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A STUDY OF THE GEOCHEMICAL AND GEOMORPHOLOGIC EVIDENCE FOR PREHISTROIC FLOODS FROM PAULINA LAKE, NEWBERRY VOLCANO, CENTRAL OREGON

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INTRODUCTION

Abandoned waterfalls and dramatic knickpoints line Paulina Creek showing evidence for catastrophic prehistoric floods of unknown origin. In addition to erosional features, there is a large flood apron (12km^2) that formed just upstream of the confluence of Paulina Creek and the Little Deschutes River. Paulina Creek originates from Paulina Lake (5.5km^2), which is the major source of water to the creek. The lake lies within the western part of the Newberry Volcano caldera, a Holocene shield-type volcano composed of dominantly basaltic lava flows. Ash flows, cinder cones and pyroclastic deposits are also common on the flanks of the volcano. Hypotheses for the flood are classified into two groups, those involving displacement of lake water—landslides into the lake or volcanic eruptions—and those involving partial draining of the lake in association with lowering of the outlet—catastrophic collapse of the outlet associated with upstream migration of a knickpoint.

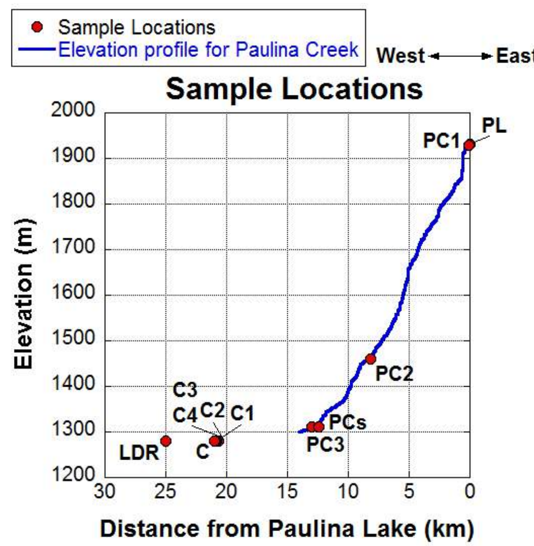

Figure 1. Graph showing sample sites in relation to Paulina Lake (distance 0) in the East and ending at the Little Deschutes River with an underlain elevation profile for Paulina Creek, showing the steep gradient from the lake to the flood apron (blue curve). Sample sites (east to west): PL, Paulina Lake; PC1, Paulina Creek cross section 1; PC2, Paulina Creek cross section 2; PCs, Paulina Creek sediment; PC3, Paulina Creek cross section 3; C1-4, confluence sediment samples; C, confluence of Paulina Creek and Little Deschutes River; LDR, Little Deschutes River abandoned oxbow sediment sample.

METHODS

Sediment and water samples were collected at various locations around Newberry Caldera and the Paulina Prairie flood plain during June 2015. Three discharge measurements were taken along Paulina Creek. Sediment cores from Paulina Lake were taken using a Hammer Action Corer (at 34m-75m water depth), while sediment cores from the flood plain were taken using a metal auger corer with extension attachments (0.5m-2m in length). Sediment was analyzed by microwave digestion for extractable metals by acid digestion using EPA method 3050A with analysis of extracts by Teledyne Leeman Labs Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), trace metals and major elements were determined by X-Ray Fluorescence, soil Hg using a Teledyne Leeman Labs Hydra C and clay minerals by X-Ray Diffraction (XRD) using powder pack and grains size separated to less than 1 micron by centrifugation at various treatments—overnight in glycol, and heating at 350°C, 550°C for 1hour. Water samples from Paulina Creek and Paulina Lake were analyzed for Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and SiO_{2aq} by ICP-OES, while alkalinity and pH were measured on a

Mettler 1012 autotitrator. Samples from the cemented streambed of Paulina Creek was powdered and run on the XRD and Scanning Electron Microscope with an Energy Dispersion Spectroscopy system (SEM-EDS). An analysis of the geomorphology of the Newberry area was done with ESRI ArcMap software using LiDAR data acquired from Oregon Department of Geology and Mineral Industries (DOGAMI). Bare earth DEMs (1m) were fit to Oregon Lambert NAD83 (HARN), Intl feet.

RESULTS

Climate

The climate is influenced by the orographic rain shadow of the Cascade Range (Lefkowitz et al., 2015). Precipitation is seasonal with most occurring as snow and rain between December and April. The mean annual precipitation for the Paulina Lake area is 76cm/year based on the OWRD weather station on Paulina Lake installed in 1982 (Morgan et al., 1997). The majority of precipitation during November–March is snow compared to rain during June–November. Storms are common, with 75% of the mean annual precipitation falling during December–May.

Geomorphology and Hydrology: Paulina Lake and Paulina Creek

Inflow to Paulina Lake comes from precipitation, surface run off from snow, hot spring discharge and groundwater inflow. Water exits the lake by surface outflow to Paulina Creek and evaporation. Paulina Creek flows 21km west from Paulina Lake, discharging into the Little Deschutes River. The Little Deschutes River has a dramatically different morphology characterized by a low gradient with abundant abandoned oxbows and a higher mean annual discharge (6cms). Mean annual discharge for Paulina Creek is only 0.50cms, with a peak mean daily flow of only 1.5cms. The Little Deschutes is dominated by depositional features while Paulina Creek is dominated by erosional features, except in the flood deposit area, and Paulina Creek has a much steeper gradient. The creek is underfit, trickling over 40m waterfalls.

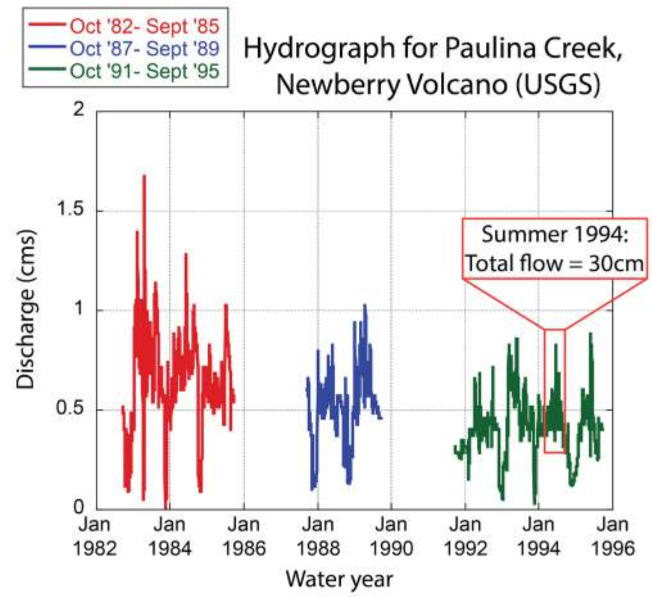

Figure 2. Hydrograph for USGS gage station data from USGS site 14063300 for Paulina Creek located on the dam at the outlet of Paulina Lake over a 13 year period from 1982–1995. The discharge over the three periods is consistent, with the highest discharge in the mid-1980s and gradually decreasing subsequently. The orange box outlines summer 1994, where a unit hydrograph was constructed to assess the total discharge for the summer months. The total amount of discharge was found to be 20cm, which can be interpreted as the total outflow for the lake during the warmest months, excluding evaporation.

A hydrograph constructed from the USGS gage station (14063300) data from the outlet of Paulina Lake shows generally uniform flow of 0.5cms over the 13 year period of record (1982-1995) with a gradual decrease since the mid-1980s (Fig. 2; Morgan et al., 1997). Discharge measured along Paulina Creek during June 2015 shows no change in flow moving downstream from Paulina Lake to the Little Deschutes River. Measured discharge values are consistent with summer values reported from the USGS gage station when it was in operation. Integration of the unit hydrograph constructed from USGS data for the 1994-95 water year yields 56cm of annual runoff. The mass balance for Paulina Lake shows 80cm of evaporation off the surface of the lake. Paulina Lake annual level changes by about 1m chiefly influenced by precipitation, evaporation and surface runoff to Paulina Creek.

The watershed area (120km^2) of Paulina Creek and Paulina Lake was determined using a LiDAR DEM. Despite tripling the size of the watershed the discharge stays the same, even decreases, by the time the creek reaches the Little Deschutes River. Within the watershed is a large flood deposit (15km^2 with 6m of relief) which is evidence of valley erosion. The feature occurs at the opening of the canyon and grows towards the Little Deschutes River (Fig. 3). To the north of this feature are intermittent streams that disappear before reaching the Little Deschutes River (based topography maps). There are many (~20) intermittent streams around the eastern flank of the volcano, showing layers of unconsolidated material.

Dramatic knickpoints, some 40m tall, and associated abandoned channels were seen in the field and on LiDAR DEMs of the area (Fig. 3). The stratigraphy of Paulina Creek is varied and contains layers of erodible and resistant material from years of volcanic eruptions and flows. This layering of volcanic material corresponds to the places of weakness along the channel creating more than 50 knickpoints along the creek (Fig. 4). The geology of the streambed changes upstream to downstream from permeable andesitic tuff deposits to non-permeable basalt and andesite lava flows (MacLeod et al., 1995). At Paulina Creek Falls, an underfit waterfall along the creek, andesitic basalt is exposed with red scoria above it. Despite these erosional features, there is little modern erosion along the bed of the creek due to a cemented streambed. Further, the creek water contains no suspended load flowing over a solid streambed of clastics. A sample of the streambed contains pyroclastics cemented together into a solid bed.

Around the south and east shorelines of Paulina Lake, evidence of paleo-shorelines from 7000 BP are apparent. These shorelines rise a few meters above the current shoreline (Fig. 3). There are also submerged paleo-shorelines around the perimeter of the lake (Lefkowitz et al., 2015). On the north rim of the crater are multiple vents showing evidence for flows into Paulina Lake.

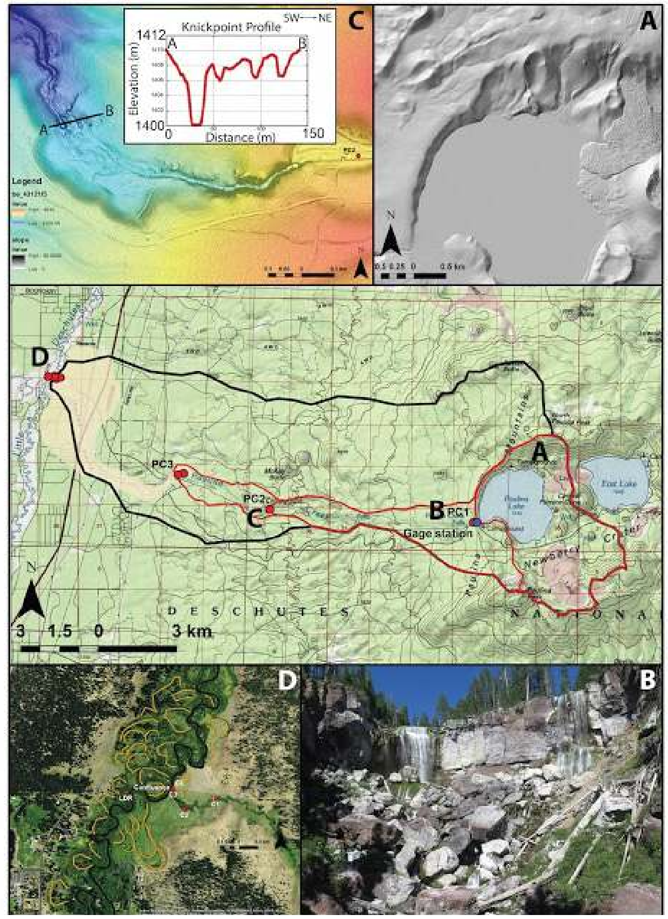

Figure 3. DEM of the study area magnifying key geomorphic features of the system. The topographic map contains watershed outlines for the watershed of Paulina Creek and the three discharge measurments that correspond to an increasing in size (from 22–40km2) but a uniform flow. The topography map also shows an estimated flood deposit (15km2) in the western edge of the map, bounded by the Little Deschutes River. Geomorphic maps along the canyon include: A) North rim of Paulina Lake with evidence for multiple vents and slides; B) Paulina Creek Falls, a 40m tall undercut waterfall; C) Current and abandoned knickpoints of decreasing depth along Paulina Creek, just one example of more than 50 along the creek of varying sizes; D) Little Deschutes River abandoned oxbows and many current meanders, a starkly different morphology compared to Paulina Creek.

Chemical Analysis: sediment and streambed samples

Arsenic is characteristically high in the water column and sediments of Paulina Lake (0.014ppm and 250ppm respectively). However, it is found to diminish in concentration traveling away from the lake (7ppm As in the flood apron, 5ppm As in the flood plain and around 1ppm As on the far side of Little Deschutes River). Along with high arsenic concentrations Paulina Lake sediments were found to contain amorphous sediment.

Chemical analyses of Paulina Lake and Paulina Creek water indicate that it is supersaturated with respect to calcite, containing high concentrations of dissolved calcium, magnesium and bicarbonate. The sample of the streambed was analyzed by XRD

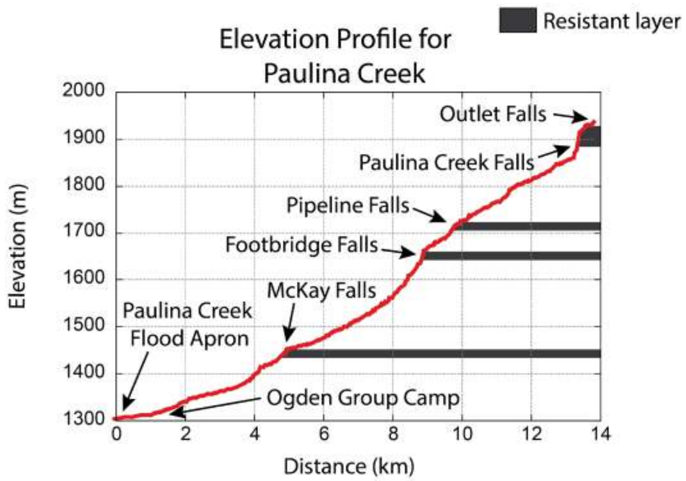

Figure 4. Elevation profile showing knickpoints and waterfalls (where indicated) and places of resistant layers over the course of the creek from lake to flood apron. The stratigraphy contains talus and recent ejecta, mazama ash, basalt, Paulina Falls andesite flow and breccia, mafic tuffs with graded bedding, red scoria and andesitic basalt (Higgins, 1973). At various locations there is more basalt exposed, creating the opportunity for differential erosion along the canyon.

and found to contain a magnesium carbonate called huntite, $Mg_4Ca(CO_3)_4$, seen with a characteristic d-spacing of 2.7Å on the diffractogram and on the saturation diagram (Fig. 5). The diffractogram for the powdered sample also shows the presence of calcite at a d-spacing of 3.02Å. Crusts on rocks in the flood apron were also analyzed by XRD and found to have a similar peak at a d-spacing of 3.02Å; they were not measured past 32° 2-theta however so did not pick up a peak for huntite.

DISCUSSION

Paulina Creek has experienced catastrophic flooding in its past as evidenced by the underfit nature of the creek at Paulina Creek Falls. Differential erosion due to layering of erodible and resistant layers has a huge impact on the creek, causing many knickpoints along the channel. As well, the creek does not experience high flow conditions as discharge only varies by 1cms throughout the year. The discharge does not impact erosion along the cemented streambed, as there is no apparent suspended load. The erosional features of Paulina Creek could not have been formed under current conditions.

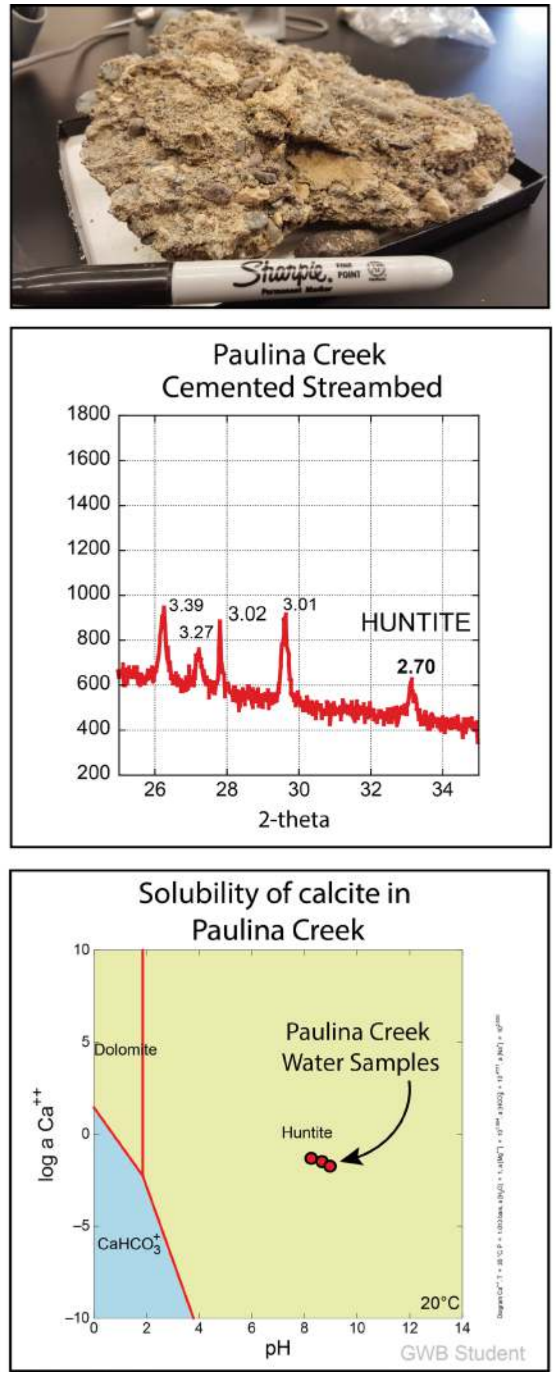

Figure 5. From top: Photograph of streambed sample; an XRD diffractogram showing the presence of huntite at the characteristic d-spacing of 2.7Å, other peaks present are those of various other materials in the cemented sample, including calcite (3.02Å); solubility diagram for Paulina Creek water showing the presence of huntite, confirmation for above findings.

Paulina Creek is chiefly fed by water coming from Paulina Lake. The water budget gave reasonable numbers suggesting that magmatic water does not have a huge influence on the system and the outflow from Paulina Lake is the major source for discharge. Paulina Lake is a flood control reservoir, dampening flooding from normal precipitation events. It would take a drastically different climate for flooding to occur via a precipitation event.

Chitwood and Jensen (2000) suggest that floods were caused due to failure of the outlet sill by the headward migration of a waterfall. They estimate the level of the lake lowered by 1.5–2.4m based on the height of the dam that presumably failed. Multiple knickpoints along the canyon suggest that headward erosion occurs in the creek. But if the outlet sill, made from unconsolidated and irregularly stratified tuff, was on the verge of failure then any event that increased lake level could hasten collapse. These events could include displacement of lake water by an avalanche of snow or rock, rapid emplacement of lava, or sudden uplift due to rapid movement along a fault.

The method for flood production is a combination of lake water displacement and dam failure. This could be failure triggered by a volcanic landslide from the north rim of the crater, leading to a large displacement of water. This combination of events occurred multiple times eroding the tuff and pyroclastics in the valley resulting in the flood deposit. The floods heavily eroded Paulina Creek valley and therefore the deposits are mainly from that area and not displaced lake sediment. Further, for a flood deposit of displaced lake sediment there should be a comparable amount of arsenic (As) to lake sediment. However, there was only 5ppm As in the flood deposit sediments and compared to Paulina Lake sediment which contains 250ppm As there is virtually no As in the flood deposits. The amount of sediment in the downstream flood deposit is insufficient to account for the amount of erosion need to form the valley, reiterating the idea of multiple floods. Each flood event was critical in shaping the valley of Paulina Creek.

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