spatial scales. A zone of intense CO_2 fluxes is found at the NW side of the lake and more modest CO_2 fluxes are found in the rest of the lake averaging to a total loss of 44 tons of CO_2/day. The biogenic silica and organic carbon measurements in the sediment show that organic productivity also constitutes an important carbon sink for the lake waters. The $\delta^{13}C$ gradient with depth is the result of these two carbon-loss processes, which withdraw isotopically light carbon. The DIC $\delta^{13}C$ gradient builds up from spring-summer-fall, but is then reset in the winter. East Lake is mesotrophic with 50-60% of the sediment composed of biogenic silica and 8-12% composed of organic carbon. We conclude that the diffusive gas loss is the main process responsible for the $\delta^{13}C$ (DIC) gradient with

depth in East Lake, as Paulina Lake has only a small $\Delta\delta^{13}C$ (DIC) (0.5‰) and lacks the diffusive loss, but ultimately has a similar active ecosystem. Life in East Lake is predominantly fueled by the geothermal inputs of CO_2, Si and P providing photosynthetic reactants while nitrogen for photosynthesis occurs via cyanobacteria N2 fixation from the atmosphere.

Further work will involve quantitative modeling of the East Lake carbon cycle calculated from photosynthetic accumulation rates in the sediment and the diffusional CO_2 losses. Diffusional CO_2 losses will be adjusted due to modulation by wind and water temperature. In addition, the sediment Hg data will provide Hg injection rates for the lake.

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