

AN EXPANDED LAVA CREEK TUFF ERUPTION: RE-MAPPING THE SOUR CREEK
DOME, YELLOWSTONE NATIONAL PARK

by

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A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

June 2023

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ACKNOWLEDGEMENTS

Without funding, this project would not have moved forward. I would like to say thank you to the National Science Foundation award EAR-2025625 and the U.S. Geological Survey EDMAP program for funding this project.

I would like to thank my advisor, Dr. Madison Myers, for guiding me through this project and giving me the opportunity to learn and grow as a scientist. Thank you to my committee members Dr. Colin Wilson and Dr. Andrew Laskowski for your support and knowledge which made this project possible. Thank you to the various field hands I had throughout my project including the volunteer and the REU students. A special thank you to Hailey Finch, Henry Stahl, and Colter Zandi for spending many weeks in the field with me hiking through rough terrain and fending off millions of mosquitoes. I am grateful to my fellow graduate students for their support and friendship throughout the last couple years. Thank you to the Yellowstone Volcano Observatory and all its constituents for allowing me to share my work and for giving me feedback. Thank you, Yellowstone National Park, for providing a research permit to our group. All fieldwork was conducted in Yellowstone National Park under permit number YELL-2022-SCI-5248. Finally, thank you to my friends and family for supporting me through this journey as well as their continued support.

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ABSTRACT

The $\sim 1000 \text{ km}^3$, $\sim 630 \text{ ka}$ Lava Creek Tuff is the product of the younger major caldera-forming eruption of the Yellowstone Volcanic Field. It is currently mapped as two ignimbrite units, hot dense flows of ash, gas, and molten material, termed members A and B, with accompanying widespread ashfalls over the western U.S. This view of the Lava Creek Tuff, and its eruption, was complicated when two, visually distinct, ignimbrites were recognized on the Sour Creek dome in Yellowstone National park (Wilson et al., 2018). These visually distinct ignimbrites on the Sour Creek dome were initially mapped as the older (2.08 Ma) Huckleberry Ridge Tuff, however, when dated by U – Pb on zircon and $^{40}\text{Ar}/^{39}\text{Ar}$ on sanidine the ignimbrites returned ages analytically indistinguishable from the Lava Creek Tuff (0.631 Ma). In the newly dated ignimbrites, one unit is found as clasts of dense welded tuff withing a lag deposit which is conformably overlain by a second, cliff-forming, densely welded ignimbrite that contains scoria. This study further complicate matters due to the discovery of two additional, previously unrecognized, ignimbrites while mapping on the Sour Creek dome, bringing the total to four ignimbrites. Physical and chemical evidence suggests there were multiple magma bodies tapped during the eruptions. This project broadens our understanding of the four ignimbrites documenting their spatial distribution and source area(s) and determine how they relate geochemically to the established members A and B. This was done through field mapping, thin section examination, and whole-rock and single crystal geochemistry. This resulted in a revised understanding of the Lava Creek Tuff stratigraphy and holds implications for reevaluating the eastern boundary of the Yellowstone Caldera.

CHAPTER ONE

INTRODUCTION AND BACKGROUND

Introduction

The largest-scale caldera-forming eruptions, often termed ‘supereruptions,’ are eruptions which produce $>450 \text{ km}^3$ of magma (Miller and Wark, 2008). These supereruptions have in many areas around the world, with 13 occurrences in the Quaternary (Wilson et al., 2021). Due to their infrequency, silicic caldera-forming eruptions are one of the least understood, yet most disastrous, events that occur in nature. Supereruptions are rare, with an average of one occurrence every 100,000 years (Mason et al., 2004; Wilson et al., 2021), but this number is just an average and should not be taken as an indicator of when the next one will be (Miller and Wark, 2008). These eruptions have the potential to displace hundreds to thousands of cubic kilometers of material on the order of weeks, to decades or longer (Wilson and Hildreth 1997; Self, 2006; Swallow et al., 2018a, 2019; Wilson et al., 2021). Currently, the best techniques to determine the volume of material erupted, how and where the original magma was stored in the crust, as well as infer the possible triggering mechanism for these eruptions is through a combination of detailed field mapping and geochemical characterization of the erupted material (e.g., Gottsmann et al., 2009; Bachman, 2010; Allan et al., 2012; Myers et al., 2016; Swallow et al., 2019; Pearce et al. 2020; Pineda et al., 2021). Historically, caldera-forming supereruptions have been thought to occur as singular, large events, where a shallow (4 - 8 km) magma chamber is effectively emptied upon eruption, causing the overlying ground to collapse into the vacated space, to form a caldera (Smith and Bailey, 1968; Lipman, 1976; Druitt and Sparks, 1984; Gudmundsson, 1988; Lipman et al.,

1997; Cole et al., 2005; Wilson et al., 2021). These eruptions produce ash fall deposits and ignimbrites, the latter of which can be hundreds of meters thick and emplaced to over 100 km from their source. These large ignimbrites are the product of pyroclastic density currents (PDCs), hot, ground hugging particulate flows of pumice, ash, lithics, and crystals that cool as a single cohesive unit (Smith, 1960; Ross and Smith, 1961; Walker, 1983; Wilson, 2008; Wilson et al., 2021). Understanding the eruptive dynamics and timing of PDCs has been a challenge due to the dangers of direct observation as well as how infrequently they have been observed (Fierstein and Wilson, 2005). Ignimbrites can show a wide variety of textures, welding, lithic and crystal content and size, and internal structure all within a single eruptive package that needs to be interpreted to reconstruct the earlier flow dynamics (Freundt et al. 2000; Wilson and Hildreth, 2003; Fierstein and Wilson, 2005). Along with the intricate layers of a flow unit, an ignimbrite may also contain a lag breccia. A lag breccia is a lithic breccia which is commonly clast supported, poorly sorted, ranging from ash to boulder sized, vent-derived wall rock fragments; the large size of the clasts suggesting proximity to a vent (Wright and Walker, 1977; Druitt and Sparks, 1982; Walker, 1985; Freundt et al., 2000). The maximum clast size decreases away from the vent due to the energy requirements of transporting large (>1 m) clasts (Freundt et al., 2000).

It is not uncommon to have multiple flow units make up a singular ignimbrite deposits, which can present itself as a single thermal cooling unit (Wilson and Hildreth, 2003). Welding in an ignimbrite refers to the degree in which the deposit has coalesced due to heat and load stress (Freundt et al., 2000; Quane and Russell, 2005). Ignimbrites can range from non-welded, meaning they can be disaggregated into their original grain sizes and components, to vitrophyre, meaning highly compacted and obsidian-like (Quane and Russell, 2005). In extreme cases, an ignimbrite

may have a rheomorphic texture which suggests that the temperature upon emplacement was high enough for the deposit to coalesce into a viscous liquid and flow in similar fashion to a lava (Freundt et al., 2000).

Though it is possible for a supereruption to occur rapidly (Ledbetter and Sparks, 1979; Wilson and Hildreth, 1997), this is not always the case. The ability to identify and quantify time breaks in caldera-forming eruptions would indicate whether an eruption was episodic in nature; consisting of periods of intense activity and gaps where no record of activity is seen (e.g., Wilson and Hildreth, 1997; Wilson, 2001; Wilson et al., 2021). For instance, the Yellowstone Volcanic Field is home to two supereruptions, the Huckleberry Ridge Tuff (HRT: 2.08 Ma), and Lava Creek Tuff (LCT: 0.631 Ma). Both the HRT and LCT were originally inferred to be the product of multiple consecutive eruptions vented from discrete locations now within the relevant caldera (Christiansen, 2001). However, studies have highlighted that the HRT had time breaks of days (Myers et al., 2016) to decades (Swallow et al., 2019). In addition, it was demonstrated that the HRT was sourced from distinct and physically separated magma bodies, with evidence for separate parental magma sources in the crust and mantle (Myers et al., 2016; Swallow et al., 2018a, b, 2019). Studying time breaks holds implications for how we perceive the possible phases of a caldera-forming eruption.

The LCT, however, has yet to be studied with the same level of detail as the HRT. The LCT was inferred to be two events, sourced from a single magma chamber and without a significant time break between eruptions (Christiansen, 2001). The recent identification of two new LCT-aged ignimbrites in the Sour Creek dome (SCD), Yellowstone National Park, has provided evidence of a significant time break within the LCT event (Wilson et al., 2018). However,

very little is known about these new ignimbrites recognized by Wilson et al. (2018). Their extent and distributions, and how they relate stratigraphically and geochemically, to the mapped Lava Creek Tuff members A and B, are unknown. This study characterizes the newly recognized ignimbrite units in the SCD area and determines how they relate to the overall eruption sequence of the LCT and its previously described members A and B. This has been done through a combination of detailed field mapping, petrographic descriptions, and geochemical analyses, with the aim of answering the following questions:

1. What is the extent (distribution) of the new units, and what are their source regions?
2. How do the ignimbrite units geochemically and petrologically relate to each other and how do they relate to the conventional extra-caldera LCT members A and B?
3. Were the ignimbrite units erupted earlier than, at the same time as, or later than, the conventional extra-caldera LCT members A and B?
4. Can the newly recognized units be projected to parts of the Sour Creek dome not physically visited?

Ultimately this project will result in a new understanding of the ignimbrite units that make up the SCD and relate these to the deposits that make up the widespread mapped extra-caldera LCT.

Background

Geologic Context

The Yellowstone Volcanic Field is home to some of the most voluminous Quaternary rhyolitic eruptions in the United States, represented, in part, through a series of three large-volume, caldera-forming eruptions that produced the Huckleberry Ridge (2.08 Ma), Mesa Falls (1.3 Ma), and Lava Creek (0.631 Ma) tuffs. The oldest and largest (2500 km³) of these ignimbrites is the

Huckleberry Ridge Tuff, which has been mapped as three separate ignimbrite units, members A, B, and C preceded and accompanied by a large, exceedingly widespread fall deposit (Izett & Wilcox, 1982; Christiansen, 2001). Based on field evidence, Swallow et al. (2019) outlined how the HRT deposits record depositional gaps between erupted units, with months to years between Members A and B and decades between B and C. It was also demonstrated the Huckleberry Ridge eruption was sourced from four magmatic systems that separately and sometimes simultaneously fed the eruption throughout its duration (Swallow et al., 2018a, 2019). The Mesa Falls Tuff is the smallest (280 km³), and least exposed of the three deposits (Christiansen, 2001). The Mesa Falls Tuff has been interpreted to represent a single depositional event containing an underlying fall deposit and an ignimbrite with a more densely welded upper portion, fed by an isotopically heterogeneous magma chamber (Christiansen, 2001; Rivera et al., 2016). The youngest of these eruptions, the Lava Creek Tuff (~1000 km³, 0.631 Ma) is divided into members A and B, separated by a reversal in welding profiles and distinguished by the presence of phenocrystic amphibole in Member A (Christiansen, 2001). (Note, however, that these designations are currently being reevaluated: Henderson et al., 2021.) These member A and B distinctions were further questioned when two additional, visually distinct, ignimbrite units with ages analytically indistinguishable to those of the Lava Creek Tuff were recognized in the SCD area (Wilson et al., 2018).

Sour Creek Dome

The Sour Creek resurgent dome is thought to have been created after the LCT eruption (Christiansen, 2001). A resurgent dome is an area of the caldera floor that is uplifted as a structural dome (Smith and Bailey, 1968; Marsh, 1984). Resurgent domes represent the product of uplift as the underlying evacuated magma chamber refills with magma; conversely, as magma leaves the

magma chamber, the resurgent dome will subside (Smith and Bailey, 1968). Often, resurgent domes are dominated by radial or concentric faulting (Smith and Bailey, 1968). However, as mapped (Figure 1), the SCD has neither radial nor concentric faulting. Rather, it is dominated by a suite of NW-SE trending faults and an orthogonal suite of NE-SW trending faults. Interestingly, the NE-SW suite of faults line up closely with the faults mapped on Elephant Back Mountain and thus must be younger than 150 ka (the age of the dome forming Elephant Back Mountain: Christiansen, 2001) due to cross cutting relationships.

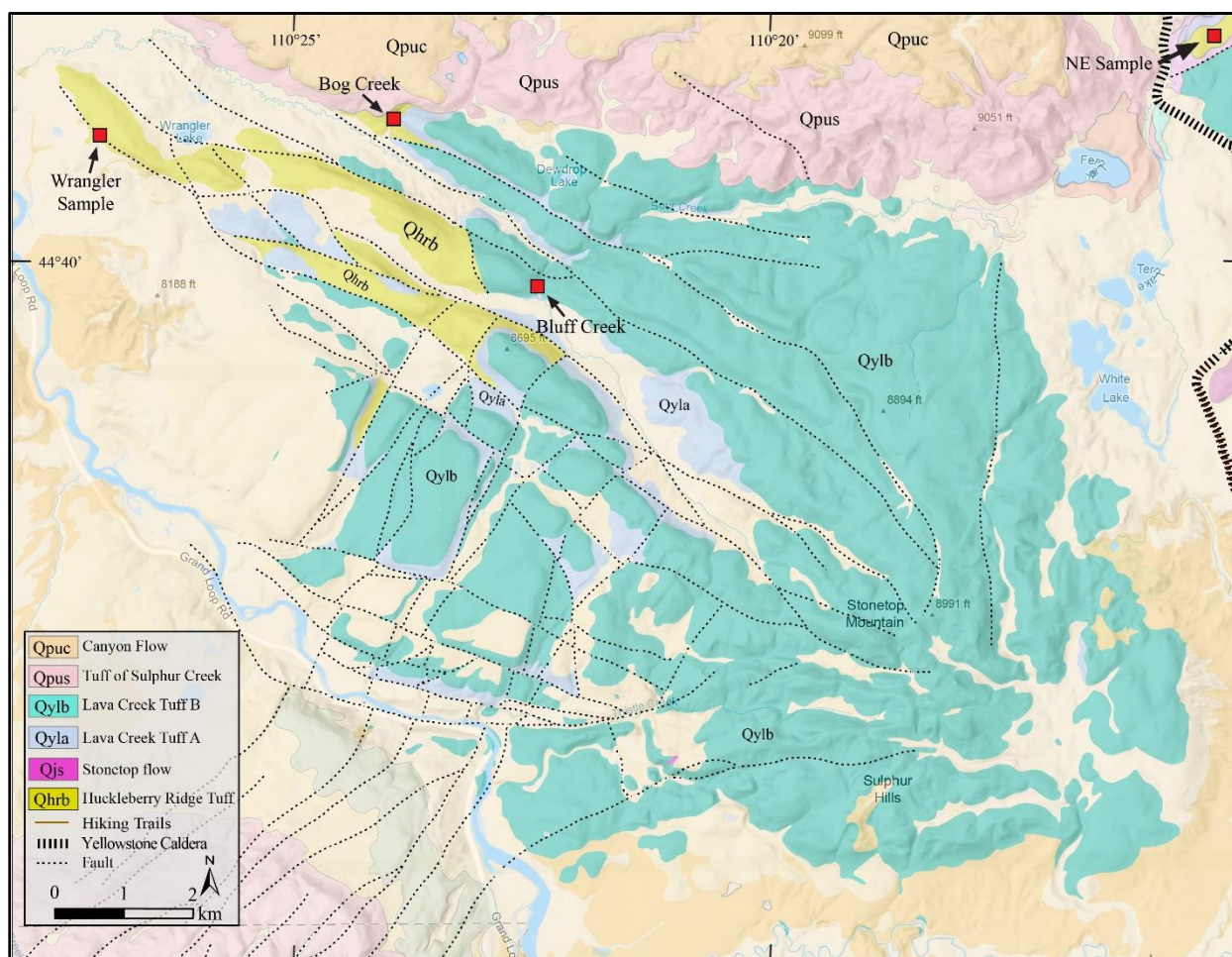


Figure 1. Current geologic map (modified from Christiansen, 2001) of the SCD area in Yellowstone National Park. Key locations are marked by red squares. Labels are as follows; Qhrb – Huckleberry Ridge Tuff; Qyla – Lava Creek Tuff A; Qylb – Lava Creek Tuff B; Qpus – Tuff of Sulfur Point; Qpuc – Canyon Flow.

Currently, Lava Creek Tuff members A (LCT-A) and B (LCT-B) and Huckleberry Ridge Tuff Member B (HRT-B) are mapped extensively in the SCD area (Christiansen and Blank, 1975; Christiansen, 2001: Figure 1), requiring established petrological and lithological descriptions to be used for distinguishing these members from the two new units. It is inferred that Member A of the LCT was erupted first, with the vent being proximal to Tuff Cliff (Figure 2), while Member B was erupted from the eastern boundary of the caldera, just outboard of the SCD (Christiansen, 2001). LCT-B is mapped more extensively in the SCD than either LCT-A or HRT-B (Figure 1). The following descriptions come from field observations of the broadly distributed LCT members A and B, HRT-B and two new units of the LCT (Figure 2; Christiansen, 2001; Wilson et al., 2018; Henderson et al., 2021).

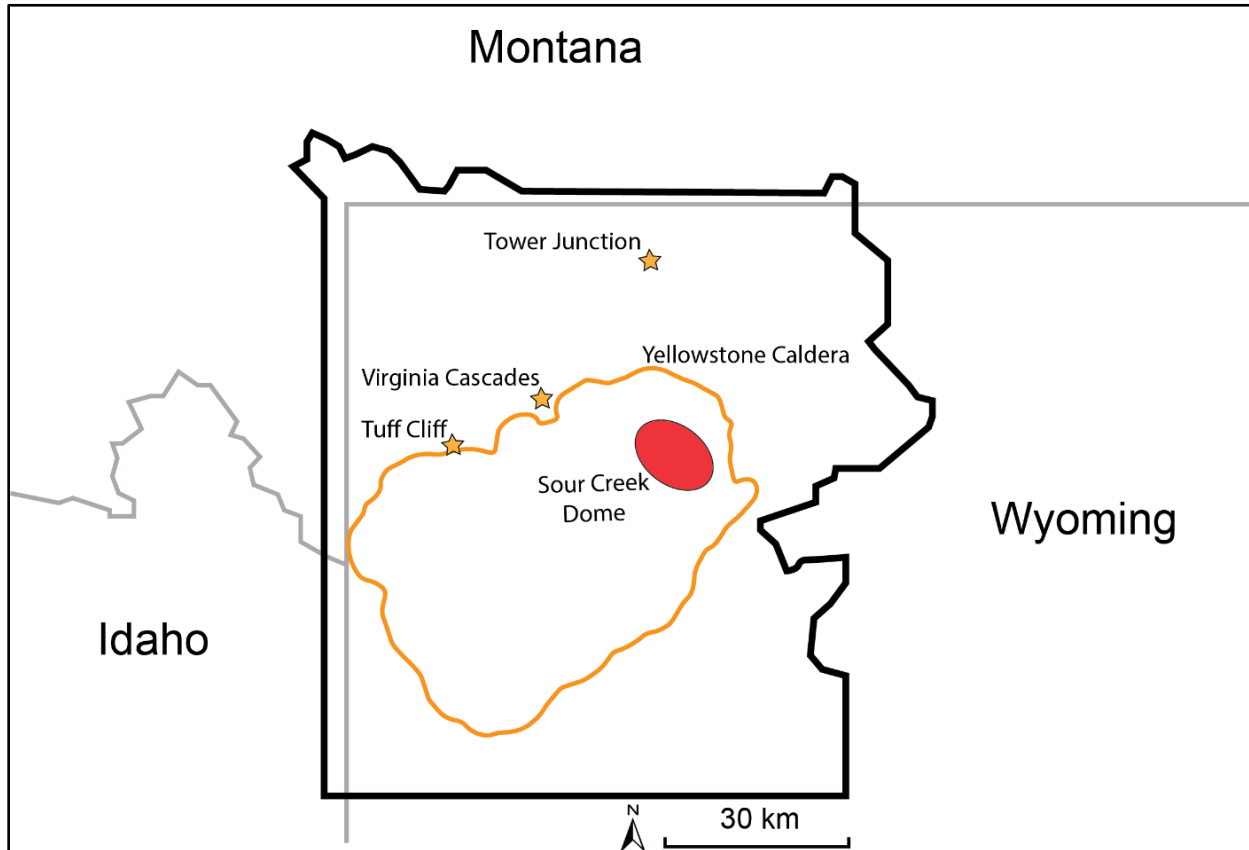


Figure 2. Outline of Yellowstone National Park. The location of the Yellowstone Caldera is shown by the orange line. The Sour Creek dome is marked by the red oval. Tower Junction, Virginia Cascades, and Tuff Cliff localities are marked by orange stars.

Lava Creek Tuff Member A

Where exposed, Member A presents in one of two ways (Figure 3). The first is densely welded, yet crumbly and thoroughly weathered, presenting as tan-yellow in color. The other is as a densely welded rock with a thick weathering rind that is hard to break. In hand sample, LCT-A has a grey matrix; however, when it is altered (as is more often the case) it appears more tan-yellow. The minerals present, listed in decreasing order of abundance, are quartz, sanidine, plagioclase, and oxides, with trace pyroxene and amphibole (Christiansen, 2001; Henderson et al., 2021). The plagioclase and sanidine are distinguishable from each other in hand specimen due to the plagioclase being yellow stained from weathering. In thin section, sanidines are square while

the plagioclase are elongate. The feldspar types also display different twinning features. Sanidine shows carlsbad twinning while the plagioclase shows albite twinning. Both feldspar types display subrounded to subangular forms. The quartz is moderately fractured and generally rounded to sub rounded. The pyroxene and amphibole, when present, all show breakdown textures (breakdown rims, mineral replacement, etc.,). The matrix of this member may show flow texture and glassy shards: in most cases the glass appears broken down due to vapor phase alteration.



Figure 3. A) Hand sample photo of a cut face of Lava Creek Tuff Member A from Virginia Cascades. B) Hand sample photo of a weathered face of Lava Creek Tuff Member B from Lewis Canyon. Both photos by Stacy Henderson.

Lava Creek Tuff Member B

In exposures, LCT Member B tends to be more competent than LCT Member A, likely due to its higher degree of welding, forming cliffs rather than weathering as rubble. However, LCT-B is also often seen as a weathered outcrop. In hand sample, the unit is dark gray when nonweathered and unaltered. Similarly to Member A, LCT-B is yellow-brown in color when weathered (Figure 3). This makes it somewhat difficult to distinguish between members A and B in the field when presented with weathered exposures that have no internal stratigraphy. The mineral assemblage and concentrations are generally indistinguishable from those of Member A (Henderson et al. 2021). In thin section, LCT Member B is nearly indistinguishable from LCT-A. LCT-B lacks phenocrystic amphibole, where LCT-A may contain some. It has subangular to subrounded feldspars and rounded to subangular quartz. The matrix in LCT-B is generally devitrified glass or a microlite groundmass.

Huckleberry Ridge Tuff Member B

The Huckleberry Ridge Tuff (HRT) Member B is the second member in the overall HRT ignimbrite stratigraphy. Though HRT-B is mapped in the SCD (Christiansen and Blank, 1975; Christiansen, 2001), this ignimbrite, as reported and visited by Wilson et al. (2018), is visually different from HRT-B and yielded a zircon crystallization U-Pb age of ~651 ka from the interior of sectioned grains (Wilson et al., 2018). As HRT-B has previously been mapped in areas not revisited in the SCD, it is important to understand what it looks like in order to accurately remap the dome. HRT-B, as mapped outside the SCD, is a grey-pink ignimbrite with common pale fiamme and with minor amounts of grey scoria in its upper parts (Christiansen, 2001).

Stonetop Mountain Flow

The Stonetop Mountain Flow is an inferred rhyolite lava flow on the SCD and is thought to be part of the Mount Jackson series of rhyolite lavas (Christiansen and Blank, 1975; Christiansen, 2001). The Mount Jackson rhyolites are porphyritic, crystal-rich (15 – 40%) lava flows containing sanidine, quartz, and lesser amounts of plagioclase (Troch et al., 2017). The rhyolite flows span the time between the Mesa Falls Tuff eruption (1.3 Ma) and the LCT eruption (Christiansen, 2001), but the majority span 1.2 – 0.7 Ma. The existing interpretation is that the Stonetop Mountain Flow is part of a pre-LCT lava dome that would have been a paleo-topographic highpoint, buried by the later ignimbrite (Christiansen, 2001). This was inferred as the topography strongly suggests a bulbous buried surface at Stonetop Mountain as well as its quaquaversal drainage pattern.

Newly Recognized Units

The following descriptions of Unit 1 and Unit 2 are taken from Wilson et al. (2018). Both units 1 and 2 were mistakenly mapped as HRT-B in the SCD and have since yielded ages that are indistinguishable from those of the LCT. Units 1 and 2 represent newly recognized ignimbrites, visually distinct from the LCT and HRT, which are inferred to be part of the LCT eruption.

Unit 1. At the Bog Creek locality (Figure 1) there is a roughly 25 m-thick exposure of welded, poorly sorted lithic-rich breccia in the creek bed. The streambed with the breccia exposure is covered with grey hydrothermal precipitates. The breccia clasts range in size from ash to meter-scale boulders and are angular to well-rounded (Wilson et al., 2018). Fiamme (flattened pumices) are rare and there are sparse fragments of irregularly cross bedded tuff, interpreted as intraclasts of reworked material. In addition, the clasts making up the breccia show no evidence of being

emplaced at or having been fragmented at high temperatures, as evidenced by a lack of chilled margins, breadcrust textures, or radial (cooling) jointing in the clasts (Wilson et al., 2018). The poor sorting of the breccia and the consistency of the tuff seen between clasts led Wilson et al. (2018) to interpret this as a lag breccia. A lag breccia of this nature is generally interpreted to be a near-source feature, within a few kilometers of vent (Druitt and Sparks, 1982; Walker, 1985; Self et al., 1986; Wilson, 2001; Wilson et al., 2018). The fact that the ignimbrite fragments within the breccia are dated to be of LCT age suggests that there was a time-break within the LCT eruptive sequence long enough for cooling of the earlier ignimbrite to have occurred, roughly estimated to be on the order of decades.

Unit 2. The next ignimbrite, referred to here as Unit 2, was first described in two locations on the SCD and in one location off to the northeast. On the SCD, it was found on the northwestern most edge of the SCD to the west of Wrangler Lake and at Bog Creek, which has carved an exposure in the cliffs. The sample off the SCD to the northeast was originally collected by Christiansen (2001) and upon review by Wilson et al. (2018), this ignimbrite appeared visually similar to the ignimbrite seen at Bog Creek and west of Wrangler Lake. At the Bog Creek location, this ignimbrite conformably overlies the breccia containing Unit 1, suggesting that it was the eruption of Unit 2 that broke through an earlier emplaced LCT-aged ignimbrite. At Bog Creek, Unit 2 creates cliffs about 40 m in height and is intensely jointed. The ignimbrite was described as crystal-rich and contains numerous fiamme. Notably, this ignimbrite also contains scoriaceous material which has been recrystallized (Wilson et al., 2018).

CHAPTER TWO

METHODS AND RESULTS

MethodsRemapping and Sample Collection

Six weeks of remapping in the SCD area began in the summer of 2021 and continued for seven weeks during the summer of 2022. Prior to leaving for the field, Google Maps was used to determine mapping transects that would include exposed materials and limit the amount of challenging terrain to be traversed. Preliminary mapping during the 2021 summer had helped constrain that steep topography and areas with mapped contacts were the most likely to contain exposures suitable for use (i.e., in-situ exposures with minimal weathering).

Once a suitable exposure, meaning minimally altered by post-emplacement processes such as vapor phase alteration was found, a sample location was marked with a GPS device and coordinates written down in field notebooks. The exposure and sample were described in the field notebooks with inferences, based on observation, as to which unit was being recorded. Samples were collected that either represented an uncertain, but prominent, unit, or were representative of a specific unit being studied. The freshest sample of the unit was then bagged in Ziploc and cloth bags to avoid contamination. Samples were brought to Montana State University for processing and analysis. Full copies of field notes with GPS locations, can be found in Appendix A.

Remote Mapping

For areas that were unable to be physically visited during these two field seasons remote mapping was attempted using GIS software to project mapped units across the remaining areas of

the SCD. Due to the differences in welding profiles of each unit, it is hypothesized that each unit will have different overall slope angles, representing different weathering resistivities. To determine slope angle of each unit, a 10-meter DEM (Digital Elevation Model) was used. The 10-meter DEM (U.S. Geological Survey, 2021) was loaded into the ESRI ArcGIS Pro program. The Fill tool was then used to fill any sinks in the data. Initially the DEM contained a region that was larger than Yellowstone National Park, so the clip function tool, housed within the Raster Function toolbox, was used to clip the DEM down to the extent of the SCD. A Hillshade layer was created from the DEM to show topography.

The slope assessment was handled by drawing lines along the ridges of known units. The ridge lines were assumed to be the original angle of emplacement. The profile tool was then used to analyze the topography beneath each line drawn along the ridge ($n = 17$). The output allowed for the measurement of the slope along the ridges.

Structural Analysis

The SCD has two general suites of faulting. There is a set of NE-SW trending faults and a set of NW-SE trending faults, with the NE-SW trending faults truncating the NW-SE faults. The NE-SW suite of faults align closely with faults seen on Elephant Back Mountain, to the SW of the SCD (Figure 4). To determine if the faults on Elephant Back Mountain are related to those of the SCD, the method described in the following paragraph was applied to Elephant Back Mountain. The relationship of faulting to the SCD holds major implications for its structural resurgence in that if the faulting of the SCD is concurrent with that of Elephant Back Mountain, the faults are not related to structural resurgence that can be linked to the Lava Creek Tuff eruption. In addition, the mapped suite of NW-SE trending faults on the dome were examined to determine if there was

any offset between the graben-like structures. If there is notable offset, there likely is NW-SE faults. However, if there is minimal to no offset, then the NW-SE valleys may simply be preferential erosional pathways along fractures related to welding and compaction of the ignimbrite.

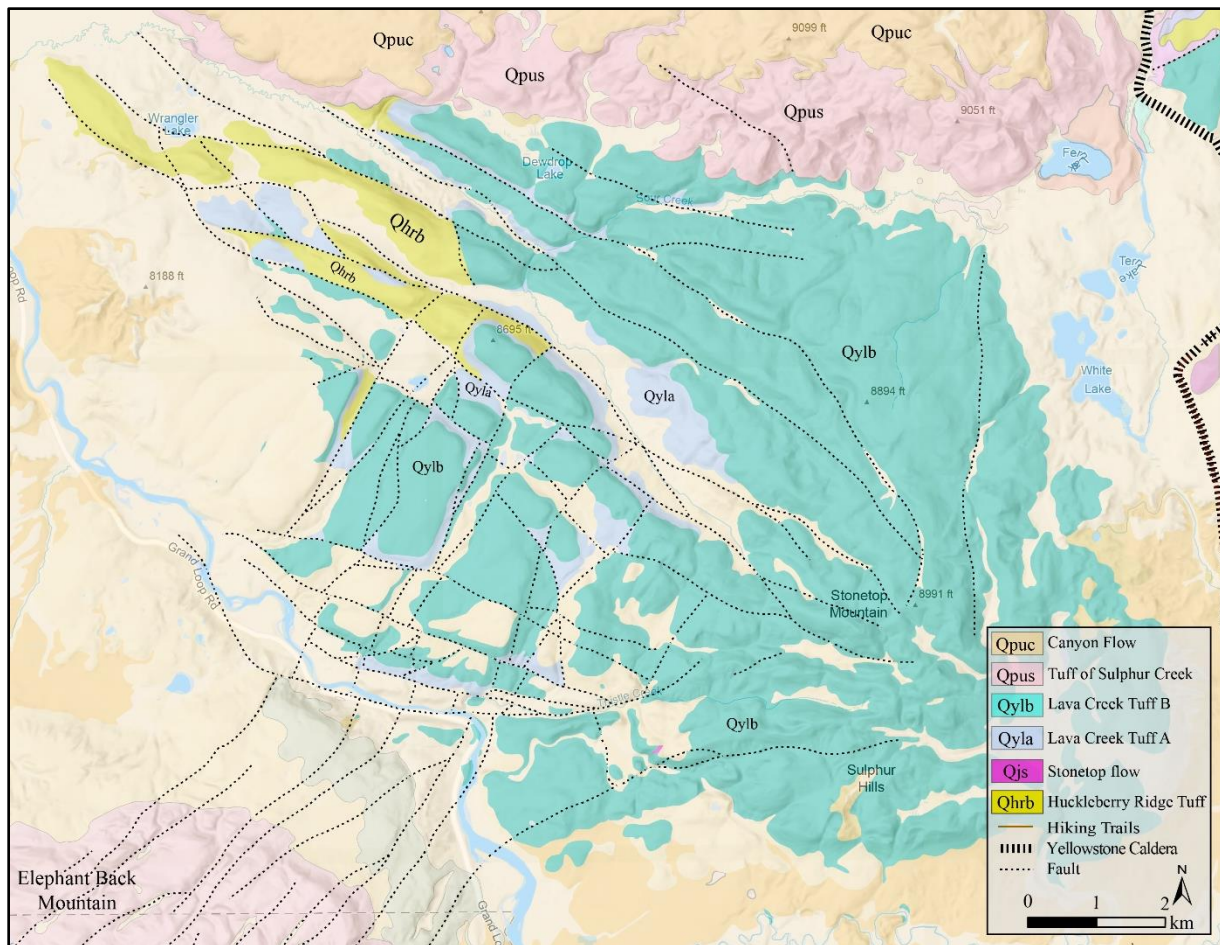


Figure 4. A map of the Sour Creek dome (Christiansen, 2001) showing the NE-SW trending faults to the SW. Elephant Back Flow is to the SW on Elephant Back Mountain.

For structural analysis, the main focus was fault displacement. There is an abundance of faults mapped on SCD, some of which were visited and others that were not. As an attempt to determine the accuracy of the mapped faults in areas not visited, the tops of ridges were used to

determine if there was displacement between them across the graben-like valleys. As above, ridge tops were assumed to represent original emplacement surfaces as they were generally ‘flat topped.’ Lines connecting ridgetops were drawn on a topographic map with 20 ft contours. The amount of offset was then noted. A general contour map of the SCD was created and used to restore the original shape of the dome before erosion.

Petrographic Overview

Collected ignimbrite samples were first cut into billets (26 x 46 x 20 mm) using the rock saw at Montana State University. The billets were then sent to Wagner Petrographic to make polished thin sections ($n = 23$). Thin sections ($n = 9$) were then point counted for major and minor mineral phases. The point counts were helpful in determining both which mineral phases are present as well as the modal abundance of these phases. Point counts were completed using an optical microscope with Plane-Polarized light (PPL), Cross-Polarized light (XPL) and Reflected light (RL). A minimum of 200 points were counted on each of the thin sections analyzed. These point counts quantified any mineralogical variations within and between the major new units to compare with concurrent work on Members A and B (Henderson et al., 2023). Modal abundances for each ignimbrite, determined by point counts, can be found in Table 1.

Whole Rock

Whole rock x-ray fluorescence (XRF) analyses to determine major and trace element signatures of each newly established ignimbrite unit were carried out at the Peter Hooper GeoAnalytical Laboratory in Pullman, Washington. To prepare for whole rock XRF analysis representative samples for each ignimbrite were crushed and milled at Montana State University. Whole rock was used rather than single clast analysis of juvenile material because although scoria

was present throughout Unit 2, individual clasts were too small for analysis (> 2 cm) and unable to be separated from the host rock. About 50 grams of each sample were brought to Pullman for analysis. At the lab, samples were powdered using a tungsten-carbide ring mill. The resulting powders were mixed with spec pure dilithium tetraborate (Johnson et al., 1999), placed in molds and left in a muffle furnace for fusion. During fusion the powders melt into glassy material called beads. After cooling from the fusion process, the beads were labeled, polished, and loaded into the XRF instrument for major and trace element analysis. Whole rock analyses for each new ignimbrite found in the SCD were completed to compare with the established Lava Creek Tuff members A and B datasets (Christiansen, 2001). Six samples from the SCD were analyzed via XRF: one from Unit one and five from Unit 2.

It was expected, based on previous work by Christiansen (2001), that whole rock analysis would be unable to distinguish any subtle differences between units. Therefore, other methods of geochemical analysis were required.

Electron Probe Micro-analysis

Subtle shifts in the geochemistry of erupted glasses and sanidines could allow for interpretation on whether new units came from separate magmas, as well as the temperature of the magma. Sanidine was focused on as it is abundant in each ignimbrite and is capable of recording shifted chemistry, while matrix glass is exceedingly challenging to find in the Lava Creek Tuff. Sanidine and any glassy matrix found in thin sections was analyzed for major elements (Fe, Si, Al, Na, Ti, Cl, K, Ca, Mn, P, Ba) using the Cameca SX-100 Electron Microprobe at the Oregon State University. Operating conditions for sanidine included a 15 kV accelerating voltage, a beam current 30 nA, and a beam size of 10 μm . For glass, operating conditions were as follows: 15 kV

accelerating voltage, a beam current 10 nA, and a beam size of 5 μm . The EPMA allows for the chemical composition of discrete zones within individual minerals to be determined, as well as the melt composition of individual points rather than average, bulk composition analysis (as obtained by XRF). Previous studies (Swallow et al., 2018a, 2019; Shamloo and Till, 2019) have highlighted that barium is abundant in magmas from Yellowstone, and highly incorporated into the sanidine mineral structure. Therefore, barium is used here to determine if the ignimbrites of the SCD were erupted from multiple magma bodies, or just one. A summary of barium data can be found in Table 2 while glass and whole rock data can be found in Table 3. The full dataset can be found in the supplement.

Sanidine – Liquid Thermometry

Thermometry is a technique used to estimate the temperature at which a magma was stored before eruption. The common occurrence of alkali-feldspar in rhyolites has garnered them a lot of traction as a thermometer in silicic systems (e.g., Swallow et al., 2018a, 2019; Shamloo and Till, 2019). Feldspar-liquid thermometry was originally presented based off the anorthite to albite exchange series (Kudo and Weill, 1969). This approach was later applied to alkali-feldspars, using albite-liquid equilibrium to estimate a model crystallization temperature (Putirka, 2005, 2008). Using the major element data collected from the EMPA, temperature estimates were determined for sanidines from the new ignimbrites found on the SCD. Although mafic minerals are more commonly used for thermometry, they are largely absent in LCT material (Table 1). It could be that they were present in the ignimbrites at the time of emplacement but then broke-down during the welding and devitrification processes, making them sparsely preserved at present day. This has been seen by breakdown of mafic minerals in thin sections. Thus, the temperature estimates

reported here are based on feldspar – glass compositions applied to the alkali-feldspar thermometer of Putirka (2008).

Argon – Argon Dating

To confirm ages of the new units established by Wilson et al. (2018) and integrate the ages of uncertain ignimbrites found in SCD, six samples were sent to the USGS Menlo Park, CA, facility for $^{40}\text{Ar}/^{39}\text{Ar}$ dating. One sample from each individual unit was dated along with samples we were unable to identify in the field, to aid in creating an accurate, updated map of the SCD. In preparation for $^{40}\text{Ar}/^{39}\text{Ar}$ dating, each sample was crushed using the chipmunk crusher at Montana State University. The samples were then sieved into <0.5 mm, 0.5 – 1 mm and >1 mm size fractions. Between 40 and 50 sanidine crystals were picked from the 0.5 – 1 mm size fraction of each sample and sent to Menlo Park, CA for analysis. The sanidine crystals then underwent neutron irradiation. When irradiated, stable radiogenic ^{40}Ar is produced along with ^{39}Ar , ^{38}Ar , ^{37}Ar , and ^{36}Ar (Kelley, 2002) via bombardment by thermal and fast neutrons (Schaen et al., 2020). Because argon is a trace element, the radiogenic argon produced is often of higher quantity than naturally produced argon (Schaen et al., 2020). After irradiation, the samples and standards are put in a high-vacuum system. Gases are then extracted from the samples by total fusion of single crystal and analyzed by a noble-gas mass spectrometer (Schaen et al., 2020). The observed ratio of $^{36}\text{Ar}/^{40}\text{Ar}$ is then compared against $^{39}\text{Ar}/^{40}\text{Ar}$ to create an isochron plot (see supplement).

Results

Unit 1 Description

In outcrop form, Unit 1 presents itself as clasts of tan, pale brown and mid to dark grey colored tuff and as black glassy clasts in a lithic-rich breccia (Figure 5). As previously described, the poor sorting and large boulders of tuff present suggest this breccia is a lag deposit (Wilson et al., 2018).



Figure 5. (A) Photo of Unit 1 presented as clasts in a lag breccia (Wilson et al., 2018). (B) Hand sample of Unit 2 noting the mafic scoria (black arrows). (C) Hand sample of Unit 3 showing higher crystal content. (D) Outcrop scale photo of the contact (red line) between upper Unit 3 (darker color) and base of Unit 4 (lighter color).

In hand sample, Unit 1 contains about 32% crystals, which is, on average, roughly the same crystal content as LCT members A and B (Table 1). The mineral phases present, in decreasing

order of abundance, are quartz, sanidine, plagioclase, and oxides. Unit 1 crystals average 1 mm long, with quartz up to 2.5 mm. In thin section (Figure 6), the sanidine and plagioclase appear as angular to sub angular elongated grains with some fracturing. The quartz is rounded to subrounded and heavily fractured. The matrix of this unit shows flow texture and displays a glassy shard texture. Unit 1 in hand sample and in mineralogy is not easily distinguishable from LCT members A and B aside from that Unit 1, as found in a lag breccia deposit, has not been found outside of the Bog Creek stream bed.

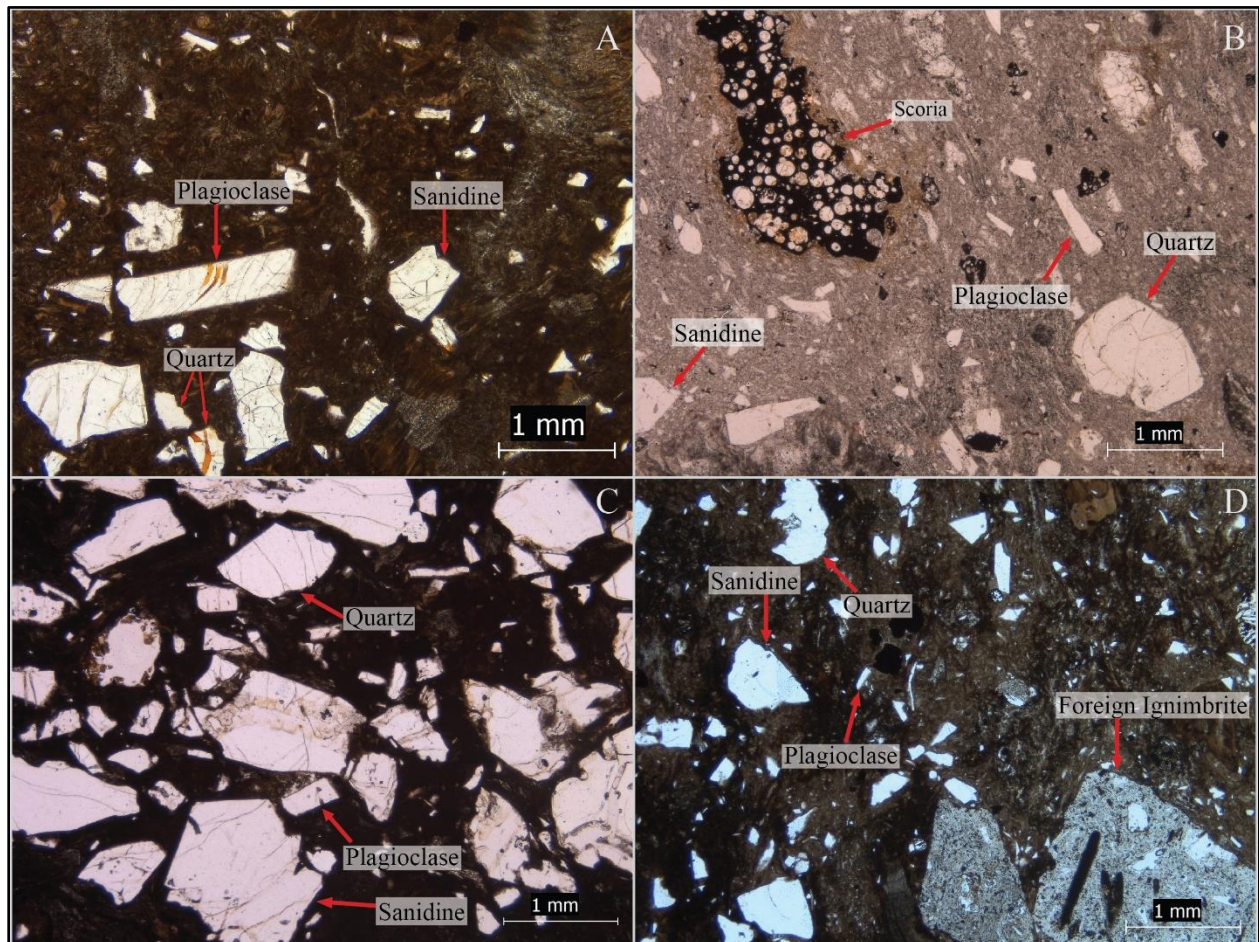


Figure 6. A) Thin section photo of Unit 1. B) A thin section of Unit 2, showing the vesicular scoria. C) Unit 3 represented in thin section. D) Unit 4 in thin section, showing foreign lithic fragments of ignimbrite incorporated into it.

Unit 2 Description

In outcrop, Unit 2 is a moderately welded ignimbrite, grey to tan in color. At the Bog Creek locality, Unit 2 has a sharp basal contact over the lag breccia that contains clasts of Unit 1 and forms cliffs ~20 meters high (Wilson et al., 2018). In other localities visited it does not form such obvious cliffs; however, it is overall a competent unit. Viewed from a distance, the outcrops are not easily distinguishable from LCT-A and -B in terms of color and general appearance (e.g., morphology and presentation). However, the identifying feature of Unit 2 is the presence of black, crenulated scoriaceous material seen throughout the unit (Figure 5). Unit 2 was found at elevations higher than 8,600 ft on the SCD, which is currently mapped within the Yellowstone Caldera. Just outside the currently mapped eastern scarp of the Yellowstone Caldera (Figure 1), Unit 2 was found no higher than 8,400 ft and at similar thicknesses to that of Unit 2 on the SCD.

In hand sample, Unit 2 is crystal-rich, containing ~27% crystals of predominantly quartz, and lesser amounts of sanidine, plagioclase, and oxides (Table 1). The average crystal size in Unit 2 is 1.5 mm though quartz and sanidine can be up to 3.5 mm. There is some variability in crystal content between samples with some being crystal-rich (~28%) and others being crystal poor (<3%). Non-weathered samples are more commonly grey to purple in color.

The presence of ubiquitous scoria and localized rounded andesite lithics are primarily what distinguish this unit from the known members of the LCT and the other ignimbrites in the Sour Creek dome area. These scoriae range from millimeters to centimeters in size and may be vesicular or crystal-rich (Figure 6). In some localities, such as the cliffs east of Bog Creek and along a portion of Bluff Creek (Figure 1), Unit 2 contains lithic clasts one to several centimeters in size

with a black matrix. These larger lithics are distinct from the scoria due to their sub-angular form and lack of a crenulated margin.

When viewed in thin section, Unit 2 sanidine and plagioclase crystals are angular to subangular and elongate with little fracturing. The quartz crystals are rounded to sub-rounded and display moderate fracturing. The appearance of the minerals in Unit 2 is similar to those in Unit 1, LCT-A and -B (Henderson et al., 2021). The matrix of Unit 2 is variable, but most often appears to be made of feldspar microlites and occasionally contains glassy shards (Figure 6).

Ignimbrite Unit	Quartz	Sanidine	Plagioclase	Mafic Mineral	Scoria Juvenile	Lithic	Crystallinity
Unit 1 (<i>n</i> =2)	20	10	2	0	0	0	32
Unit 2 (<i>n</i> =3)	20	6	1	0	2	2	27
Unit 3 (<i>n</i> =3)	18	7	9	0	0	1	34
Unit 4 (<i>n</i> =1)	12	6	6	1	1	5	25

Table 1. A summary table displaying modal abundances of minerals, listed in percentage, that define each ignimbrite unit in the SCD area. Point counts (200 – 300 points) were completed using thin sections. When possible, point counts were conducted on multiple thin sections (specified above), where a total of 9 thin sections were analyzed. Crystallinity excludes lithic and scoria content. All reported values are percentages.

Unit 3 Description

In the southern part of the SCD the Stonetop Flow is mapped as a small exposure of rhyolitic lava (Christiansen and Blank, 1975). However, when exposures in this area were visited, they were found to contain fiamme, suggesting this unit is an ignimbrite, not a lava flow. Further exploration of areas mapped as LCT-B in the southern part of the SCD revealed more exposures (*n* = 6) of the same ignimbrite. In its exposures this ignimbrite creates both platy outcroppings of

material emerging from the hillside and large (>60 m) cliffs. This ignimbrite appears less faulted and jointed than Unit 2, with a clear difference in its petrologic makeup. For instance, it contains 5-10% fiamme along with mafic juvenile clasts up to 32 cm long with most above 10 cm and lacks any black scoria. Mafic juvenile clasts have roughly 35% crystallinity with feldspars up to 1 cm and quartz up to 7 mm. In hand sample, this unit has a black to medium grey to tan appearance, with some samples having a light purple hue. The highly-welded portion of this unit appears black (when fresh) to dark grey when weathered. Where seen, the fiamme and the compaction of the matrix are evidence of intense welding in this unit.

The mineral phases in order of abundance are quartz, plagioclase, sanidine, pyroxene, and oxides, representing a similar assemblage to units 1 and 2 (Table 1). The mean crystal size is 2 mm with feldspar crystals up to 6 mm. There is also a small (<1%) component of foreign lithics. However, a notable difference is there is more plagioclase than sanidine present and the mean crystal abundance (~34%) tends to be slightly higher than the other ignimbrites visited in the SCD region (Table 1). In thin section (Figure 6), Unit 3 displays a strong eutaxitic texture in a matrix composed of glass and ash. The feldspar crystals have light to moderate fracturing while the quartz has moderate fracturing. Altogether, this ignimbrite is taken to represent a new and distinct ignimbrite in the SCD, which is herein refer to as Unit 3. The lack of scoria, and other characteristic differences, such as higher crystallinity and degree of welding, distinguish this unit from Unit 2. As Unit 3 is a new and distinct ignimbrite, its association to the LCT was not confirmed until a sample was dated (results below).

In the area where the Stonetop Mountain flow was originally mapped, large cliffs tan-pink in color, become apparent as does a shallow dip in the eutaxitic texture and a strong shift in welding

intensity is observed. At this location the angle of jointing in this new unit changes from shallowly dipping ($\sim 3^\circ$), to horizontal, to dipping ($\sim 3^\circ$) in the opposite direction and leading to a brecciated pipe structure. Where Unit 3 approaches the breccia pipe, Elongated “S”-shaped tension cracks are present in the area where the dip changes direction from roughly west-southwest to northeast. Unit 3, in this location, appears to be mildly rheomorphic, meaning it began to aggregate and flow, which is possibly why it was mapped as a lava. Thus, the area previously mapped as Stonetop flow appears to be the highly welded facies of the newly recognized Unit 3.

Approximately 1 kilometer from the pipe structure, there is a rapid change from intense to moderate welding, signifying a locally hotter emplacement near the brecciated pipe. Further observations at the top of the cliffs proximal to the breccia pipe revealed there is another, visually distinct, rock unit overlying the strongly welded Unit 3 material, which has been termed Unit 4 for now, and is described below.

Unit 4 Description

The rock termed Unit 4 is tan in color and has a similar crystal abundance (25%) to the other rock units found in the SCD. It is a bedded lithic-rich tuff with juvenile material distinct from the juvenile material in the below Unit 3. The juvenile material has lower crystal content ($\sim 5\%$) and smaller crystals (around 4 mm). Where observed, Unit 4 directly overlies Unit 3 and has a sharp, continuous contact. Further inspection revealed the base of Unit 4 is welded to the top of Unit 3, implying that Unit 3 was still hot when Unit 4 was emplaced. Unit 4 at the site visited was slope forming and vegetation covered; however, it was at least 4 m thick where seen. In thin section (Figure 6) Unit 4 contains quartz, plagioclase, sanidine, with trace amounts of mafics and oxides.

Unfortunately, Unit 4 was discovered at the end of the field season, meaning its extent is currently unknown.

Finding and mapping these ignimbrite units has culminated in an updated geologic map of the SCD created using the data gathered in the field (Figure 7). Field notes and GPS locations can be found in Appendix A. Though all field mapping took place on the western half of the SCD, remote mapping techniques were attempted on the eastern half of the dome.

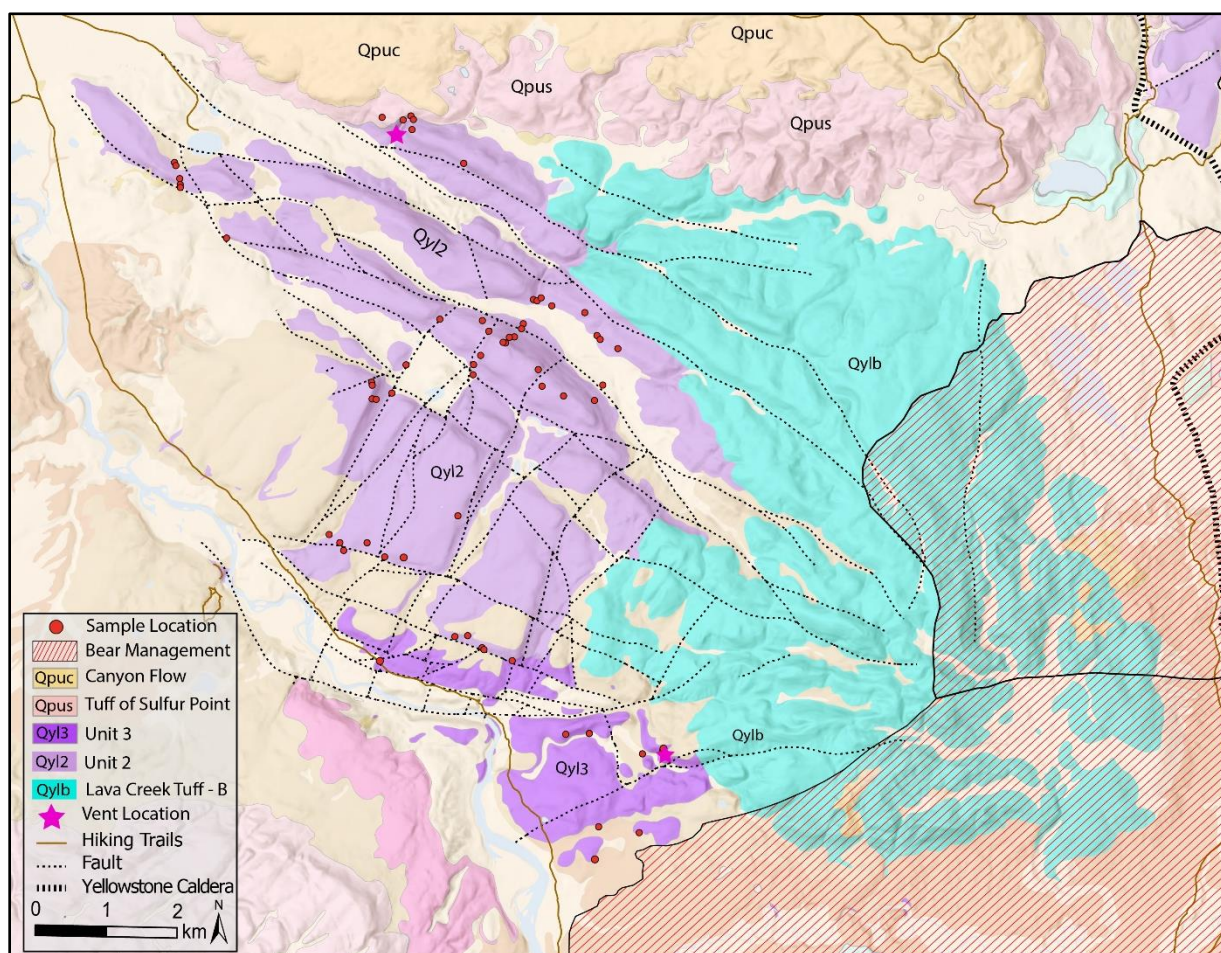


Figure 7. An updated map of the SCD adapted from the original Christiansen (2001) map. Ignimbrite units 2 and 3 have been added to the map. Units 1 and 4 are left off the map as Unit 1 is not mappable and Unit 4's extent is unknown. All locations visited while mapping are marked by a red circle.

Remote Mapping and Structural Analysis

The eastern side of the Sour Creek Dome was found to be difficult to access due to lack of trails or established campsites, and the eastern most region being marked as off-limits due to bear management (Figure 7). Therefore, remote mapping of east SCD was used to project the extent of the newly recognized ignimbrites to areas not visited. As a first order attempt to remotely map the aerially dominant units 2 and 3 of this region, which during field work were found to have differences in their welding intensity, a slope analysis was performed on their surfaces. An assessment of slopes in the SCD indicates the slope for Unit 2 ranges from $\sim 4 - 7^\circ$, while the slope of the more highly welded Unit 3 ranges from $1 - 6^\circ$. This overlap in slope between units 2 and 3 was thus, unhelpful. However, a projected geologic map of the SCD was created based on field observations (Figure 8).

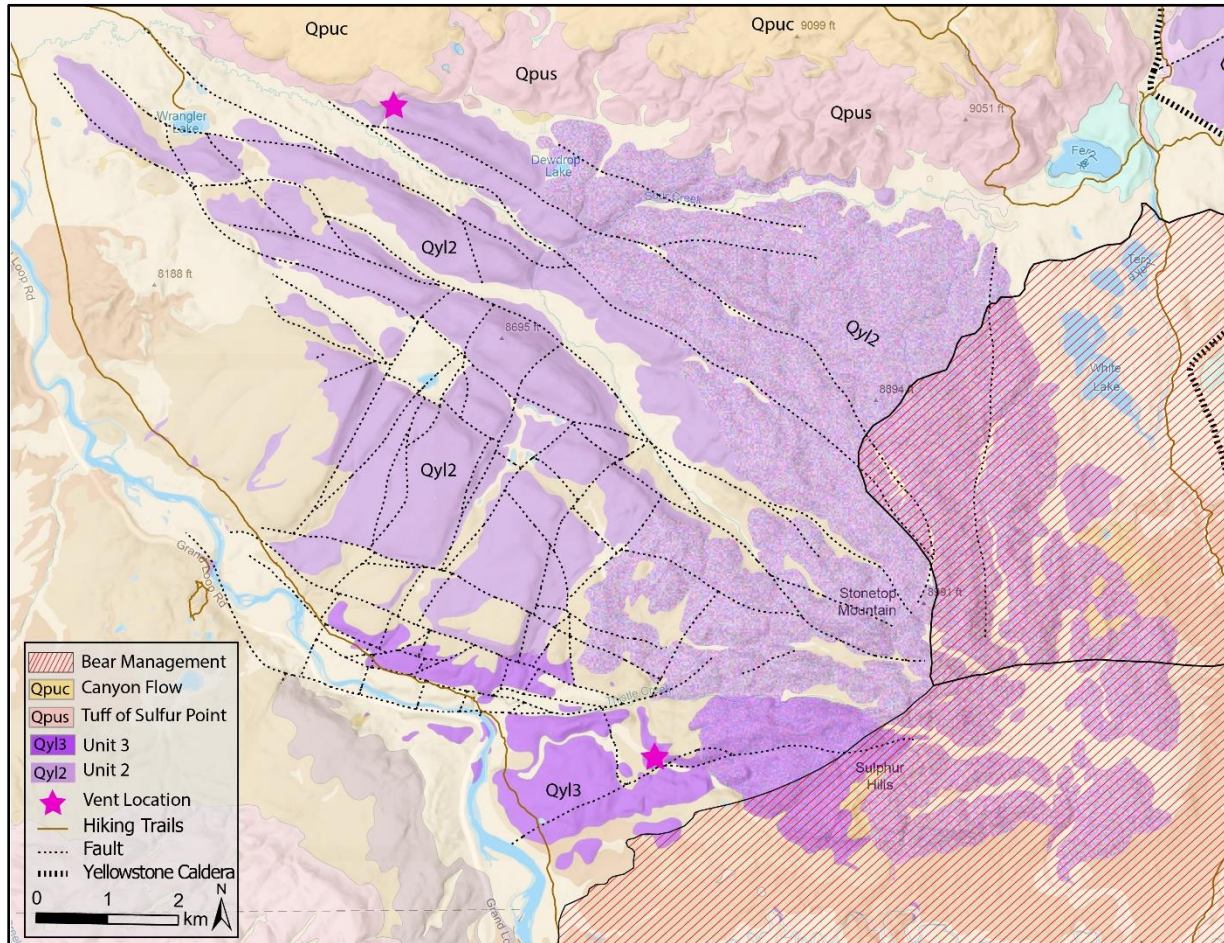


Figure 8. An updated map of the Sour Creek dome geology. The grainy / mottled look shows where the units have been projected using remote mapping methods. Note the NE corner of the map, outside the caldera boundary, was originally mapped as HRT-B but has been reclassified as Unit 2. All HRT and conventional LCT have been removed from the map as they were not found in the field.

In the SCD there are numerous NE-SW and NW-SE faults, interpreted to represent post-Lava Creek resurgence (Christiansen, 2001). However, it is observed that the younger, more southwesterly Elephant Back Mountain also contains the same NE-SW faults. Elephant Back Mountain was constructed via multiple lava flows, the youngest of which is the Elephant Back flow (150 ka; Obradovich, 1992). The lava flows making up Elephant Back Mountain are cut by what appear to be the same faults as observed on the SCD, which would suggest the faults can be

no older than 150 ka. The implication of this observation would suggest that the NE-SW trending faults along the SCD are not related to the structural resurgence of the SCD. Further, there is evidence that the NE-SW trending faults are not related to ongoing deformation of the SCD. This is inferred because the faults of the Elephant Back flow cross the modern Yellowstone River, and as mapped, continue under the sediment deposited by the river (Figure 4). LiDAR data of the region shows the sediments deposited by the Yellowstone River are undisturbed by the NE-SE faults, thus these faults are not presently active although active deformation is occurring in the region (Chang et al., 2010).

To confirm or refine some of these observations, these NW-SE faults were then analyzed to assess their relationship to structural resurgence. First the elevation of individual ridgetops within the dome that were bisected by the NW-SE faults were used to determine if any vertical or lateral displacement had occurred. Vertical displacement between ridgetops ranged between 0 – 140 ft and lateral displacement was not seen. A generalized contour map of the SCD was then created (Figure 9) to estimate the original shape of the SCD. The slope of the original shape was estimated to be around 6° starting from Stonetop Mountain and traveling NW along the long axis of the dome.

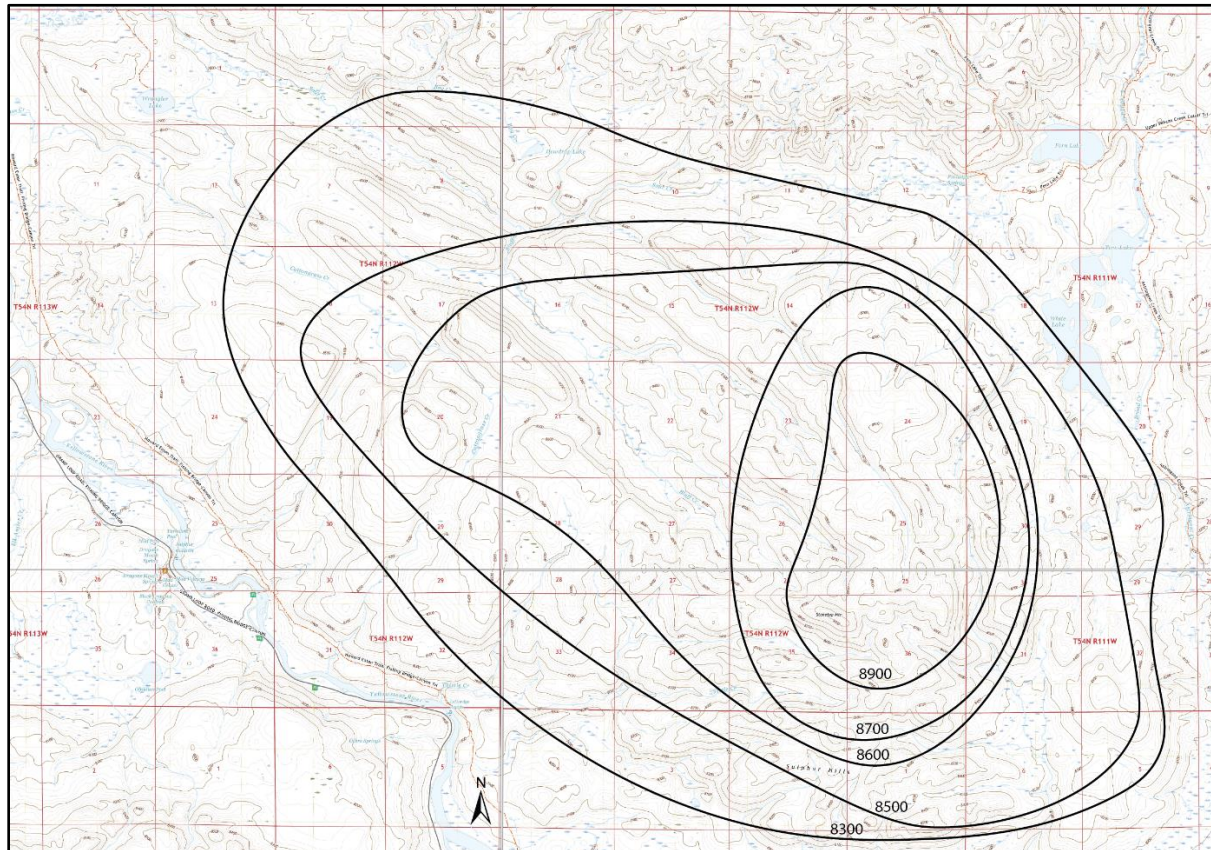


Figure 9. Topographic map of the Sour Creek dome with generalized contours drawn on to restore the original shape of the dome pre-erosion and without the NE-SW suite of faulting. Contour intervals vary.

Sanidine Composition

Sanidine analyses were used to compare the newly recognized units found in the SCD to the established LCT-A and -B members. Sanidine was used as it is the second most abundant mineral in most of the ignimbrites, common between all the ignimbrites and because sanidine shows chemical variations which can correlate to changing melt sources. Sanidine from Unit 1 ($n = 40$) yield orthoclase (Or) contents of Or₄₈₋₅₆ and barium (Ba) concentrations up to 17940 ppm, with most grains falling between 2000 – 3500 ppm (Full dataset in supplement; summary in Table 2). Unit 2 sanidines ($n = 82$) have a slightly larger range of Or₄₀₋₅₆ but demonstrate an overlapping Ba range with Unit 1, ranging from below detection limit (i.e., <200 ppm) up to 9400 ppm (Figure

10). The cores and rims of most sanidines analyzed have similar concentrations of Ba (full dataset in supplement).

The data obtained here are compared to sanidines from 'conventional' LCT-A and -B samples taken from multiple localities (Henderson et al., 2023). LCT-A sanidines ($n = 258$) range over Or₄₈₋₅₈ and have barium concentrations up to 15540 ppm, while LCT-B sanidines ($n = 132$) yield a narrower barium range, from <200 – 7910 ppm but overlapping Or values (Or₄₈₋₅₇). When units 1 and 2 are compared to LCT-A and -B, an overlap with LCT-A from the Virginia Cascade section becomes apparent (Figure 10).

Unit	Min Ba (ppm)	Max Ba (ppm)	Min Or (%)	Max Or (%)	Average (ppm)	1 S.D. (ppm)
Unit 1	BDL	17940	45	56	3596	4267
Unit 2	BDL	9370	49	56	2205	1889
Unit 3	BDL	7120	51	55	3449	2226
LCT-A	BDL	15540	45	59	2194	2834
LCT-B	200	7910	50	57	2699	2739

Table 2. Upper and lower values for barium (Ba; ppm) and orthoclase (Or; %) for ignimbrites 1 – 3 found in the SCD as well as for samples of LCT-A and -B, taken from Henderson et al. 2023. Barium detection limit (BDL) is 200 ppm.

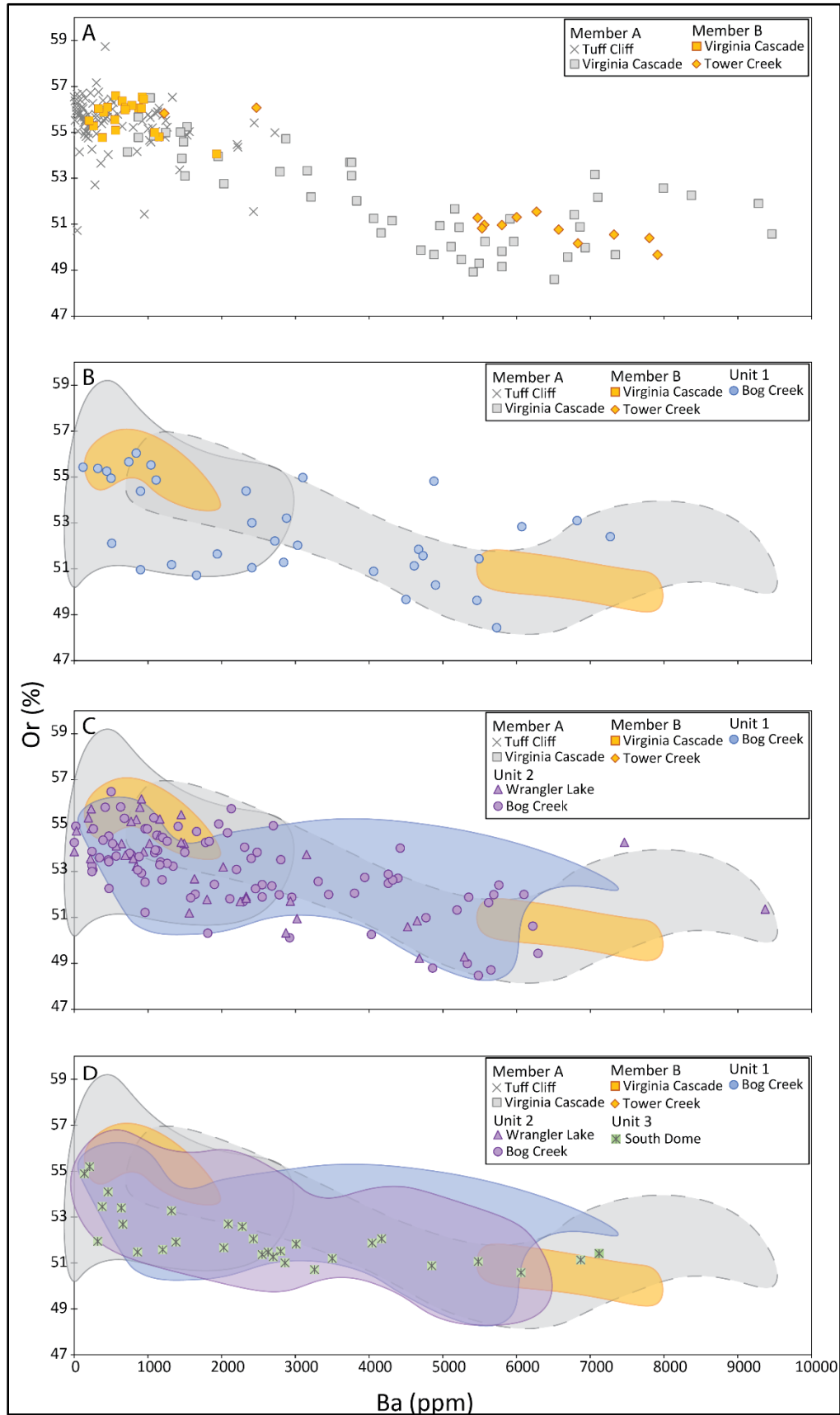


Figure 10 (facing page). Plots showing orthoclase (Or, mol %) plotted against the concentration of barium (Ba, ppm). (A) LCT-A from Tuff Cliff (grey X) and Virginia Cascade (grey squares); LCT-B from Virginia Cascade are shown in yellow squares while those from Tower Creek are yellow diamonds. Data from Henderson et al. (2021). (B) Unit 1 collected from the lag breccia at Bog Creek (blue filled circles). (C) Unit 2 sanidines collected from Bog Creek (purple filled circles) and Wrangler Lake (purple filled triangles). (D) Unit 3 sanidines collected from the southern part of the SCD. The color of the shaded in areas correspond to the same color symbol. The shaded areas represent the general population distribution.

Melt Composition

Matrix glass ($n = 27$) and/or whole rock ($n = 6$) compositions from units 1 and 2 were collected (Table 3, glass; Table 4 whole rock) to determine how they relate to LCT-A and -B and if there is an overlap in geochemistry. Unit 3 and 4 was not analyzed here. The level of post-depositional devitrification in these ignimbrites means that matrix glass cannot be measured for all samples. For all glass measurements, any totals below 95% were considered to represent a poor analysis, likely due to post-eruptive hydration and deterioration of the glass, and not used in thermometry analysis. The remaining glass measurements ($n = 14$) were normalized to 100% and used for thermometry calculations (see below). Whole rock data for Units 1 and 2, along with LCT-A and -B ($n = 8$), were also used for thermometry, primarily in cases where matrix glass could not be measured due to lack of glass or due to the previously mentioned poor totals

Glass Samples	Unit	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Cl	Total
<i>1 S.D. Error</i>		<i>0.49</i>	<i>0.005</i>	<i>0.01</i>	<i>0.04</i>	<i>0.03</i>	<i>0.004</i>	<i>0.01</i>	<i>0.05</i>	<i>0.09</i>	<i>0.26</i>	(ppm)	<i>0.61</i>
SCD20_0912_BC01	1	78.86	0.02	11.97	0.22	-0.01	0.01	0.35	3.88	4.58	0.01	1000	99.58
SCD20_0912_BC01	1	78.28	0.07	12.09	0.20	-0.01	0.00	0.29	3.54	5.42	0.01	900	100.78
SCD20_0912_BC01	1	77.67	0.07	12.56	0.40	0.04	0.00	0.39	4.12	4.59	0.01	1400	98.92
SCD20_0912_BC01	1	79.03	0.09	11.64	0.31	0.03	0.00	0.23	3.16	5.44	-0.02	600	99.44
SCD20_0912_BC01	1	79.53	0.03	11.13	0.47	0.03	0.01	0.18	2.69	5.84	0.01	900	98.41
SCD20_0912_BC01	1	77.74	0.06	12.38	0.23	-0.01	0.01	0.19	3.14	6.17	0.01	700	101.31
YELL20-0806BC001	1	77.85	0.24	11.79	0.66	0.00	0.00	0.26	3.01	6.04	0.01	700	95.34
YELL20-0806BC001	1	78.70	0.27	11.66	0.79	0.00	0.01	0.29	2.10	6.03	0.01	800	95.32
SCD210803-002A	Scoria	51.59	3.04	12.83	13.63	0.25	2.80	5.54	3.80	4.24	1.75	900	96.49
SCD210803-002A	Scoria	49.96	3.01	12.94	14.29	0.29	2.78	8.19	4.71	1.82	1.70	700	95.85

35

Table 3. Normalized concentrations of major elements in wt% oxide. All totals represent original values. Glass data was gathered using an EPMA (described above).

Whole Rock Samples	Unit	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Cl	Total
YELL20-0912-BC001	1	76.70	0.20	12.32	1.52	0.02	0.02	0.40	3.39	5.41	0.01	--	98.81
SCD210707-002A	2	75.76	0.21	13.40	1.37	0.01	0.06	0.39	3.30	5.48	0.01	--	98.34
SCD210803-001A	2	76.20	0.17	12.66	1.60	0.02	0.01	0.39	3.62	5.32	0.02	--	98.88
SCD210803-002A	2	75.57	0.21	12.89	1.85	0.02	0.06	0.52	3.59	5.25	0.05	--	98.63
SCD210804-002A	2	75.06	0.21	12.89	2.14	0.03	0.11	0.64	3.60	5.26	0.07	--	99.19
SCD210811-009A	2	76.08	0.22	12.98	1.82	0.03	0.09	0.50	3.14	5.12	0.02	--	97.62

Table 4. Normalized concentrations of major elements in wt% oxide. All totals represent original values. Whole rock data was gathered using x-ray fluorescence (described above).

Thermometry

Thermometry estimates were used to look at the storage temperature of the newly found ignimbrite units, 1, 2, and 3 to determine if they were stored at similar levels within the crust as established Members A and B. Due to the lack of mafic minerals (e.g., pyroxene, amphibole), Fe-Ti oxides and two-feldspar pairs, sanidine-melt pairs were relied on for thermometry estimation on each of the SCD ignimbrites recognized. However, due to the challenge of collecting matrix glass material (i.e., melt) to use with measured sanidine rims, the accuracy of applying whole rock chemistry as an alternative to glass chemistry was explored.

Applying whole rock chemistry as an alternative to glass chemistry was evaluated by exploring the technique applied to a more robust dataset from the older ignimbrite unit, the Huckleberry Ridge Tuff (HRT). Studies of the HRT initial fall deposit have yielded consistent temperatures while using differing techniques. For instance, zircon saturation temperatures yielded a temperature range of 746 – 833 °C with a mean of 801 °C (Myers et al., 2016) while two-feldspar thermometry revealed a range of 768 – 854 °C with a mean of 807 °C (Swallow et al., 2018a). Although we have a good understanding of the temperatures associated with the HRT, sanidine-melt thermometry was not applied. Swallow et al. (2018a) analyzed sanidine independently from the glass, making this data set ideal to explore the error introduced by using sanidine not in equilibrium with the glass, as well as using sanidine paired with whole rock.

The sanidine-melt thermometer was first tested to determine whether it produced temperature results for the HRT that agreed with previously published results, and then explored if the same results could be reproduced using whole rock rather than matrix glass compositions. The sanidine-melt thermometer of Putirka (2008; reported 1 S.D. of ± 23 °C) was applied to the

HRT through various melt, whole rock, and sanidine compositions previously collected (Swallow et al., 2018a). The sanidine rims and cores were paired with melt compositions from within the same unit, and across varying units, to determine how sensitive the thermometer was to both conditions. It was determined the difference in sanidine core and rim composition has a negligible effect on the thermometer (± 2 °C STD), with temperatures produced being within error of previously published estimates (Figure 11). It was also found that there was only a 15 °C variation by applying matrix glass compositions from different units than where the sanidine were taken. However, matching sanidine compositions with whole-rock compositions from different erupted ignimbrite members did influence the thermometer. For instance, matching sanidine and whole rock data from HRT Member A yielded an average temperature of 835 ± 23 °C (1 S.D.; $n = 305$), higher than the sanidine-glass values, while mixing sanidine from Member A and whole rock from Member B showed an average of 844 ± 23 °C (1 S.D.; $n = 305$). Overall, the alkali-feldspar-liquid thermometer most closely recreated previous temperature estimates using co-erupted glass composition. The application of whole rock data, as glass, yielded temperatures ~ 30 °C higher. Though pairing sanidine with whole rock and glass from different units is not ideal, it allowed us to assess the error of applying this technique to the LCT.

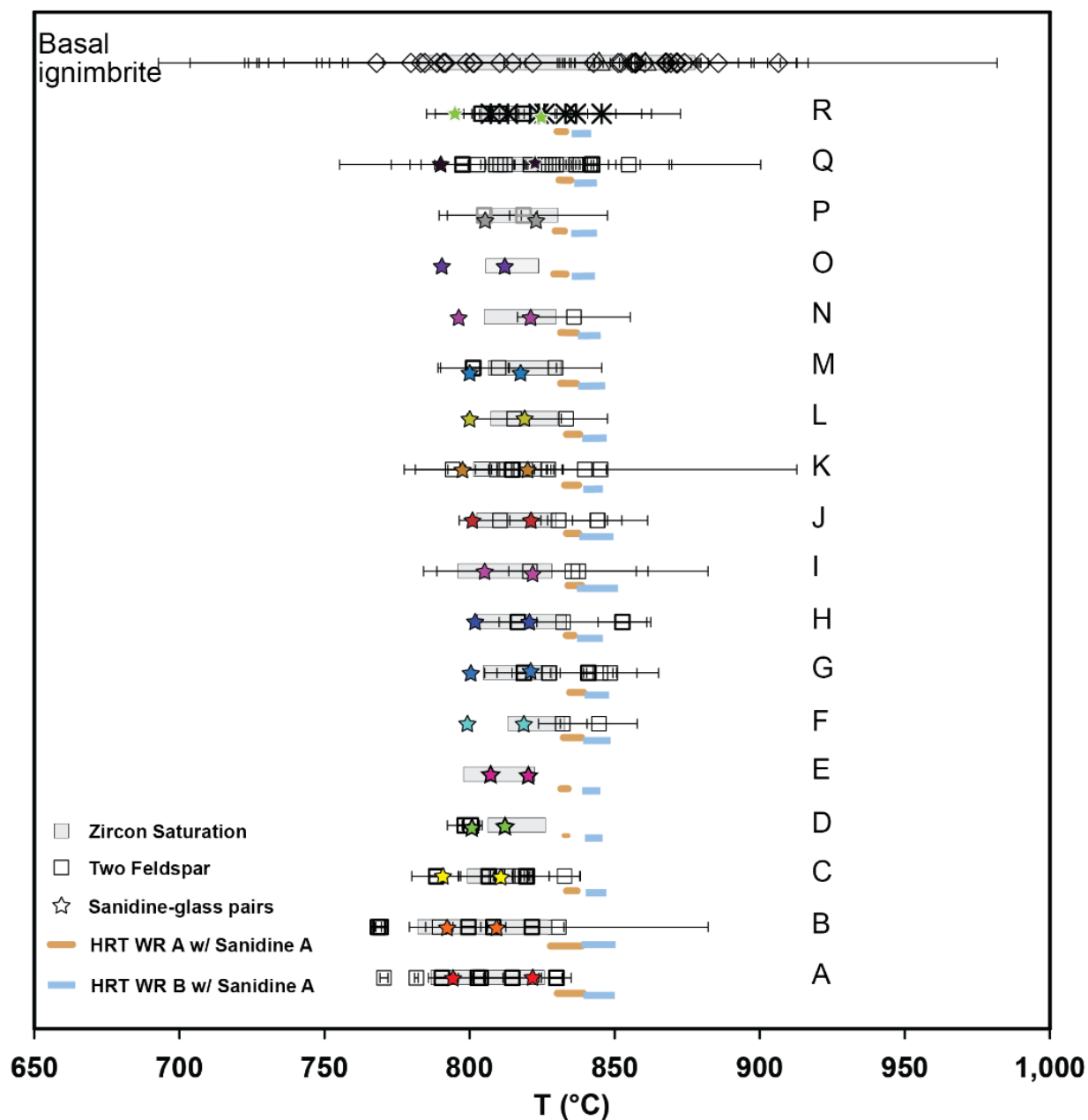


Figure 11. Two feldspar thermometry temperature estimates of the HRT initial fall deposit (box and whisker) compared to whole-rock/glass and Sanidine pair thermometry. Figure adapted from Swallow et al. (2018a).

Based on the previous testing on the sanidine-melt thermometer, where possible I paired sanidine compositions with glass analyses from within the same unit (Putirka, 2008). These calculations assumed a pressure of 150 MPa, which is in agreement with the pressure restored

from volatile contents in sealed melt inclusions and modelling using rhyolite-MELTS (Gansecki, 1998; Shamloo and Till, 2019). Furthermore, arbitrarily changing the pressure by 100 MPa has negligible effect (<1 °C) on the thermometer. Sanidine-melt pairs from Units 1, 2, and 3 yield mean temperatures of 764 ± 13 °C (1 S.D.; $n = 45$), 780 ± 5 °C (1 S.D.; $n = 82$), and 753 ± 2 °C (1 S.D.; $n = 29$), respectively. LCT members A and B yield average temperatures of 767 ± 9 °C (1 S.D.; $n = 98$) and 788 ± 6 °C (1 S.D.; $n = 36$), respectively (Figure 12). The variations reported are the range of values in each suite of samples, whereas the 1 S.D. error on this thermometer is ± 23 °C (Putirka 2008), meaning that all temperature estimates including variability within and between units are within error of each other.

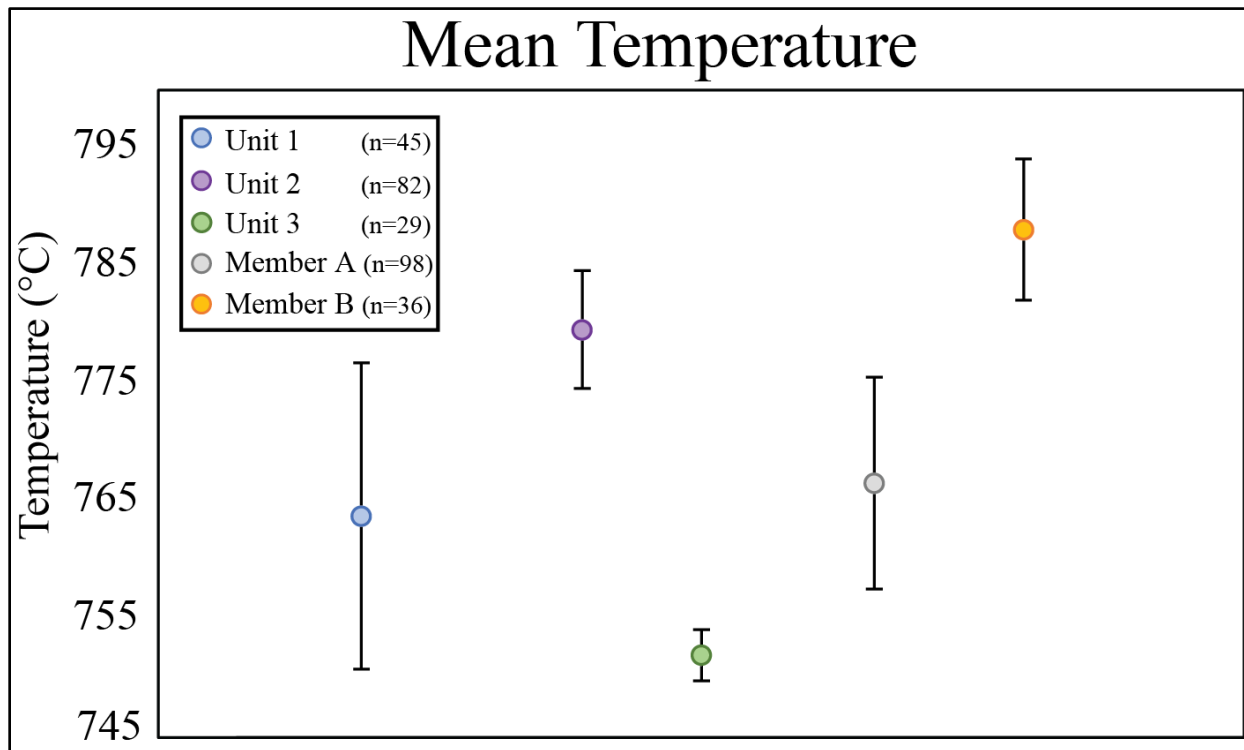


Figure 12. Model sanidine-melt temperatures of units 1, 2 and 3 from the Sour Creek dome area compared to established LCT-A and -B. Error bars are uncertainty of analysis, not including the calibration error of ± 23 °C.

The temperatures calculated in this study fall within error of temperatures reported by others for the LCT established members (Matthews et al., 2015; Shamloo and Till, 2019). For instance, previous Ti-in-zircon thermometry applied to the LCT has estimated temperatures of 743 ± 26 °C and 784 ± 34 °C for the lower and upper LCT-A while the basal and upper LCT-B are estimated to be 819 ± 39 °C and 741 ± 12 °C, respectively (Matthews et al., 2015). Further alkali-feldspar-liquid thermometry (Putirka, 2008) on LCT-B yields an average rim temperature of 814 ± 23 °C (Shamloo and Till, 2019). Variations in the temperatures presented above are most likely due to the difference in thermometer applied.

Argon – Argon Dating

The $^{40}\text{Ar}/^{39}\text{Ar}$ method of dating was used on six samples of ignimbrites collected from locations throughout the Sour Creek dome (Figure 13). This study dated one sample from the breccia (Unit 1), two from the scoria-bearing unit (Unit 2), and three from the intensely welded Unit 3 ignimbrite (Figure 13). Assuming that any trapped, non-radiogenic gas is atmospheric, YELL20-0912-BC01 (Unit 1) returned a weighted mean age of 629.6 ± 1.2 ka (2 of 25 rejected; MSWD 1.52; Figure 14). SCD220706-26A (Unit 2) yielded a weighted mean age of 630.7 ± 1.1 ka (2 of 9 rejected; MSWD = 1.95). SCD220706-022A (Unit 2) yielded a weighted mean age of 631.4 ± 0.9 ka (0 of 9 rejected; MSWD = 1.95). SCD220623-005A (Unit 3) yielded a weighted mean age of 633.2 ± 1.2 ka (4 of 9 rejected; MSWD = 1.21); the oldest four ages were rejected to achieve a MSWD consistent with a single population.

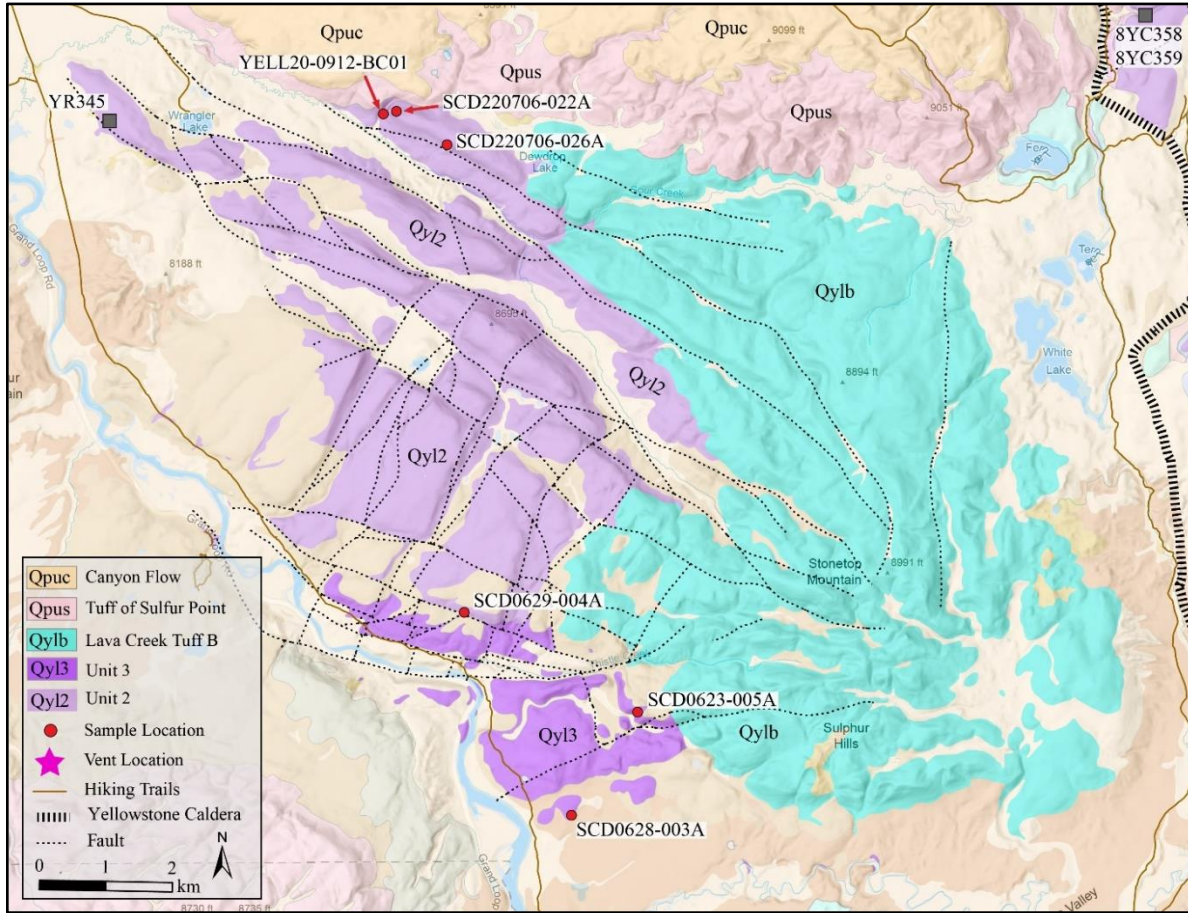


Figure 13. A map of the Sour Creek Dome area, modified from Christiansen (2001), showing the locations of samples used for $^{40}\text{Ar} - ^{39}\text{Ar}$ dating in this study as red circles. The grey squares represent dates from Wilson et al. (2018). All dates are indistinguishable to the LCT.

SCD220629-004A (Unit 3) yielded a weighted mean age of 632.7 ± 1.5 ka (5 of 9 rejected; MSWD = 0.61). SCD220628-003A (Unit 3) yielded a weighted mean age of 632.1 ± 1.2 ka (2 of 9 rejected; MSWD = 1.51). This shows each previously non-mapped ignimbrite in the southern part of the SCD is statistically within uncertainty the same age as the LCT eruption. A comparison of dates from this study and other studies shows both zircon and sanidine ages from the LCT (Figure 14). The full summary document of dated samples can be found in Appendix B.

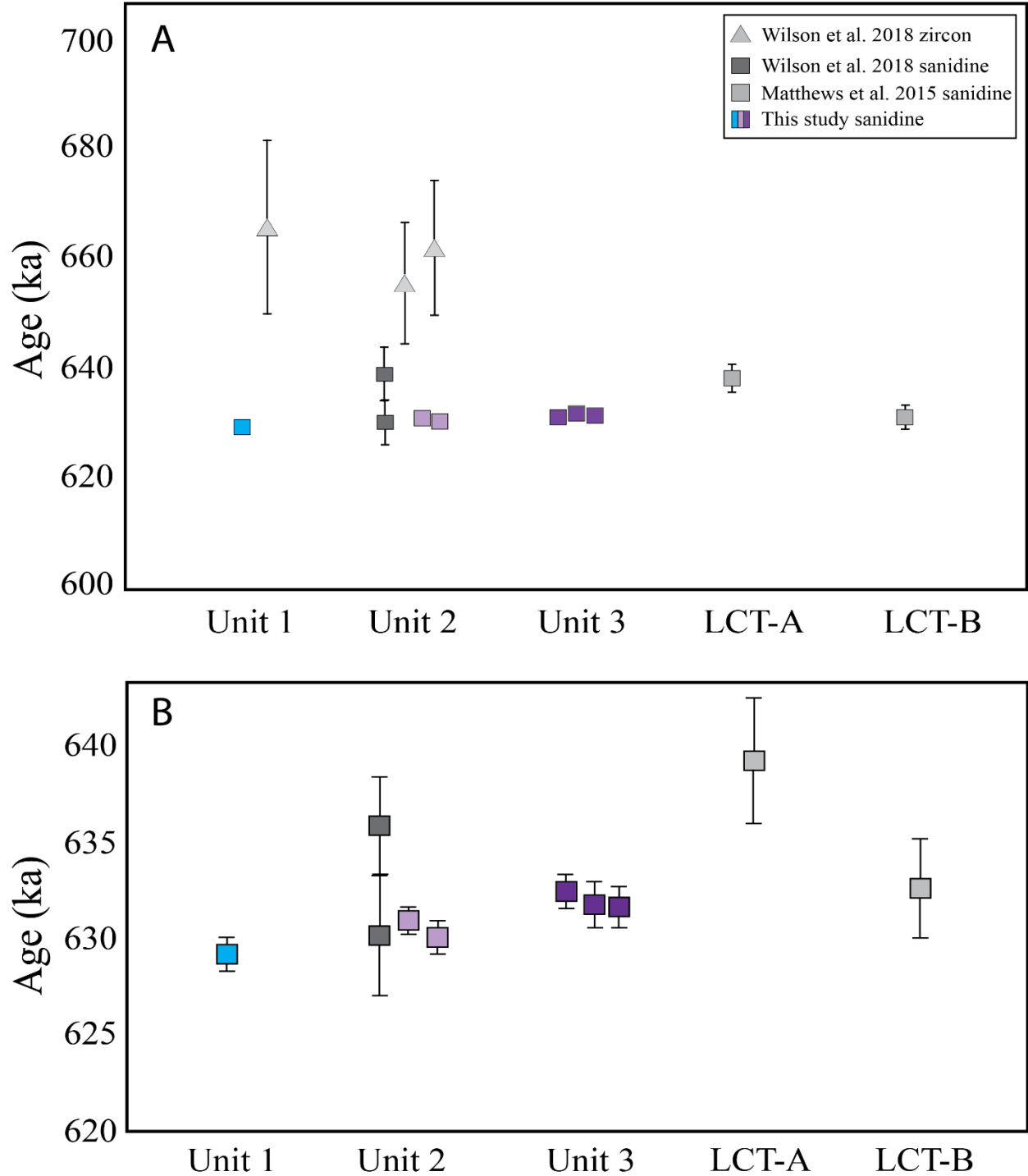


Figure 14. The weighted mean age of each ignimbrite dated from the SCD compared to previously published ages of LCT-A and -B. A) Includes U-Pb dates on zircon from Wilson et al. (2018). B) Excludes U-Pb from Wilson et al. (2018) and zoomed in to see the errors on ages from this study. Error bars are error on analysis.

CHAPTER THREE

DISCUSSION AND CONCLUSIONS

DiscussionDistribution of New Units

Early field mapping confirmed the presence of the two newly recognized ignimbrite units first identified by Wilson et al. (2018) in Bog Creek and at Wrangler Lake. Subsequent mapping found that the previously defined Unit 1-bearing lag breccia is not present outside of Bog Creek. However, the possibility that Unit 1 could be found in other areas of the Sour Creek dome cannot be discounted. Therefore, the Unit 1 ignimbrite is not a mappable unit in the SCD, and thus the distribution and volume of this ignimbrite is not able to be constrained. It is possible that a location in the summit area of Stonetop Mountain visited by Christiansen (2001), but not visited in this study, could be the same Unit 1 ignimbrite. This unit is described as a >150-meter-thick sequence of ignimbrite with abundant welded-tuff inclusions. The inclusions are up to several meters long and are visually similar to the LCT (Christiansen, 2001), much like those observed in Bog Creek. Visiting this location would be an important next step for understanding the full eruption dynamics of these units but is outside of the scope of this particular study.

Though Unit 1 is petrographically indistinguishable from LCT-A and -B, its positioning as a breccia underlying Unit 2 in the Sour Creek Dome represents a unique feature in the LCT eruption. This relationship represents a clear time break between Units 1 and 2 that is not matched by any stratigraphic discontinuity yet found in LCT-A and -B. It was previously inferred that there must have been an eruption that produced Unit 1, followed by complete cooling of Unit 1, and

then a second eruption that produced Unit 2 beginning with the lithic breccia incorporating cooled, angular blocks of Unit 1.

In contrast, based on areas visited (Figure 7), Unit 2 has been found throughout the Sour Creek Dome. Based on descriptions of LCT-A and -B (Christiansen, 2001; Henderson et al., 2021, 2023) and HRT Member B (Christiansen, 2001), it was determined that no visited location on the SCD had outcrop of the 'conventional' HRT-B, LCT-A or -B, as mapped originally by Christianson (2001, Figure 1). Neither LCT-A nor LCT-B is known to have scoriaceous, juvenile material; yet numerous locations mapped as LCT-A and -B presented exposures containing scoriaceous, juvenile material. HRT-B is known to have scoria in outcrop, however, dating samples from multiple locations (see Argon – Argon Dating above) has returned LCT ages rather than HRT ages.

The overlying Unit 2, scoria-bearing ignimbrite, is extensive throughout the Sour Creek dome. Unit 2 is easily distinguishable from LCT-A and -B due to the dominant juvenile scoria and the localized andesite lithics it contains, which are not seen in any other mapped LCT lithology. The scoria-bearing Unit 2 was found at every locality visited where the rocks were originally mapped as HRT-B, or LCT-A and -B in the western and central areas of the SCD. This makes Unit 2 the dominant ignimbrite throughout the SCD. Unit 2's distribution, however, is not constrained solely to the SCD. Earlier samples collected (Christiansen, 2001) and dated (Wilson et al., 2018) outside the SCD to the northeast, near Fern Lake (Figure 1), demonstrate that the scoriaceous Unit 2 ignimbrite is found outside of the currently mapped Yellowstone Caldera boundary. Unit 2 in this location, near Fern Lake, is roughly the same thickness as Unit 2 in the SCD (Christiansen, 2001; Wilson et al., 2018). It is important to note that the similar thicknesses of Unit 2 in these

two locations, on opposite sides of the mapped caldera boundary, is at odds with the currently mapped caldera boundary and its concept as a location of major displacement.

Through further mapping in the southern part of the SCD, the intensely welded Unit 3 was recognized and described. Based on the distribution seen in this study, Unit 3 is a spatially smaller, localized ignimbrite unit confined to the southern end of the SCD. However, Unit 3 is likely to continue northeast to parts of the SCD not visited, as cliffs made of Unit 3 were seen continuing in that direction. An unknown and unidentified ignimbrite was also found stratigraphically above Unit 2 at Bog Creek. This unidentified ignimbrite could be Unit 3 as it most closely resembles Unit 3, however, it lacks the characteristic large minerals. Further testing will be required to sort out this unit's placement in the updated LCT stratigraphy. Unit 4 is potentially a mappable ignimbrite but was unable to be mapped here due to its discovery at the end of the field season. However, the observation that Unit 4 is back welded to Unit 3 is important because it shows that even though these were separate outbursts of material, with contrasting characteristics between them, they were temporally erupted close together. This spatial and temporal link between the ignimbrites suggests a relationship between them which needs further investigation.

Stratigraphy

The stratigraphic relationships between LCT-A, -B and the four indistinguishably aged ignimbrites in the Sour Creek dome are difficult to determine. As no conventional LCT-A or -B has been found in the Sour Creek dome area, there is no clear stratigraphic ordering of eruptive events. Originally, it was thought that units 1 and 2 were erupted prior to LCT-A, meaning they underlie it (Wilson et al., 2018). This stratigraphy was suggested by Wilson et al. (2018) because the area originally mapped as HRT-B, and now recognized as Unit 2, was stratigraphically below

the then-mapped LCT-A and -B (Christiansen, 2001). However, it is now shown here that there is no LCT-A or -B on the Sour Creek dome, meaning the stratigraphic relationships between the Sour Creek dome ignimbrites and the extra-caldera LCT members A and B cannot yet be constrained through classic field mapping techniques. This issue also persists, though not as severely, within the ignimbrites of the Sour Creek dome as although there is clear stratigraphy between Units 1 and 2 as well as between Units 3 and 4, however there was no contact observed between units 2 and 3. Therefore less traditional approaches for determining sequence must be applied. One potential approach to use the geomorphic relationships of these units to help discern the stratigraphic relationships.

Field work and mapping show that Unit 2 sits atop the breccia containing Unit 1, making their relationship clear. As seen in this study, Unit 2 is widespread and underlies most of the SCD, including the highest elevation areas visited (central dome; 8695 ft). This suggests that Unit 2 was voluminous enough to cover paleo topographic highs or that Unit 2 created the high points itself. In contrast, Unit 3, where seen in this study, is largely lapping up against the topographic high that is Unit 2, suggesting, although not conclusively, that it erupted later. It has been proposed that after the LCT eruption a structural event took place, currently thought to be post-eruptive resurgence (Christianson 2001), creating the faults through the SCD. However, as mapped, the NE-SW trending faults on the SCD appear to be related to those in the younger Elephant Back Flow, on Elephant Back Mountain. The fault planes for the series of NE-SW faults on Elephant Back Mountain are inferred to continue through the rock overlain by the modern Yellowstone River and its post-glacial sediments and onto the SCD. The Elephant Back flow, on Elephant Back Mountain has an age of ~150 ka implying that the NE-SW trending faults must be younger. Both suites of

faulting (NE-SW and NW-SE) crosscut Unit 2, which has a general slope away from Stonetop Mountain. In contrast, Unit 3 has little faulting and at the contact between units 3 and 4 (Figure 5), the top of Unit 3 is horizontal. Unit 4 was observed conformably overlying Unit 3, meaning that relationship is known. At the Bog Creek locality, there is a previously mentioned, unidentified ignimbrite towards the top of the section. If this unidentified ignimbrite is Unit 3, this would be strong evidence that Unit 3 erupted after Unit 2 and emplaced around it. Further evidence is supplied by faulting and the depositional angle of units 2 and 3. This creates the stratigraphic order, oldest to youngest, of Units 1, 2, 3, and 4.

In relation to the overall LCT eruption, it is inferred here, the ignimbrites found in the SCD are thought to have been erupted and emplaced during an intermediate or later stage of the overall eruption, with a still evolving understanding on how these events relate to caldera development. This is based largely on the inference from sanidine compositions that Unit 1 from the SCD is the same ignimbrite as LCT-A from Virginia Cascade. Before the emplacement of Unit 2, there had already been the emplacement and complete cooling of Unit 1 which potentially was a lobe of material associated with the basal part of the LCT-A member at Virginia Cascades.

Source Area(s)

It was originally proposed that a/the source vent for the eruption of LCT-B was the eastern boundary of the Yellowstone Caldera (Christiansen, 2001). However, LCT-B has not been encountered on the SCD. It could be that the LCT-B ignimbrite was covered by units 2 and 3, but if that was the case, one would expect to see LCT-B material in the lag breccia that contains Unit 1. Christiansen (2001) did, however, note that the Stonetop Mountain area (not visited in this study) is home to an ignimbrite greater than 150 m thick and containing angular welded-tuff clasts

several meters long that appear similar to the established members of the LCT. The large, angular, welded tuff clasts suggest another lag breccia, meaning another vent area on the SCD. As Stonetop Mountain is the highest point on the SCD, and Unit 2 slopes away from it, there is a strong possibility that Unit 2 was erupted from the Stonetop Mountain area and built an accumulation cone, which became Stonetop Mountain.

The source areas for ignimbrite units 2 and 3 are inferred based on field observations. As previously suggested (Wilson et al., 2018), a/the Unit 2 source region may be in the northwest region of the SCD. This is due to the presence of the lithic-breccia in which Unit 1 is contained, which was interpreted to be a proximal lag breccia deposit (Wilson et al., 2018). Lag deposits are proximal deposits associated with caldera collapse and are generally found within 3 – 5 km of the vent (Wright and Walker, 1977; Druitt and Sparks, 1982; Walker, 1985; Freundt et al. 2000). Further, Wilson et al. (2018) proposed that this vent would be inboard of the current boundary, because of the presence of Unit 2 within the Sour Creek dome as well as off the dome to the NE, outside of the currently mapped caldera boundary (Figure 1). Additional evidence that a/the vent is somewhere near the SCD comes from the lithic blocks found in multiple locations in the SCD, including Bog Creek and Bluff Creek (Figure 1).

The source region of Unit 3 is thought to be in the southern part of the SCD where the Stonetop Mountain Flow was previously mapped. The rapid change in welding intensity, rheomorphic flow and eutaxitic textures, change in dip direction, and vertical breccia pipe are inferred to represent proximity to a vent. The vent structure associated with Unit 3 is found in a low-elevation area, relative to the interior of the SCD where Unit 2 is found. This again suggests that Unit 3 was erupted after, and lapped up against, the paleographic high area formed by the

earlier Unit 2 ignimbrite. The several-meter angular tuff clasts seen by Christiansen (2001) near Stonetop Mountain could indicate the presence of a source area (vent) or caldera collapse also in this region, a hypothesis that merits further investigation.

Implications for the LCT Eruption

Sanidine compositions from the Sour Creek Dome ignimbrites reveal overlap in some units and distinct clustering in others. Units 1, 2 and 3 show a strong overlap in Ba vs Or space despite the presence of juvenile scoria in Unit 2. The lack of significant breakdown rims on the few mafic minerals (pyroxene and amphibole) observed in thin sections (<1%), as well as limited reaction rims present in the scoria are evidence that the scoria was a late input to the magma system and primarily physically mixed. It is thought (Sparks and Marshall, 1986) that before significant chemical mixing can take place the magmas have to reach a thermal equilibrium. In addition, the lack of bright rims on the main mineral components (sanidine and quartz) suggest an absence of chemical mixing. Together, this suggests the scoria did not chemically mix with the rhyolite (Sparks and Marshall, 1986; Morgavi et al., 2017). Units 1, 2 and 3 also show a chemical overlap with LCT-A collected from Virginia Cascade, but not LCT-A or LCT-B from other locations (Henderson et al. 2023). Due to the proximity of Virginia Cascade to the Sour Creek Dome, it is inferred here that the overlap in chemistry between the SCD ignimbrites and LCT-A, from Virginia Cascade, is evidence they were all tapped from the same magma body or magma bodies with similar storage conditions. The indistinguishable mineralogy and Ba geochemistry between Unit 1 and LCT-A and -B, as well as the proximity of Unit 1 to Virginia Cascades, also suggests the possibility that the LCT-A analyzed from Virginia Cascades is the same ignimbrite as Unit 1.

The presence of four previously undocumented and uncharacterized ignimbrite units, all with radiometric ages indistinguishable from the accepted Lava Creek age, in the Sour Creek dome area further demonstrates that the LCT eruption was more complex than originally presented (Christiansen, 2001). As mentioned previously, the existence of a brecciated deposit containing clasts of welded ignimbrite (Unit 1) shows there were time breaks of decades during the eruption and emplacement of the LCT (Wilson et al., 2018). Further complexities are seen when considering the proposed stratigraphy. Unit 2 contains a juvenile, mafic component, which has not been seen in subsequent ignimbrite units from the SCD. In addition to Unit 3 being a locally hotter eruption due to its higher degree of welding, Unit 3 has larger crystals than other ignimbrites associated with the LCT. The juvenile scoria in Unit 2 and the characteristically large crystals in Unit 3 suggests these two ignimbrites were fed by separate magma bodies that contain similar sanidine compositions. These newly recognized ignimbrites are also evidence that the LCT did not erupt in just two phases producing two large ignimbrite sheets. More likely, there were multiple, distinct lobes which erupted separately, throughout the caldera-forming event (cf. Bishop Tuff; Wilson and Hildreth, 1997, 2003). The Bishop Tuff is the end-member type for a single compositionally stratified magma body (Hildreth and Wilson, 2007; Chamberlain et al., 2015) which started as a single vent eruption and then changed to a multi-vent eruption, feeding multiple, sectorially distributed lobes of ignimbrite (Hildreth and Mahood, 1986). Analysis of Ba in sanidine (Henderson et al., 2023) has shown the LCT eruption was likely fed by multiple magma bodies; while field work in this study has shown there are, at minimum, two vent sites for the newly recognized ignimbrites that are LCT in age.

The LCT was originally inferred to have been erupted from a single compositionally stratified magma body (Christiansen, 2001). For decades other researchers have accepted how the LCT is mapped and inferred as fact when sampling (e.g., Shamloo and Till, 2019). Evidence from this study changes how the LCT should be viewed. The LCT is more akin to having multiple melt-dominant magma bodies with pre- to syn-eruptive mixing of more mafic magma (Wilson et al. 2021). These discoveries were all made in the, relatively, small area of the SCD. With further investigation of the LCT there are likely to be more shifts in how we view the makeup of Yellowstone's youngest supereruptions.

Implication for Yellowstone Caldera

Caldera-forming eruptions are often thought to be fed via vents forming along ring fractures, though venting may also occur at a more central location (Smith and Bailey, 1968; Hildreth and Mahood, 1986; Self et al., 1986; Wilson et al., 2021). Caldera collapse then occurs along these ring fractures either during, or after the underlying magma chamber(s) have emptied (Smith and Bailey, 1968; Cole et al., 2005; Wilson et al., 2021). If a vent was present within the ring fractures, it is likely the vent would be destroyed upon formation of the caldera or buried by caldera volcanic infill and sedimentation (Smith and Bailey, 1968). The current Yellowstone Caldera boundary is roughly 8 km east of the center of the Sour Creek dome. The presence of a probable vent structure as well as a lag breccia that implies a vent source within 5 km (Wright and Walker, 1977; Druitt and Sparks, 1982; Walker, 1985; Freundt et al., 2000; Wilson et al., 2018) suggest that the east boundary of the Yellowstone Caldera is likely mis-mapped and that its location needs to be reevaluated. On the basis of the evidence in this thesis, the east margin of the caldera boundary should lie inboard of the SCD. The presence of Unit 2 on both sides of the

currently mapped caldera boundary further supports this suggestion (Figure 1; Wilson et al., 2018). The similar elevations and thicknesses of Unit 2 in these locations counts against a caldera boundary separating these locations.

Conclusions

Few large-scale caldera-forming eruptions have been observed in modern human history. This infrequent eruptive cycle makes understanding their eruption dynamics challenging. However, detailed field work, paired with geochemical characterization, can reveal the nuances of these massive eruptions. Out of Yellowstone Volcano's three major, caldera-forming eruptions only one, the Huckleberry Ridge Tuff, has been studied in detail (e.g., Myers et al. 2016; Swallow et al. 2018a, b, 2019). In comparison, little is known about the Lava Creek Tuff and its eruption. For example, in this study up to four ignimbrites of LCT age were discovered in the Sour Creek dome area, with two of the ignimbrites being extensive. Along with these four ignimbrites, the likely source regions for at least two of the ignimbrites were discovered in the Sour Creek dome area, holding implications for where the Yellowstone Caldera is mapped. Geochemical analyses on sanidine revealed that the Sour Creek dome ignimbrites are all related. However, the ignimbrites in the SCD cannot have been sourced from the same magma body due to appearance of juvenile scoria in Unit 2 and the larger crystals in Unit 3. EPMA analyses also revealed that the sanidine from LCT-A at Virginia Cascades is compositionally similar to Unit 1 of the Sour Creek dome ignimbrites, suggesting these units may have erupted after the established members of the LCT eruption.

These newly recognized ignimbrites change the eruptive history of the LCT, providing evidence the eruption was spasmodic, and hold implications for how the Yellowstone Caldera is

mapped. The lag breccia identified by Wilson et al. (2018) shows there was a time break of decades during the eruption, meaning the eruptive period lasted longer than previously assumed. The presence of four unique ignimbrites in the SCD alone, show that the Lava Creek eruption had multiple eruptive events, making it discontinuous, and suggests that multiple magma bodies were tapped during the eruption. Finally, the presence of vent structures on the SCD as well as Unit 2 appearing at similar elevations and thicknesses across the caldera boundary suggests that the boundary of Yellowstone Caldera needs to be reevaluated. However, this study was unable to completely remap the SCD. Further research in the SCD region is required to determine the full extent of the new ignimbrites and gain a better understanding of the eruption which produced the LCT.

Based on the insights and conclusions of this study, there are multiple directions for future work in the Sour Creek dome area. Foremost, the eastern portion of the Sour Creek dome needs to be mapped in full and the ignimbrite units projected to the east part of the dome need to be ground-truthed. The main areas of focus for future field work should be Stonetop Mountain and its immediate surroundings, the northeast portion of the SCD directly southwest of Fern Lake and east of White Lake as well as the area east of Sulphur Hills that lies within the bear management. Determining which ignimbrites are in the above locations could further change how we understand the dynamics of the LCT eruption and provide more evidence regarding how the caldera boundary is mapped. Further research should consider the nature of the SCD itself and how it was formed. Evidence presented here suggests the resurgence of the SCD is not associated with the LCT eruption, rather, the faulting is a more modern process, likely younger than 150,000 years. It is hypothesized here that Unit 3 was erupted after and flows around Unit 2. Visiting locations around

the Stonetop Mountain and Fern Lake areas can provide more evidence for or against, this hypothesis. A point to consider when thinking about the caldera boundary is that large lithic clasts have been found in three locations throughout the SCD during this study: Bog Creek; Bluff Creek; and the Unit 3 vent area. Connecting these features creates a line segment which is parallel to the eastern boundary of the caldera formed by the HRT eruption. There are also large lithic clasts reported in the Stonetop Mountain area (Christiansen, 2001), potentially signifying another lag breccia and eruptive vent on the SCD. Also important to understanding the LCT eruption would be the addition of more geochemical characterization of units 3 and 4, as well as a fuller description and mapping of Unit 4. There are few analyses of sanidine from Unit 3 and none from Unit 4. Comparing Unit 4's sanidine compositions and physical characteristics to those of other SCD ignimbrites will establish if Unit 4 is from another distinct magma body or from a magma body that was tapped in an earlier eruption.

The LCT was originally mapped as two ignimbrite members that were proposed to have been erupted from a single compositionally stratified magma chamber (Christiansen, 2001). New evidence from the Sour Creek Dome shows that this model is too simple. The Sour Creek dome contains four separate ignimbrite units, all yielding radiometric ages that are within uncertainty the same as those reported from the Lava Creek Tuff. Sanidine geochemistry from the ignimbrites on the SCD suggests units 1, 2, and 3 are all related magmatically. However, characteristic difference between units 2 and 3 are evidence there were multiple magma bodies tapped during the eruptions. This shows the LCT eruption was more complex than assumed and was fed by multiple magma bodies throughout the eruption.

REFERENCES CITED

- Allan, A.S.R., Wilson, C.J.N., Millet, M.A., and Wysoczanski, R.J., 2012, The invisible hand: Tectonic triggering and modulation of a rhyolitic supereruption: *Geology*, v. 40, p.563-566, doi:10.1130/G32969.1.
- Bachmann, O., 2010, The petrologic evolution and pre-eruptive conditions of the rhyolitic Kos Plateau Tuff (Aegean arc): *Open Geosciences*, v. 2, p. 270-305, doi:10.2478/v10085-010-0009-4
- Chamberlain, K.J., Wilson, C.J.N., Wallace, P.J., and Millet, M.-A., 2015, Micro-analytical perspectives on the Bishop Tuff and its magma chamber: *Journal of Petrology*, v. 56, p. 605-640, doi:10.1093/petrology/egv012.
- Chang, W.-L., Smith, R.B., Farrell, J., Puskas, C.M., 2010, An extraordinary episode of Yellowstone caldera uplift, 2004–2010, from GPS and InSAR observations: *Geophysical Research Letters*, v. 37, L23302, doi:10.1029/2010GL045451.
- Christiansen R.L., 2001, The Quaternary and Pliocene Yellowstone Plateau volcanic field of Wyoming, Idaho, and Montana. US Geological Survey. Prof Pap 729-G:1–143
- Christiansen R.L., and Blank, H.R., 1975, Geologic map of the Canyon Village quadrangle, Yellowstone National Park, Wyoming, US Geological Survey map GQ-1192
- Cole, J.W., Milner, D.M., and Spinks, K.D., 2005, Calderas and caldera structures: a review: *Earth-Science Reviews*, v. 69, p. 1–26, doi:10.1016/j.earscirev.2004.06.004.
- Druitt, T.H., and Sparks, R.S.J., 1982, A proximal ignimbrite breccia facies on santorini, Greece: *Journal of Volcanology and Geothermal Research*, v. 13, p. 147–171, doi:10.1016/0377-0273(82)90025-7.
- Druitt, T.H., and Sparks, R.S.J., 1984, On the formation of calderas during ignimbrite eruptions: *Nature*, v. 310, p. 679–681, doi:10.1038/310679a0.
- Fierstein, J., and Wilson, C.J.N., 2005, Assembling an ignimbrite: Compositionally defined eruptive packages in the 1912 Valley of Ten Thousand Smokes ignimbrite, Alaska: *GSA Bulletin*, v. 117, p. 1094–1107, doi:10.1130/B25621.1.
- Freundt, A., Wilson, C.J.N., and Carey, S.N., Ignimbrite and block-and-ash flow deposits, 2000, *Encyclopedia of Volcanoes*, p. 581-599.
- Gansecki, C.A., 1998, Argon-40/argon-39 geochronology and pre-eruptive geochemistry of the Yellowstone Plateau volcanic field rhyolites [Ph.D.]: Stanford University, 212 p., <https://www.proquest.com/docview/304454192/abstract/751A75C52EB1477BPQ/1> (accessed November 2022).

- Gottsmann, J., Lavallée, Y., Martí, J., Aguirre-Díaz, G., 2009, Magma–tectonic interaction and the eruption of silicic batholiths: *Earth and Planetary Science Letters*, v. 284, p. 426–434, doi:10.1016/j.epsl.2009.05.008
- Gudmundsson, A., 1988, Formation of collapse calderas: *Geology*, v. 16, p. 808–810, doi:10.1130/0091-7613(1988)016<0808:FOCC>2.3.CO;2.
- Henderson, S.L., Myers, M.L., Wilson, C.J.N., and Salazar, R., 2021, Storage Configuration and Evacuation of the Lava Creek Tuff, Yellowstone, Investigated Using Sanidine Chemistry: Abstract V35B-0141 presented at 2021 Fall Meeting, AGU, New Orleans, Louisiana
- Henderson, S., Myers, M.L., Wilson, C.J.N., and Schwartz, D., 2023 From Magma to Tuff: Using sanidine to interrogate the physical distribution plumbing systems and the Lava Creek Tuff, Yellowstone. IAVCEI Scientific Assembly, Rotorua, New Zealand
- Hildreth, W., and Mahood, G.A., 1986, Ring-fracture eruption of the Bishop Tuff: *Geological Society of America Bulletin*, v. 97:4, p. 396–403, [https://doi.org/10.1130/0016-7606\(1986\)97%3C396:REOTBT%3E2.0.CO;2](https://doi.org/10.1130/0016-7606(1986)97%3C396:REOTBT%3E2.0.CO;2)
- Hildreth, W., and Wilson, C.J.N., 2007, Compositional zoning of the Bishop Tuff: *Journal of Petrology*, v. 48, p. 951–999, doi:10.1093/petrology/egm007.
- Izett, G.A., and Wilcox, R.E., 1982, Map showing localities and inferred distributions of the Huckleberry Ridge, Mesa Falls, and Lava Creek ash beds (Pearlette family ash beds) of Pliocene and Pleistocene age in the western United States and southern Canada: US Geological Survey IMAP, doi:10.3133/i1325.
- Johnson, D.M., Hooper, P.R., and Conrey, R.M., 1999, XRF analysis of rocks and minerals for major and trace elements on a single low dilution Li-tetraborate fused bead: *Advances in X-ray Analysis*, v. 41, p. 843–867.
- Kelley, S., 2002, K-Ar and Ar-Ar Dating: *Reviews in Mineralogy and Geochemistry*, v. 47, p. 785–818, doi:10.2138/rmg.2002.47.17.
- Kudo, A.M., and Weill, D.F., 1969, An igneous plagioclase thermometer: *Contributions to Mineralogy and Petrology*, v. 25, p. 52–65, <https://doi.org/10.1007/BF00383062>.
- Ledbetter, M.T., and Sparks, R.S.J., 1979, Duration of large-magnitude explosive eruptions deduced from graded bedding in deep-sea ash layers: *Geology*, v. 7, p. 240–244, doi:10.1130/0091-7613(1979)7<240:DOLEED>2.0.CO;2
- Lipman, P.W., 1976, Caldera-collapse breccias in the western San Juan Mountains, Colorado: *Geological Society of America Bulletin*, v. 87, p. 1397–1410, doi:10.1130/0016-7606(1976)87<1397:CBITWS>2.0.CO;2.

- Lipman, P., Dungan, M., and Bachmann, O., 1997, Comagmatic granophyric granite in the Fish Canyon Tuff, Colorado: Implications for magma-chamber processes during a large ash-flow eruption: *Geology*, v. 25, p. 915–918, doi:10.1130/0091-7613(1997)025<0915:CGGITF>2.3.CO;2.
- Marsh B.D., 1984, On the mechanics of caldera resurgence: *Journal of Geophysical Research: Solid Earth*, v. 89, p. 8245-8251, doi:10.1029/JB089iB10p08245
- Mason, B.G., Pyle, D.M., and Oppenheimer, C., 2004, The size and frequency of the largest explosive eruptions on Earth: *Bulletin of Volcanology*, v. 66, p. 735–748, doi:10.1007/s00445-004-0355-9.
- Matthews, N.E., Vazquez, J.A., and Calvert, A.T., 2015, Age of the Lava Creek supereruption and magma chamber assembly at Yellowstone based on $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb dating of sanidine and zircon crystals: *Geochemistry, Geophysics, Geosystems*, v. 16, p. 2508–2528, doi:10.1002/2015GC005881.
- Miller, C.F., and Wark, D.A., 2008, SUPERVOLCANOES AND THEIR EXPLOSIVE SUPERERUPTIONS: *Elements*, v. 4, p. 11–15, doi:10.2113/GSELEMENTS.4.1.11.
- Morgavi, D., Arienzo, I., Montagna, C., Perugini, D., and Dingwell, D. B., 2017, Magma mixing: History and dynamics of an eruption trigger, *Advances in Volcanology, Volcanic Unrest*, p. 123-137
- Myers, M.L., Wallace, P.J., Wilson, C.J.N., Morter, B.K., and Swallow, E.J., 2016, Prolonged ascent and episodic venting of discrete magma batches at the onset of the Huckleberry Ridge supereruption, Yellowstone: *Earth and Planetary Science Letters*, v. 451, p. 285–297, doi:10.1016/j.epsl.2016.07.023.
- Obradovich, J.D., 1992, Geochronology of the late Cenozoic volcanism of Yellowstone National Park and adjoining areas, Wyoming and Idaho: U.S. Geological Survey Open-file Report 92-408, 45p.
- Pearce, N.J.G., Westgate, J.A., Gualda, G.A.R., Gatti, E., and Muhammad, R.F., 2020, Tephra glass chemistry provides storage and discharge details of five magma reservoirs which fed the 75 ka Youngest Toba Tuff eruption, northern Sumatra: *Journal of Quaternary Science*, v. 35, p. 256-271, doi:10.1002/jqs.3149.
- Pineda, C., Hammer, J., First, E., and Morata, D., 2021, Storage conditions of a caldera-forming volcanic eruption: Insights from the Pudahuel rhyolitic ignimbrite in central Chile (32° 10'S): *Lithos*, v. 400, Article 106382, doi: 10.1016/j.lithos.2021.106382.

- Putirka, K.D., 2005, Igneous thermometers and barometers based on plagioclase + liquid equilibria: Tests of some existing models and new calibrations: *American Mineralogist*, v. 90, p. 336–346, doi:10.2138/am.2005.1449.
- Putirka, K.D., 2008, Thermometers and barometers for volcanic systems: *Reviews in Mineralogy and Geochemistry*, v. 69, p. 61–120, doi:10.2138/rmg.2008.69.3.
- Quane, S.L., and Russell, J.K., 2005, Ranking welding intensity in pyroclastic deposits: *Bulletin of Volcanology*, v. 67, p. 129–143, doi:10.1007/s00445-004-0367-5.
- Rivera, T.A., Schmitz, M.D., Jicha, B.R., and Crowley, J.L., 2016, Zircon petrochronology and $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine dates for the Mesa Falls Tuff: Crystal-scale records of magmatic evolution and the short lifespan of a large Yellowstone magma chamber: *Journal of Petrology*, v. 57, p. 1677–1704, doi:10.1093/petrology/egw053.
- Ross, C.S., and Smith, R.L., 1961, Ash-flow tuffs: Their origin, geologic relations, and identification: *US Geological Survey Prof. Pap.* 366, p. 1-87, doi:10.3133/pp366
- Schaen, A.J., Jicha, B.R., Hodges, K.V., Vermeesch, P., and Stelten, M.E., 2020, Interpreting and reporting $^{40}\text{Ar}/^{39}\text{Ar}$ geochronologic data: *GSA Bulletin*, v. 133, p. 461–487, doi:10.1130/B35560.1.
- Self, S., 2006, The effects and consequences of very large explosive volcanic eruptions: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, v. 364, p. 2073–2097, doi:10.1098/rsta.2006.1814.
- Self, S., Goff, F., Gardner, J.N., Wright, J.V., and Kite, W.M., 1986, Explosive rhyolitic volcanism in the Jemez Mountains: Vent locations, caldera development and relation to regional structure: *Journal of Geophysical Research: Solid Earth*, v. 91, p. 1779–1798, doi:10.1029/JB091iB02p01779.
- Shamloo, H.I., and Till, C.B., 2019, Decadal transition from quiescence to supereruption: petrologic investigation of the Lava Creek Tuff, Yellowstone Caldera, WY: *Contributions to Mineralogy and Petrology*, v. 174: 32, doi:10.1007/s00410-019-1570-x.
- Smith, R.L., 1960, ASH FLOWS: *GSA Bulletin*, v. 71, p. 795-841, doi:10.1130/0016-7606(1960)71[795:AF]2.0.CO;2
- Smith, R.L., and Bailey, R.A., 1968, Resurgent Cauldrons, *in* Coats, R.R., Hay, R.L., and Anderson, C.A. eds., *Studies in Volcanology*, Geological Society of America, v. 116, p. 613-662, <https://doi.org/10.1130/MEM116-p613>.

- Sparks S.R.J. and Marshall L.A., 1986, Thermal and mechanical constraints on mixing between mafic and silicic magmas: *Journal of Volcanology and Geothermal Research*, v. 29, p.99–124, [https://doi.org/10.1016/0377-0273\(86\)90041-7](https://doi.org/10.1016/0377-0273(86)90041-7).
- Swallow, E.J., Wilson, C.J.N., Charlier, B.L.A., and Gamble, J.A., 2019, The Huckleberry Ridge Tuff, Yellowstone: evacuation of multiple magmatic systems in a complex episodic eruption: *Journal of Petrology*, v. 60, p. 1371–1426, doi:10.1093/petrology/egz034.
- Swallow, E.J., Wilson, C.J.N., Charlier, B.L.A., and Gamble, J.A., 2018b, Mafic inputs to the rhyolitic magmatic system of the 2.08 Ma Huckleberry Ridge eruption, Yellowstone. *American Mineralogist*, v. 103, p. 757-775, doi:10.2138/am-2018-6273.
- Swallow, E.J., Wilson, C.J.N., Myers, M.L., Wallace, P.J., Collins, K.S., and Smith, E.G.C., 2018, Evacuation of multiple magma bodies and the onset of caldera collapse in a supereruption, captured in glass and mineral compositions: *Contributions to Mineralogy and Petrology*, v. 173:33, doi:10.1007/s00410-018-1459-0.
- Troch, J., Ellis, B.S., Mark, D.F., Bindeman, I.N., Kent, A.J.R., Guillong, M., and Bachmann, O., Rhyolite generation prior to a Yellowstone supereruption: insights from the Island Park–Mount Jackson Rhyolite series. *J. Petrol.* 58, 29–52 (2017).
- U.S. Geological Survey, 2021, 3D Elevation Program 1/3 Arc Second Digital Elevation Model n45w111, 20210614: U.S. Geological Survey. <https://www.sciencebase.gov/catalog/item/63c78c27d34e06fef14edbd0> accessed April 16, 2022.
- Walker, G.P.L., 1985, Origin of coarse lithic breccias near ignimbrite source vents: *Journal of Volcanology and Geothermal Research*, v. 25, p. 157–171, doi:10.1016/0377-0273(85)90010-1.
- Walker G.P.L., 1983, Ignimbrite types and ignimbrite problems: *Journal of Volcanology and Geothermal Research*, v. 17, p. 65-88, doi:10.1016/0377-0273(83)90062-8
- Wilson, C.J.N., 2008, Supereruptions and Supervolcanoes: Processes and Products: *Elements*, v. 4, p. 29–34, doi:10.2113/GSELEMENTS.4.1.29.
- Wilson, C.J.N., 2001, The 26.5ka Oruanui eruption, New Zealand: an introduction and overview: *Journal of Volcanology and Geothermal Research*, v. 112, p. 133–174, doi:10.1016/S0377-0273(01)00239-6.
- Wilson, C.J.N., Cooper, G.F., Chamberlain, K.J., Barker, S.J., Myers, M.L., Illsley-Kemp, F., and Farrell, J., 2021, No single model for supersized eruptions and their magma bodies: *Nature Reviews Earth & Environment*, v. 2, p. 610–627, doi:10.1038/s43017-021-00191-7.

- Wilson, C.J.N., and Hildreth, W., 2003, Assembling an Ignimbrite: Mechanical and Thermal Building Blocks in the Bishop Tuff, California: *The Journal of Geology*, v. 111, p. 653–670, doi:10.1086/378335.
- Wilson, C.J.N., and Hildreth, W., 1997, The Bishop Tuff: New Insights from Eruptive Stratigraphy: *The Journal of Geology*, v. 105, p. 407–516, <https://doi.org/10.1086/515937>.
- Wilson, C.J.N., Stelten, M.E., and Lowenstern, J.B., 2018, Contrasting perspectives on the Lava Creek Tuff eruption, Yellowstone, from new U–Pb and ⁴⁰Ar/³⁹Ar age determinations: *Bulletin of Volcanology*, v. 80, p. 53, doi:10.1007/s00445-018-1229-x.
- Wright, J.V. and Walker G.P.L., 1977, The ignimbrite source problem: Significance of a co-ignimbrite lag fall deposit: *Geology*, v. 5, p. 729-732 [https://doi.org/10.1130/0091-7613\(1977\)5%3C729:TISPSO%3E2.0.CO;2](https://doi.org/10.1130/0091-7613(1977)5%3C729:TISPSO%3E2.0.CO;2)

APPENDICES

APPENDIX A

FIELD NOTES AND SAMPLE LOCATIONS

Location South WL Date 2/8/21

Project / Client _____

Name Pattern for Samples

SCD21MMdd-001

x) SCD210628-001

SCD210802-001

A

0544421 2423

4947591

Hiked into WL today, saw
some pison.

Mostly cloudy, many bugs.

Outcrop scattered up-hillside

Very weathered, some are
weathered throughout, likely
altered hydrothermally.

~ 20% pumice, Qtz, Sanidine

visible, up to 4mm,

mostly weathered white/red,

best face is grey-purp.

outcrop ~ .5-1m,

Location South Wrangier Date 2/8/21 69

Project / Client _____

Scale _____

SCD210802-002

A

0544574 2435m

4447414

likely same rock as before,
moderate welding, Qtz, Sanidine
fresh-ish is grey-purple.
xtals up to ~4mm, lacking
pumice, perhaps a few ~~weathered~~
pumice.

SCD210802-003

0544629 2440m

4447388

Tree roots for the win! Still
kinda shitty, but it's something.
Qtz + Sanidine abundant
perhaps small pumice? xtals
up to 3mm, purp. matrix in one
sample, the other is light
grey and weathers (?) to purp.
In light grey samp. purple is
~~more~~ has more xtals, most
xtals weathered orange

Location	SomeWhere IN SCD	Date	3/8/21
Project / Client			
SCD 210803-001	A		
0545773	2434m		
4947642			
Sample collected from tree root. Seems unweathered, pink-purp matrix, seems ashy, definitely buff/ig-brite.			
70-80% matrix, xtals ~ 25%, 5% pumice, xtals are san., Qtz, some possible lithics.			
Xtals up to ~4mm, pumice ~3mm, lithics ~1-2cm			
SCD 210803-002	A		
0545854	2451m		
4947677			
likely LCT unit 2, Grey matrix, poor to mod. welding, xtals are mostly sanidine, some Qtz, xtals up to 5mm, pumice up to 7mm, ~60% matrix			

Location _____ Date _____ 71

Project / Client _____

Scale _____

SCD210803-003 A
 0548223 2443 m
 4947445

Tree root rock, we've found
 other outcrop but its
 weathered beyond use,
 this is weathered, but to
 a lesser extent.
 grey matrix, moderate welding,
 few pumice up to ~4mm, 1, thick
 up to ~7mm, sanidine abundant,
 Qtz common,

SCD210803-004
 0548309 2458m
 4947567

Very weathered, crumbly outcrop,
 sample not possible, light
 grey to white, orange/red in
 areas. 60+% xtals, largely sanidine,
 few Qtz

Rite in the Rain

72 Location east of BC Date 10/3/8
 Project / Client _____

SCD210803-005		A
0548334	2460m	
4947569		
Outcrop, matrix weathered purp. ~70% matrix, sanidine dominant, few lithics		
10% > Qtz, mod-dense welding		
SCD210803-006		
0548535	2513m	A + B
4947623		
A White matrix, ~75%, x'tals are mostly sanidine, some Qtz, pumice ~ 1mm, x'tals up to 5mm, moderate welding, weathered areas are tan/orange.		
B Matrix is purp/grey, seems more weathered, possible flow, Sanidine + Qtz, perhaps pumice. Samp. B is ~3m uphill of A. Weathers yellow/red. Might be more xtal rich.		

73

Location _____ Date _____

Project / Client _____

Scale _____

SCD210803-007
 0548610 2537m
 4947619

Top of hill, I think I found stick on lines. There are cliffs about 7m high and 50+ m long. Outside is all weathered red, some places have ~~a~~ many pumice, other places don't. Could be the top of the flow, a couple rocks also have ~~the~~ what looks like an enclave, ~~or~~ or perhaps contry rock?

SCD210803-008
 0547586 2448m A
 4948125

Sample collected from left cliff face as you walk up Bog Creek (West Cliff). Moderate welding, white/light grey matrix, a few pumice, xtal rich, ~40-50% xtals. Mostly Sanidine ~70% sanb, ~30% Qtz. Large xtals up to 8mm. Some 30 Qtz. Cliff is ~10m tall and very long.

Rite in the Rain

74	Location	Date	75	Location	Date
	Bog Creek	3/8			
	Project / Client			Project / Client	
	Scale			Scale	
	SCD210803-009			SCD210804-001	
	0547547 2424m	A		Map says fault, no fault,	
	4948137			big open flat meadow.	
	Sample from right cliff as			Point on iPad.	
	you walk up (east). Cliff is			SCD210804-003	
	~15-20m tall, very long.			0545801 2458m	
	Matrix is light grey/white,			4946839	
	~50% xtls, mostly Sanidine,			Came across a lot of outcrop	
	some Qtz, some minerals			along the top of a hill, mostly	
	weathering red. lithics present,			boulders sticking out of the ground	
	looks same as -008A			Rock is moderately welded,	
		4/8		Sanidine and Qtz present,	
	SCD210804-002	A		few pumice, xtls up to ~8mm,	
	0545868 2428m			pumice are up to ~5mm, matrix	
	4946921			is grey to light grey, weathered	
	On a hill mapped as Qyla,			area is yellow-ish, same rock	
	lots of weathered flat which			as sample -002A.	
	matches weathered outcrop			SCD210804-004	
	finally got a *less* weathered			0545875 2468m	
	outcrop. Mostly grey matrix,			4946495	
	makes up ~70% of rock, majority			Rock looks the same as -002A.	
	Sanidine xtls up to 8mm (80%),			Found on top of hill/fin with	
	~20% Qtz, 5% pumice, moderately			lots more outcrop. Xtls are	
	welded, unusually large lithic.			smaller and there are fewer	

Location Bog CreekDate 3/8

Project / Client _____

SCD210803-009

0547547 2424m

A

4948137

Sample from right cliff as
you walk up (east). Cliff is
~15-20m tall, very long.

Matrix is light grey/white,
~50% xtals, mostly Sanidine,
some Qtz, some minerals
weathering red. lithics present,
looks same as -008A

4/8

SCD210804-002

A

0545868 2428m

4946921

On a hill mapped as Qyla,
lots of weathered float which
matches weathered outcrop.
Finally got a *less* weathered
outcrop. Mostly grey matrix,
makes up ~70% of rock, majority
Sanidine xtals up to 8mm (80%),
~20% Qtz, 5% > pumice, moderately
welded, unusually large lithic ~

75

Location _____ Date _____

Project / Client _____

Scale _____

Closest thing, Clast is dense, has
xtals,
Outcrop is ~ 1m by 1m

SCD210804-001

Map says fault, no fault,
big open flat meadow.
Point on iPad.

SCD210804-003

0545801 2458m
4946839

Came across a lot of outcrop
along the top of a hill, mostly
boulders sticking out of the ground.
Rock is moderately welded,
Sandstone and Qtz present,
few pumice, xtls up to ~ 3mm,
pumice are up to ~ 5mm, matrix
is grey to light grey, weathered
area is yellow-ish, same rock
as sample - 002A.

SCD210804-004

0545875 2468m
4946495

Rock looks the same as 002A.
Found on top of hill/fin with
lots more outcrop. Xtls are
smaller and there are fewer

Rite in the Rain

76	Location	Date	77
	SE of WL	4/8	
Project / Client			
Scale			
SCD210804-005		A	
0545808		2485	
4946461			
Appears to be the same rock as -002A, HOWEVER, ~~there~~ there are fewer x'tals and there are fiamme.			
X'tals ~30%, Matrix ~40%, pumice + lithics ~30% (mostly lithics?) X'tals are sanidine + Q+z.			
SO much outcrop! Pancake weathering. ~30m tall x ~8m wide			
SCD210804-006			
0545713		2488m	
4946417			
Came across an odd bowl/"U" shaped ~~out~~ half circle of outcrop. ~~at least~~			
~1.5-2.5m tall and ~30m wide			
unfortunately, outcrop is completely altered, no fresh face can be found. Everything is bright red and yellow, fresh & as found face is greyish, matrix, pumice are present but very yellow, sanidine are deep yellow, possible gas pockets.			
SCD210804-007		A	
0545763		2490m	
4946365			
Appears to be a less weathered version of -006. Grey/brown matrix so much pumice, X'tals are mostly sanidine, few Q+z, poor to moderate welding, X'tals up to 2mm, highly weathered, lithics ~3mm, mapped as HRT			

78 Location West of Bog Date 11/8/21
 Project / Client _____

Sunny day w/ few clouds, we hiked from Wrangler, got to West of BC.

* ~~SCD210811-002~~ SCD210811-002
 0546855 2408m
 4948204

Likely the front of Opus. We are at a flow-front of a ~~tear~~ lobe. For sure reworked volcanics. Volcanic ss with some grain size sorting. Also looks conglomerate-y. larger clasts up to ~~1.5cm~~ ~1.5cm present in the lower outcrop. grains are smaller as you gain vert. Clast supported, Plag, Qtz, Obsidian. Seems like there are layers of coarse ~~matrix~~ grains (~2mm) inter-bedded w/ fine grains (~~matrix~~ ~1mm). possible pumice. Overall rock is white/ten and weathers orange/red.

79 Location hiked up drainage Date 11/8/21
 Project / Client _____

Scale _____

SCD210811-004
 0546939 2431m
 4948337

Mapped as Opus. Seems like it could be a flow or tuff. Black matrix. Large Plag xtabs up to 6mm. Very sparse Qtz up to 1mm. Plag are angular/blocky. Rock is xtab rich, likely ~50% xtabs.

SCD210811-005
 0546950 2464m
 4948388

Wild new rock, I Dk man. Pink ignimbrite with clasts of the rock below (-004). Clasts are 1cm - 6cm. Clasts are dominate. There are some small glassy chunks, perhaps some trachyte. Glass chunks make ~30% of rock, lithic clasts ~20% of rock.

Rite in the Rain

Location Top west cliff BC Date 11/8/21

Project / Client _____

SCD210811-008

A

0547549 2506m

4948235

Hiked up to the cliff @ BC. On top of west cliff in Qpus unit. Rock looks same as sample collected @ bottom of cliff in BC light grey w/ hint of purp for matrix. Some lithic clasts. Matrix and clasts have proud ~~in~~ Sanidine up to 5mm. ~~Perp~~ Perhaps some Pumice exist. The clasts are more xtal rich than the matrix.

SCD210812-00~~86~~⁸⁵ A
Lat/Lon on iPad

Walked up a hill and found some shit rock. Pumaceous, grey/tan/purp. matrix. Sanidine + Plag. Xtals up to 5mm. likely glacial veneer.

81

Location _____ Date _____

Project / Client _____

Scale _____

After exploring, it seems this
rock is only found in boulders
along entire hillside. The bedrock
seems to be LCT unit 2.
The soil is all light and
looks like LCT.

Rite in the Rain

Location _____		Date _____	
Project / Client _____			
IC220602-006			
12T	0499225	1979m	
	5042882		
Wandered for awhile, no outcrop seen, but soil changes from dark to light and float appears abundantly.			
Disregard above			
Last day of training in Hyalite			

Location East of Howard-Eaton Date June 23, 2022
 Project / Client Stonetop Mtn. Flow
 Scale _____

SCD220623-001

0550017 2456m

4939336

The rock all looks the same getting to this point. Grey/whit matrix, some purple hue, xtal-rich, ~30% xtals, looks like more Plag than Qtz.

The hill North of the meadow is this rock. Likely Qyla b/c it's a bit hard/competent.

SCD220623-002

N 44.605920

W 110.365648

7943ft Till samp.

Halfway down hill, ~~blob~~ blob of scoreaceous material in the rock. Localized to ~ 8 ft tall and 70 ft wide.

The hill is likely a flow end

SCD220623-003

0551133

4939052

7955ft

C.iffs facing west into a meadow. 10's of meters tall, ~100ish long. Weathered in a red/pink way, not any fresh

Rite in the Rain.

90

Location _____

Date 06/23

Project / Client _____

Continued... 003

Sanidine are huge, up to 5mm.

Smaller Qtz, xtal-rich 40-50%

Small band of finer, xtal poor material

SCD220623-004

0550359

4939346

Cliffy outcrop, Looks like

LCT but darker and more xtal

rich. Plag / sani dominant, few Qtz

Matrix is black or v. drk grey.

SCD220623-005

0551422

2482m

4939083

A

We are in the QJS Stenotop flow.

Black / drk grey. Plag / sani dominant.

Looks like -004

Location Howard Eaton, SCD SW Date 06/28

Project / Client _____

Scale _____

SCD220628-001

~~PS 0520933~~

2393 m

0550495

~~4964541~~

4937990

Rock found in tree root. Multiple
Chunks found. Similar rock in
nearby tree root.

Grey matrix w/ light grey pumice.
Pumice chunks are oriented / squishy.
Moderate to dense welding.

~20% xtls, San, qtz, trace plag.

San ~2mm, qtz ~1mm.

Mostly San ~65%.

SCD220628-002

0551086

2398 m

4937905

Light grey matrix, fiamme-like
structures. poor to mod weld.
Super buggy. These notes will be
bad. Xtl poor. 5-10%.

San + Qtz, all xtls ~1mm
at largest.

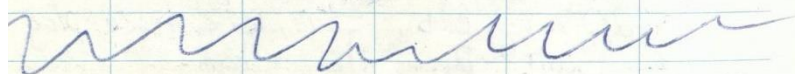
Rock found in tree roots,
no outcrops around.

Location SCD Howard-Eaton Date _____

Project / Client _____

SCD220628-003 (A)

SO BUGGY!!
grey matrix flow texture
Xtal rich ~40%
Sani + Qtz, few mm



SCD220628⁹-001

0547313 2406m

490402

we walked along the
Howard-Eaton trail ~ 4.5 mi.
Came to a creek mapped as
a fault. Looks like a
fault. lots of rock around.

All weathered, grey/purp matrix
with red weathering bands through
it, ~ 25-30% Xals, Sani + Qtz

I walked alone downstream
to follow the fault. I fell
on a log and I think a
stick went up my butt. "

Location Howard-Eaton Date 06/28 93

Project / Client _____

Scale _____

9

SCD220628-C02
0548404 2443m
4940757

Good few boulder-y outcrops.
All look the same through
the area.

They are very weathered. No. 2pm.
Dark grey to charcoal matrix w/ deep
purple here. ~ 20% xtls. Gross looking
sand, some qtz. The rock likes
to crumble.

SCD220628-C03
0548540 2524
4940711

Steep gully / drainage. No mapped
fault but it looks a fault.
No outcrop or slickenlines
I should draw a topo profile
of this spot.

SCD220628-C04
0548800 2516m
4940595

(A) (B)

This is the same rock we've
seen all day.

Taking a point and sample

Just b/c why not.

Sample B is fresher, but xtal poor
and looks different. Found under a tree
not much of it.

Rite in the Rain.

Location Howie be eatin Date 6/29

Project / Client _____

CD220629-005

(A)

0549238 2490m

4940406

We crossed a fault (steep gully)
and came into a new unit.

Grey matrix w/ purple hue.

Some weathering w/in the
rock. Xtal poor, small xtals.

<15% xtals up to ~1mm. Sam 1, Q12,

SCD220629-006

0549530 2481m

4940436

Very cool area, definitely
controlled by structure/faulting.

Theres a dry creek bed made of
rock. Then a nick point. ~10-15m
drop. Cliffy and large boulders
Rock looks like -005. Maybe
just more xtal rich. ~40%

Location Trap Conference Room Date 7/1 95

Project / Client _____

Scale _____

SCD220623-005A
stone top flow xtal count

Sandine : ~20
biggest : ~5mm
mean : 1.5 mm

Quartz : ~13
biggest : ~1.5mm
mean : 1 mm

Plag : ~10mm
biggest : ~1.5mm
mean : ~1mm

SCD220628-003A
xtal count, looks like a glow.

Sandine : ~17
biggest : ~3mm
mean : ~1mm

Qtz : ~9
biggest : ~1mm
mean : 1 mm

Plag : ~11
biggest : ~5mm
mean : ~1mm

Rite in the Rain

Location Trap Conference Room Date 7/1

Project / Client _____

SCD220628-001A

Xtal counts

Sandine : ~13

biggest : 1.5mm

mean : 2mm

Quartz : ~14

biggest : Small

mean : Small

Plag : ? ~ 4?

July 5th

Super buggy day

SCD220705-001

Ipod coordinates

Hiked up the hills south of
Wrangier lake. Found unit 2
in a tree well. Grey matrix,
light purp. hue, Qtz & Scori
present. Qtz up to ~1mm, Scori a
bit bigger. Scoria up to ~1cm.
Scoria makes ~3-5% of the
rock. ~10% Xtals.

Location Trap 121 Date 07/07 97

Project / Client Rock descriptions

Scale _____

SCD220705-002 unit 2 cap?

Walked ~ 8m up slope. This rock forms a ledge that continues laterally for 30+ m. The rock is beige to cream color matrix. it has slightly grey sections and possible pumice. It feels ash/chalky. Qtz up to 3mm, most ~ 1mm. Sanidine ~ 1-1.5mm. ~ 15% xtals

SCD220705-003 opus?

Walked up the hill. Looks like a lava flow. Very dense, possible Q PLUS? Large pumice up to ~ 4cm. Fiamme present too. Purp. matrix. ~ 40% xtal Plag, San, ~~San~~ Qtz, Plag 1mm San, up to 2mm, Qtz up to 2mm

SCD220705-004 (A)

WTF? It's a breccia on the south slope of the hill. Most clasts are 1-3mm. Possible obsidian/vitrophyre. IDK if its cement supported or not. I think cement??? There are chunks of ignimbrite in the breccia. up to 7cm. Xtal poor. Qtz + San ~ 1mm

Rite in the Rain

Location Trap 121 Date 7/7

Project / Client _____

CD220705-005

(A)

A very red stained breccia. The rock looks similar to -004A, but it's just red. Likely alteration from fluids or gases. Definitely cement supported. Clasts up to 3 cm.

CD220705-008

Looks like a Qv1a? Definitely unit A or B. Grey / drk grey matrix, kinda dense, Pumice (~2mm, scarce), Plag (2-3mm), San (2mm), Qtz (~3mm) lithics present. ~30-35% x'tals.

Location Trap 121 Date 7/7 99

Project / Client _____

Scale _____

July 6th notes: what do we remember?

Grot to bog creek to go up the west cliffs. On the way up we noticed a lil ledge and followed it. There was lots of down trees but very little rock. even tree wells were empty. Point 001 here.

We headed west along the ledge and toward Madison and I's. Previous transect up the cliff. We started seeing boulders ~~etc~~ rounded, mottled boulders, Point 2.

Points 3-7 are finding the boundary between Unit 2 and Qpus. Unit 2 is the topographic high, its surrounded by Qpus.

Point 8 is Qpus, boulders outcrop

We stopped seeing rocks, the soil changed color to LCT color soil. Point 9 is a small LCT 2 float. As we move NW, there is less and smaller scoria.

Points 10-13 are walking around the hill / topo high point.

SCP220706-011

There are large scoria. LCT 2

Rite in the Rain

Location Trap 121 Date 7/7

Project / Client _____

Point 12 is still LCT. there is QPUS west. ~~A~~ Tracing the boundary between QPUS and LCT 2.

Point 13-14 is QPUS. We started walking toward the cliffs above Bog Creek. Outcrop looks a bit platy, but is QPUS. Point 15. Point 16, we started following QPUS and LCT 2 upstream along cliffs.

Boundary is no more than 8m above.

Point 17, Contact. We Walked down to the creek bed. Point 18 is a weird lobe of LCT 2 that comes down and is surrounded by QPUS.

Point 19 is in the creek bed.

The outcrop has variation. QPUS or LCT A? 20 is a bit up the cliffs. ~half way up. This looks like QPUS but damn, what?

Point 20 is really hard.

Location _____ Date _____

Project / Client _____

Scale _____

Is the clasts juvenile material?

Is the red related to cooling of the tuff?

- Fugitive cooling below releases gas

Is the breccia ~~unit~~ ~~overlying~~ unit 2 hosting unit 1?

If Stonetop is 630 ka, is it a dome?

If Stonetop is old, everything there is LCT?

- IS there A.B. there?

The big "scoria" is lithics. Probly from vent.

Is there any sign of crenulation on edges? cooling?

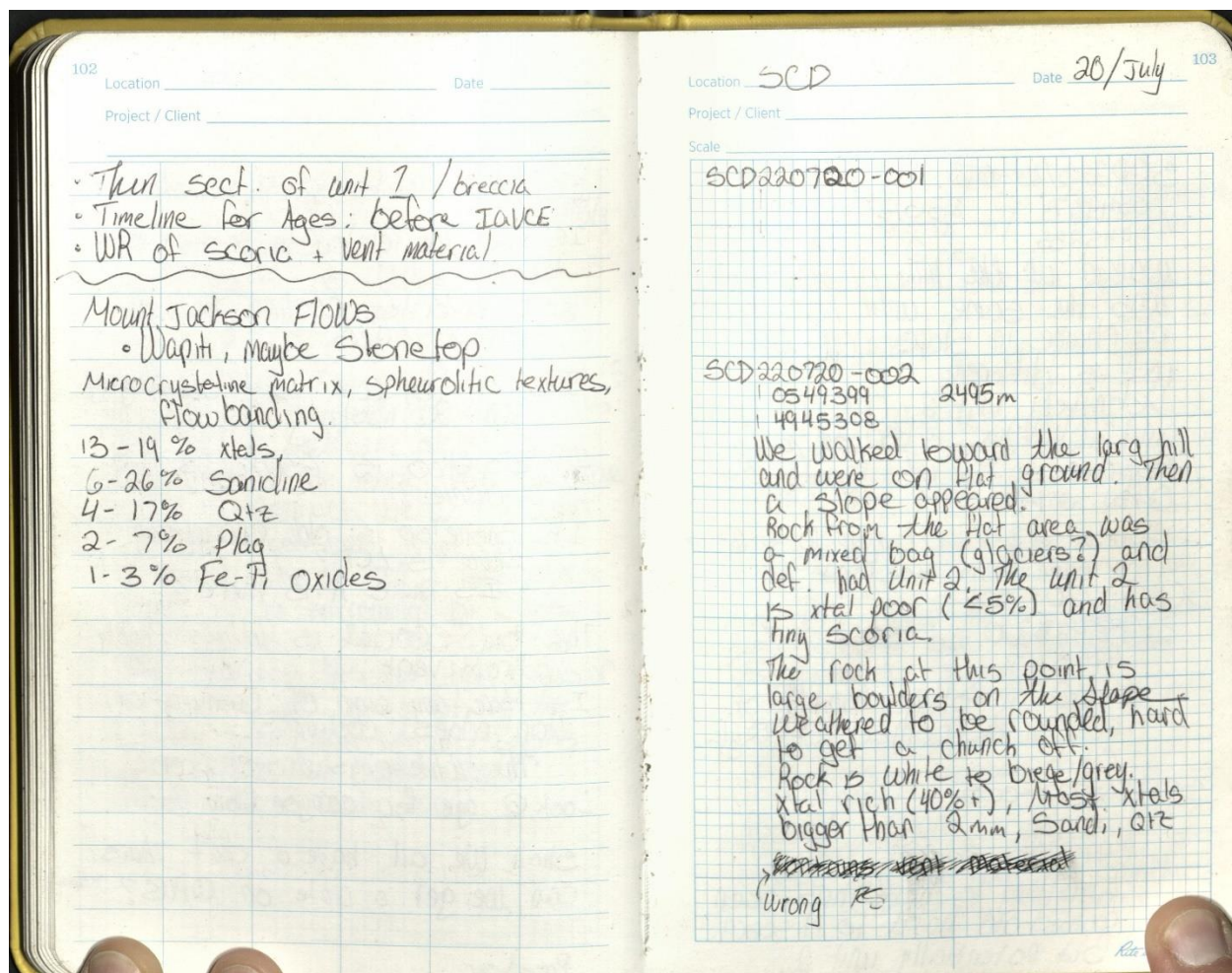
- The white rings around scoria

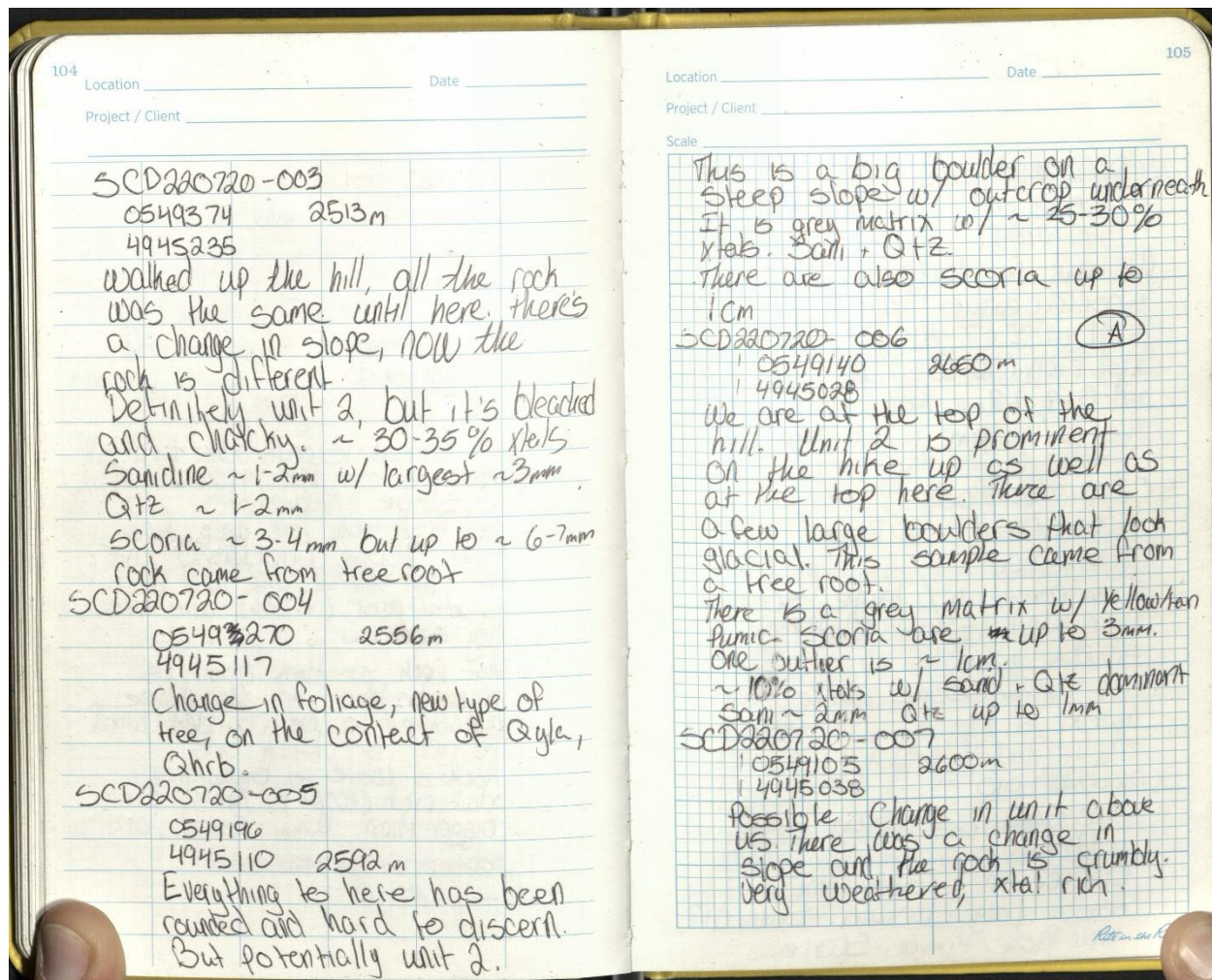
Look @ age for canyon flow

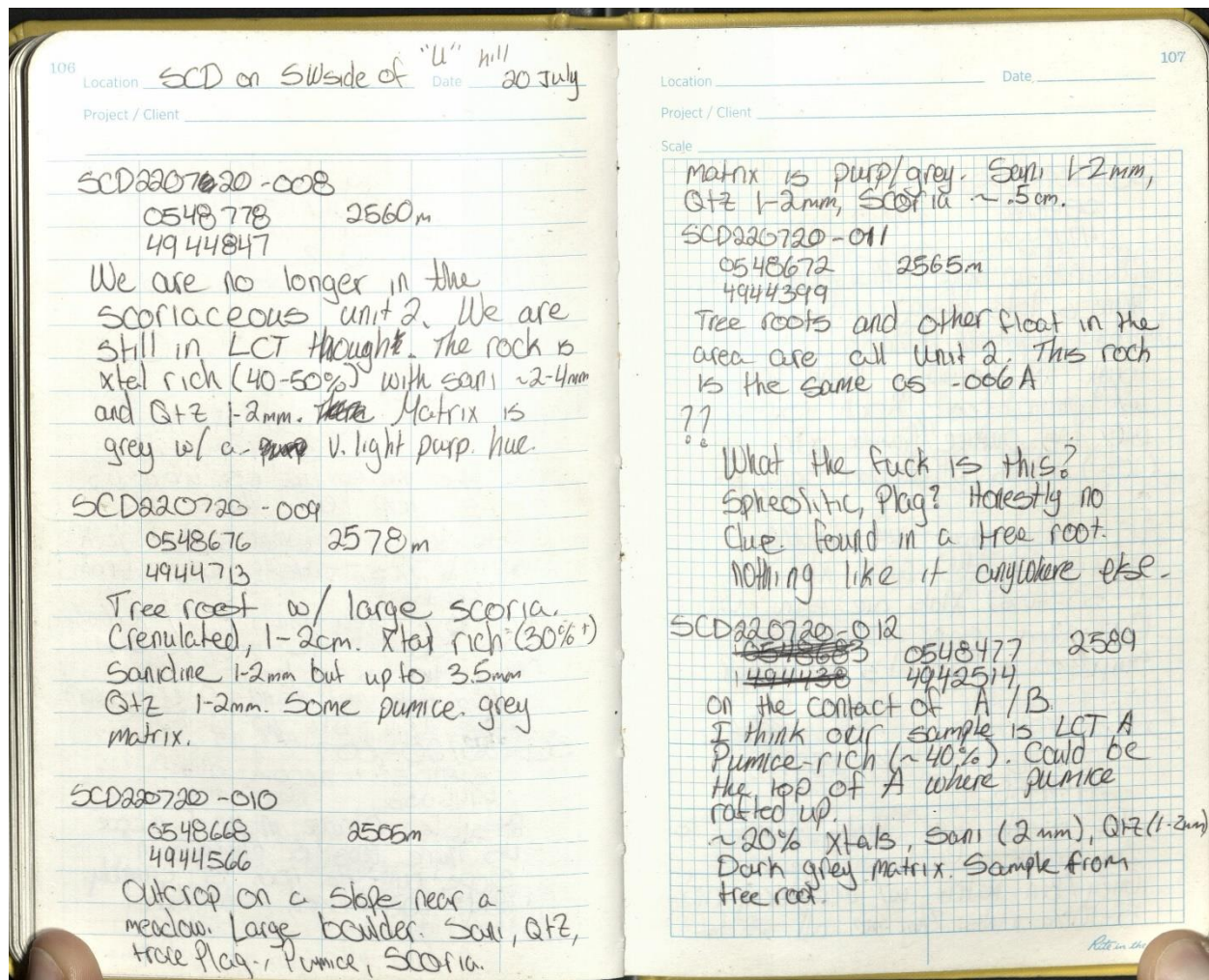
Shall we all have a chat Thurs?
Can we get a date on QPUS? ~4pm

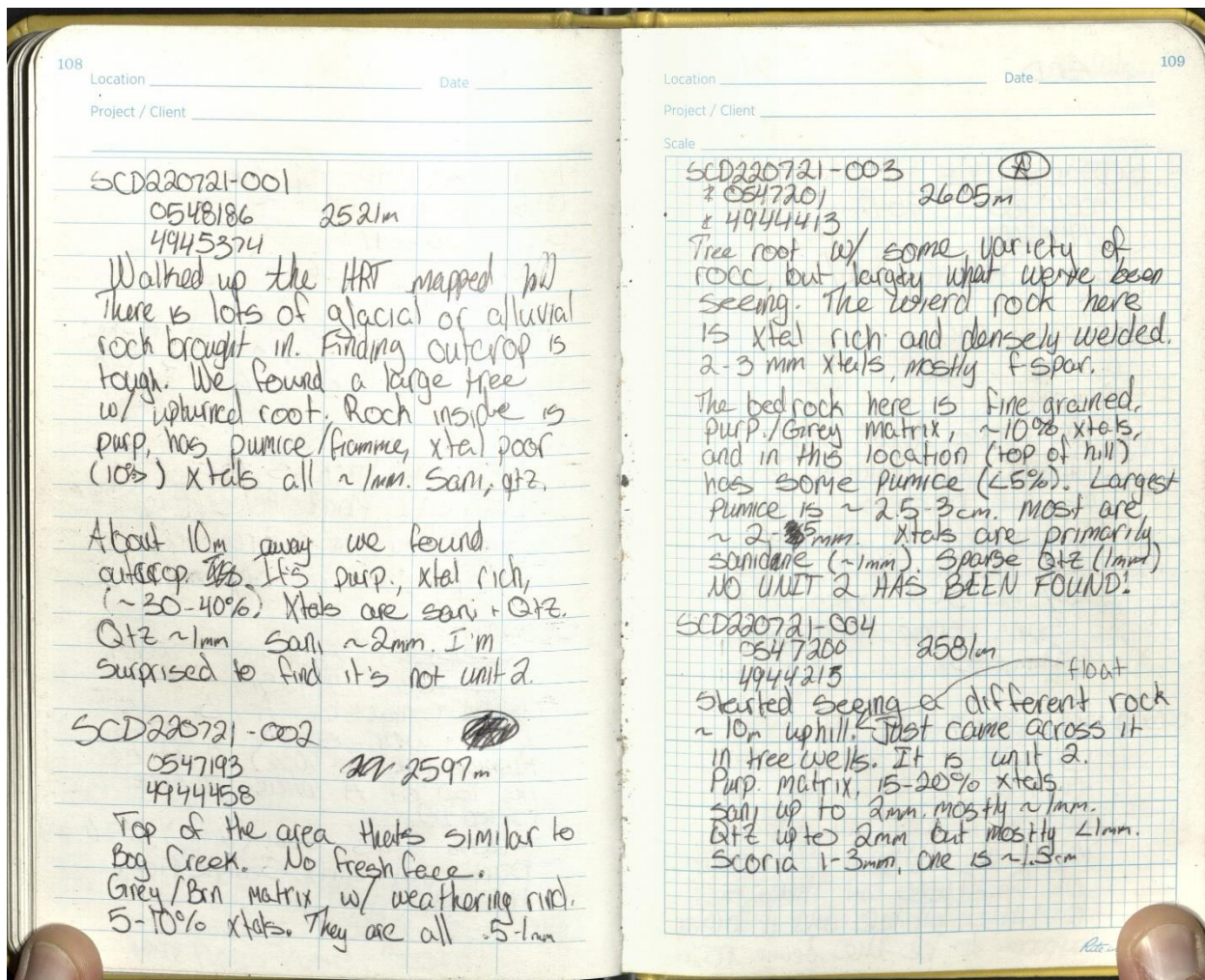
Prost ka

Rite in the Rain









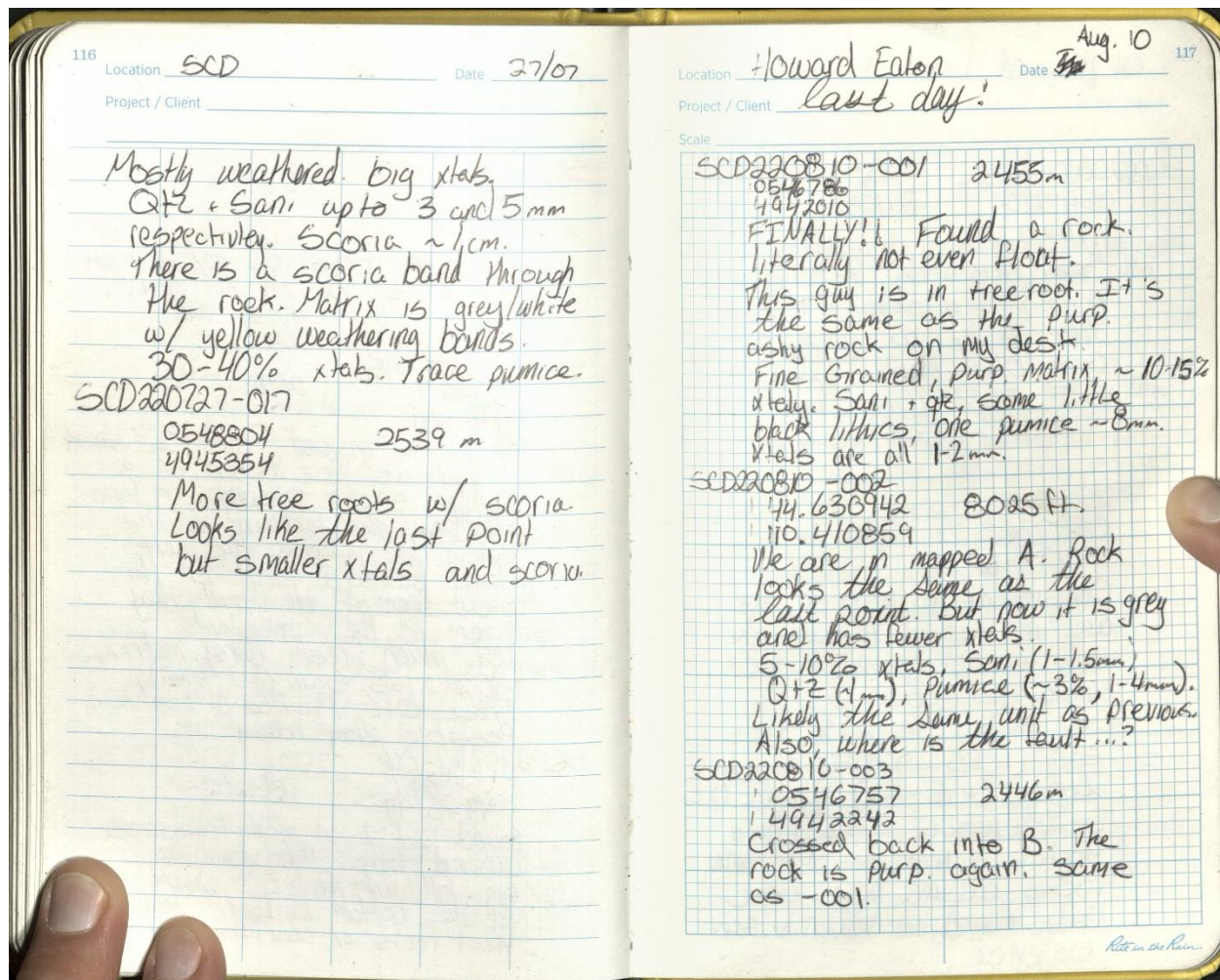
110	Location	Date
SCD	SCD	24 July
Project / Client		
SCD220721-005	0547258 2547m 4944208	
Rock in tree root w/ scoria.		
SCD220721-006	0547488 2520m 4944299	
We came down the hill into a drainage. There are many boulders along the cliffy section of the gully. No scoria. Rock is purp. w/ 20-30% xtab, mostly sani. some good sized pumices.		
SCD220721-007	0547694 2511m 4944710	
There is a weird lil blob mapped as Gylb in the middle of Qa. Turns out there is a little hill here and it largely appears to be the same rock.		

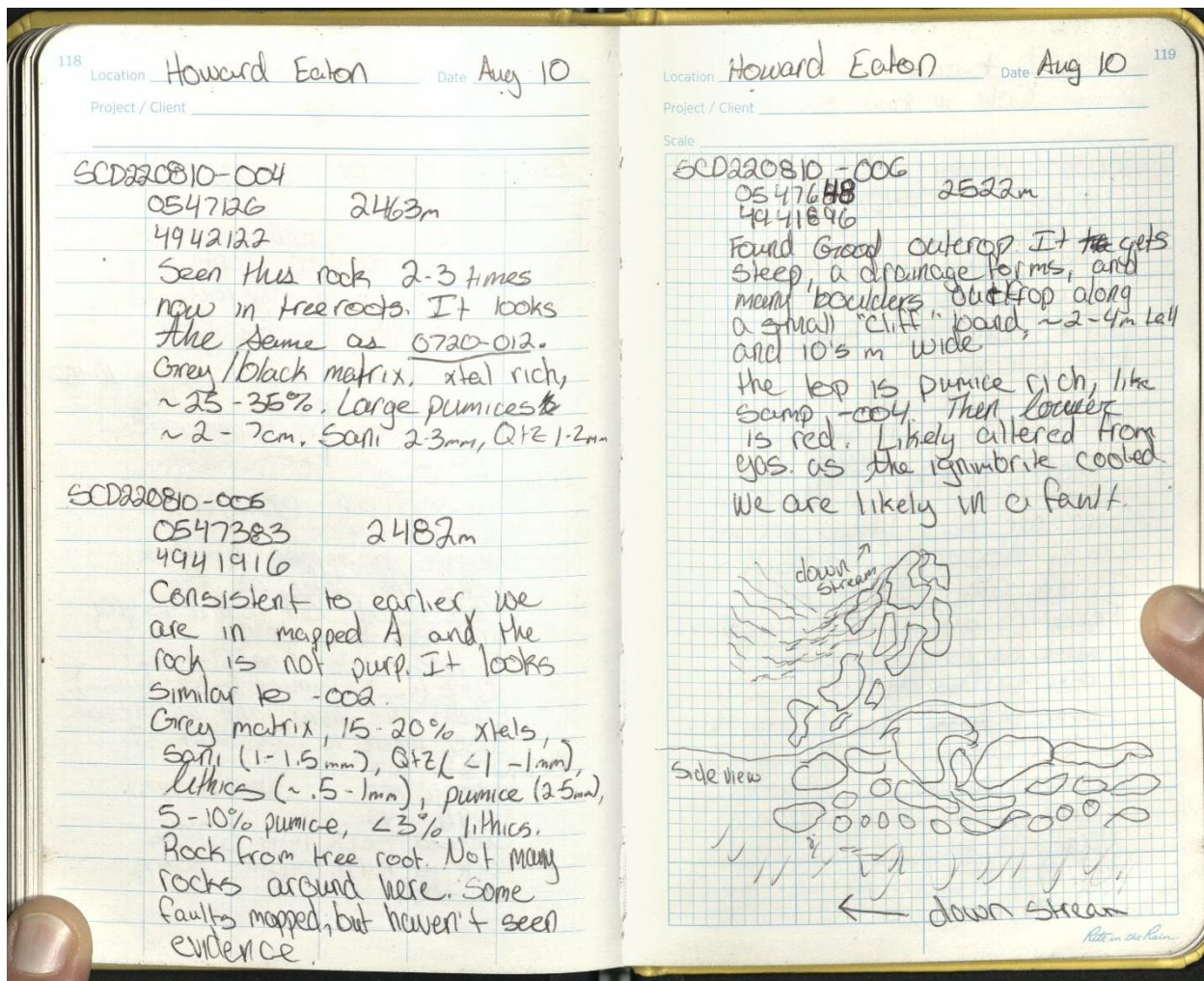
111	Location	Date
SCD	SCD	24 July
Project / Client		
Scale		
The rock looks like point -006. Some have more pumice than others. ~ 5-20%.		
27 July (A)		
SCD220727-001	0549546 2468m 4945660	
Just west of Bluff Creek. The LCI-B mapped here is Unit 2. Sani + Qtz 1-2mm and scoria up to 1cm. Found contact 43m SE of Point. Sample taken of unit mapped as A.		
SCD220727-002	0549549 2476m 4945642	
Crossed the stream and scrambled down the cliffs. Found unit 2 and vent material w/in it. Scoria ~ 1cm, vent material ~ 8m, few lithics present. ~ 1.5 in. Little purp lithics too. I punched a rock !! ~ 10% xtab. Sub mm to ~ 1.5mm.		

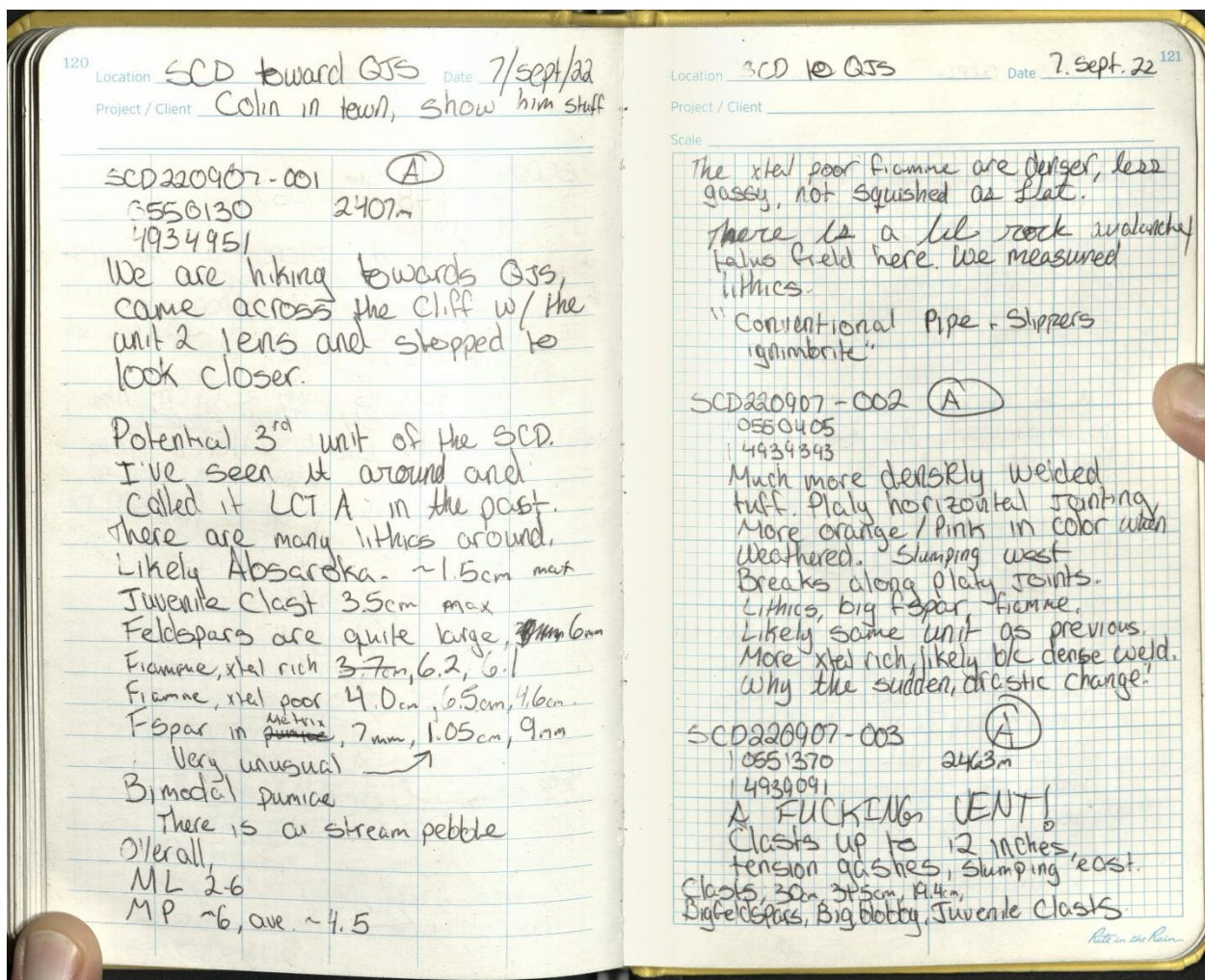
112	Location	Date	113	Location	Date
	SCD E of Wrangler	27 July		See previous	27 July
	Project / Client			Project / Client	
	Scale			Scale	
	SCD220727-003			SCD220727-005	
	0549658 2480m			0550294 2531m	
	4945685			4945470	
	There isn't much rock around but we found float and tree root to be consistent.			Continued wandering in the hills. Not much rock but we found tree roots. Rock is Unit 2.	
	Grey groundmass w/ ~20% xtals			Grey matrix, ~10-15% xtal,	
	Sani + Qtz. Most xtals ~1mm			SCOPIA ~1cm. Few pumice.	
	but both phases have 2mm xtals.			Sandine dominant, ~1-2mm.	
	pumice ~.5cm. Scoria ~3-4mm and smaller. The rock is really hard.			Few Qtz ~1mm.	
	SCD220727-004			SCD220727-006	
	0549814 2474m			0550471 2509m (A)	
	4945569			4945136	
	Rock found in a tree root.			Crossed a ~~creek~~ /stream in a gully. Now mapped Qyla. Seems like a flow to me.	
	There is glacial cover on the hill so we are being careful.			Black matrix, 30-40% xtals,	
	The rock has grey groundmass.			Sani + Plag, Plag ~1mm, Sandine ~2mm	
	Xtal-rich (~30% xtals). Sani + Qtz.			One Sani ~4-5mm. Very dense.	
	All xtals are 1.5-3mm. large			Not convinced that is Qyla.	
	Scoria (~3cm). One scoria has a pumice w/in and the pumice has a large Sani. Sani dominant.			SCD220727-007	
				0550518 2519m	
				4945080	
				Looks like LCT. The last point was maybe dense, dense welded of this rock.	
				Grey matrix ~30% xtal. Lots of Qtz.	
				Some Sani. A bit pumice.	

Rite in the Rain

Location	Date	Project / Client
SCD	27 July	
SCD220727-008	2545m	
0550775 4944946		
Back in unit 2. Grey/purp. matrix. ~10% xtal. Sandine ~1-3mm. ~~Trace~~ Trace plag. Few qtz. Small scoria, ~~by~~ ~1-4mm		
SCD220727-011	2543m	
0550555 494461		
Crossed a meadow and started uphill. Came across tree root w/ large rock. xtal rich ~40%. Very weathered. Most xtal 1-2mm. San + some qtz. Most plag has weathered yellow. No scoria.		
SCD220727-012	2558m	
0550435 4944192		
Dark grey/purp matrix ~20% xtal. San + qtz, small pumice, xtal ~1mm		
SCD220727-013	2641m	
0549985 4944258		
Many tree roots all w/ varying ignimbrites. Variety of xtal content, Matrix colors, and weathering profiles		
SCD220727-015	2646m	
0549617 4944641		
Top of a mapped fault. I think fault is here based on a sudden steep change in topography. The terrain is flat below and above the fault. Many boulders exist on the steep face of the fault. They seem to be consistent. Not much fresh. Grey matrix, ~10% xtal, San (~2-4mm), Trace qtz, Pumice (~4mm-1cm), Possible plag 1-3mm.		
SCD220727-016	2567m	
0548897 4945199		
Found unit 2 in many tree roots around here. Hiked down the big hill w/ the "C" shape HRT. At the bottom we found many tree roots w/ scoriaceous rock		







24

Location

Sheep eater cliffs

Date

9 Sept.

Project / Client

Colin brought us to the cliffs. We walked roughly east along the trail until we passed the columnar basalts. There is an outcrop of an older rhyolite flow w/ basalt clasts in it. The basalts are crenulated and have a chilled margin. This is one of the few true examples of bimodal magma mixing.

Lost Creek Trail.

We hiked to Lost Creek Falls and scrambled up to the cliffs on the east. The tuff is dense welded and contains clasts of a welded tuff w/ scoria. Colin thinks it to be HRT-B. that has the scoria. The main tuff here has many lithics (~2cm - 30cm) and is columnar jointed.

123

Location _____ Date _____

Project / Client _____

Scale _____

A few m West of the last spot
Colin found a contact.
The dense welded tuff below
was still hot when the upper
unit was deposited. Hot enough
there is back welding at
the contact. The juvenile
clasts are different between
the two.
Upper unit: Clasts are xtal poor,
w/ small xtals. There are
clasts w/in here as well.
Could be LCT unit 1.
Lower unit: xtal rich, ~~no~~ clasts
w/ large xtals. ~~no~~ No clasts
w/in these clasts.
We are w/in meters of the vent.

SHEEPEATER CLIFFS
Friday, 9 Sept. 22

Colin brought us to Sheep eater
cliffs. We almost ran out
of gas this morning. The power
outage for the last day and a
half prevented us from getting
gas in the park.

Next PAGE

Rite in the Rain

Location Lost Creek Falls Date 9 Sept. 22
 Project / Client _____

Colin and I hiked along the talus/scree to the base of the falls. There was a somewhat risqué traverse of a landslide scarp.

At the base of the falls we see a poorly welded tuff below the small blocks of dense tuff. (Drawing on previous page)

Below this ~~dense~~ poor/non welded tuff is a fall deposit (55cm). The fall deposit sits atop a non welded tuff.

Fall deposit is xtal rich (0.5-4mm). Appears thinly bedded. Qtz are BP.

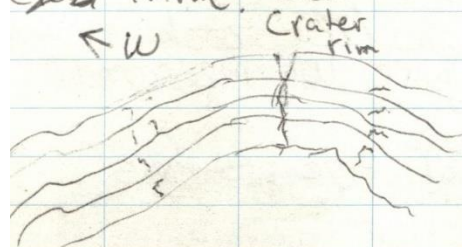
Overlaying tuff is 90cm w/ ~~many small~~ ~~thin~~ ~~crystals~~ ~~crystals~~ xtal poor but many pumice. Qtz are BP.

Transition from poor weld tuff to dense is ~35cm. dense is small blocks ~2.1m until columns begin.

Location QTS areaDate 7 Sept. 22

Project / Client _____

poor scoria: few around, 7.9cm
 1.4m: 2cm



This is evidence the caldera
 is mismatched. We see the local
 topo rim.

CD220907-004

①

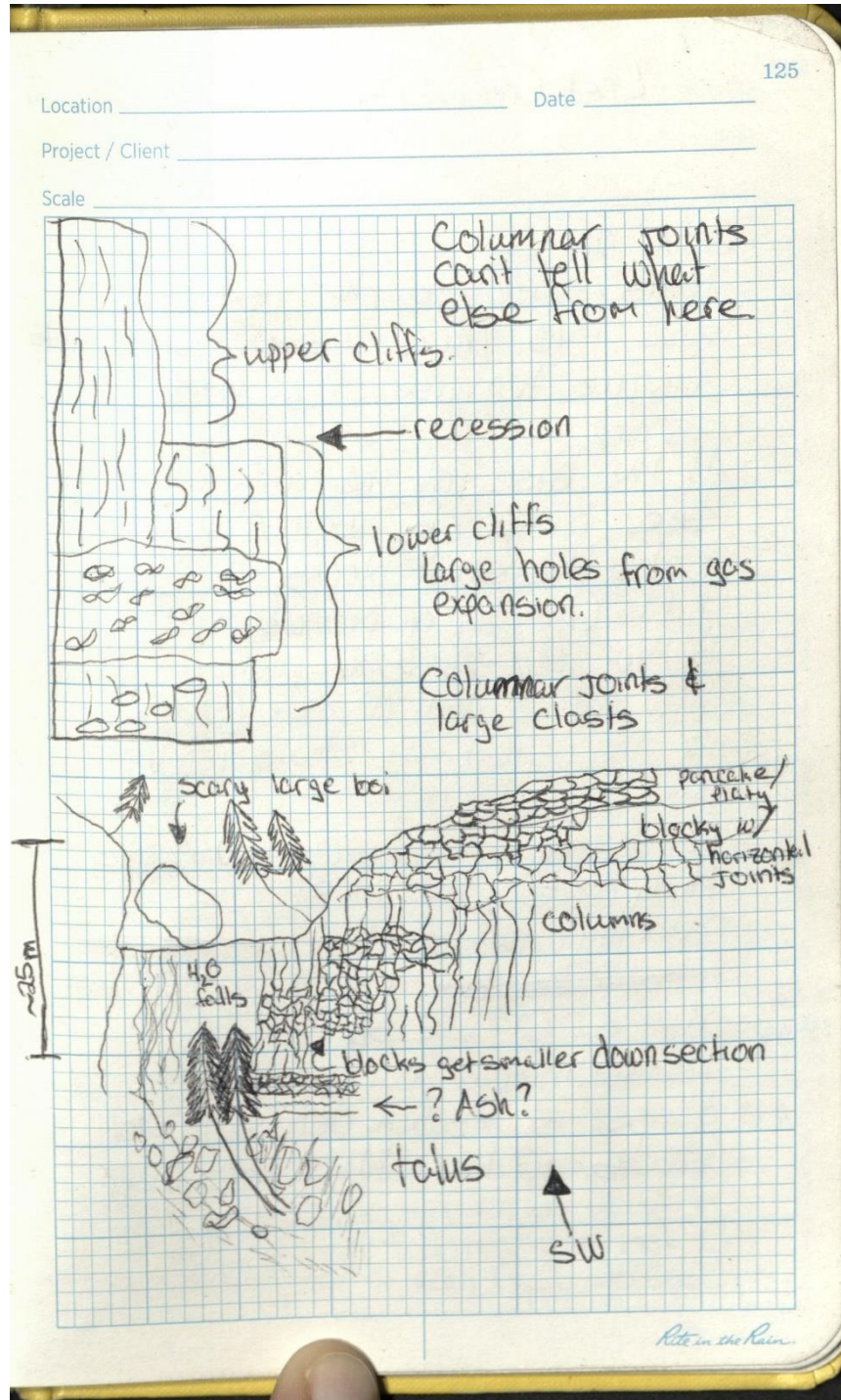
0551407

2488m

4939045

Top of cliffs, found another
 tuff that is poorly welded
 and thinly bedded. Looks
 remarkably similar to the
 breccia by WL.
 There are large clasts in
 here.

Continued next Page



Location _____ Date 9 Sept. 127.

Project / Client _____

Scale _____

Sample 620/1

top 3cm of unit below fall

620/2

Bottom 7cm fall

620/3

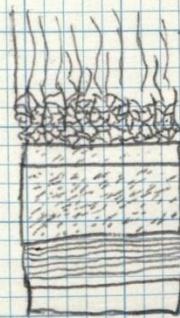
upper 4cm fall

620/4

Lower 10cm tuff above fall

620/5

60 cm above where ~~the~~ blocky
dense tuff appears.



← Columnar joints

Small, prismatic blocks
transition to dense weld
gradation of welding, xtal pools
denser at top, pumice rich
Thin bedded ash, xtal rich
Moderate xtal, massive ash

This trip w/ Colin has been fantastic. It's
what I needed to get excited about my
project again. I feel ready to look at
everything w/ a new, fresh perspective.

Rite in the Rain.

18 Location Tower Falls road cut Date 10 Sept.

Project / Client _____

It was a brutally cold morning. It dipped to 20°F last night. Because Colin is sick we are leaving the park today rather than tomorrow. After packing up a frosty camp, we took our new pass to Tower Falls road cut. We are looking for the ~~basal~~ lithophase ~~to~~ at the road cut to compare against the Lost Creek Falls.

Here we find fewer and smaller lithics. The lithophase zone is also ~~is~~ thinner.

APPENDIX B

ARGON – ARGON DATA

NGX-600 40Ar/39Ar ages calculated relative to Bodie Hills sanidine [9.7946 ± 0.0031 Ma, Fleck et al. (2019)]																
Reactor Constants: Shielded																
36/37	± 1 sigma	40/39	± 1 sigma	39/37	± 1 sigma	38/37	± 1 sigma	38/39	± 1 sigma							
0.000281	0.00000621	0.001003	0.000379	0.00071	4.96E-05	3.29E-05	7.5E-06	0.01314	0.000012							
Decay constants from Steiger and Jager (1977). Assumed atmospheric 40Ar/36Ar from Lee et al. (2006).																
Analysis	Age (Ma)	± 1 sig. (Ma)	K/Ca	± 1 sig.	40Ar*/39Ar	± 1 sig.	40Ar (V)	± 1 sig. (V)	39Ar (V)	± 1 sig. (V)	38Ar (V)	± 1 sig. (V)	37Ar (V)	± 1 sig. (V)	36Ar (V)	± 1 sig. (V)
YELL20-0912-BC1	J = 0.000255442	IRR385-UJ	44630.16													
Total Gas Age (Ma)	Bulk K/Ca = 24.665 ± 1.314 (1 sig.)															
F3	0.612294168	0.01942218	26.28614	15.56859	1.32888	0.04216	0.000452	1.49E-06	0.000312	1.17E-06	4.24E-06	7.81E-07	6.23E-06	3.68E-06	1.26E-07	4.35E-08
F4	0.615935418	0.01283202	19.79037	4.465294	1.336784	0.027854	0.001364	1.9E-06	0.000628	1.63E-06	9.47E-06	1.57E-06	1.66E-05	3.66E-06	1.76E-06	5.77E-08
E3	0.618470922	0.00729434	28.54628	2.429365	1.342288	0.015834	0.004631	2.44E-06	0.002385	4.01E-06	3.08E-05	1.02E-06	4.38E-05	3.03E-06	4.79E-06	1.25E-07
E13	0.621388954	0.00552884	24.04868	2.040511	1.348622	0.012002	0.002948	1.84E-06	0.001805	3.44E-06	2.21E-05	1.36E-06	3.94E-05	2.71E-06	1.73E-06	7.05E-08
E10	0.622969114	0.00413852	21.9708	1.951451	1.352052	0.008984	0.0029	3.57E-06	0.001676	3.31E-06	2.31E-05	1.54E-06	4E-05	2.95E-06	2.13E-06	4.65E-08
F1	0.624392274	0.00479661	28.87607	3.761572	1.355141	0.010412	0.001662	2.05E-06	0.001149	2.94E-06	1.54E-05	1.18E-06	2.09E-05	2.51E-06	3.56E-07	3.71E-08
E8	0.626071901	0.00342248	27.38068	2.338267	1.358787	0.007429	0.00405	3.22E-06	0.002699	3.55E-06	3.32E-05	1.44E-06	5.17E-05	3.6E-06	1.29E-06	6.42E-08
E2	0.627213688	0.00321623	28.50223	1.712712	1.361266	0.006982	0.005036	3.12E-06	0.003373	3.98E-06	4.41E-05	8.65E-07	6.21E-05	2.11E-06	1.5E-06	7.59E-08
E7	0.628016755	0.00621474	27.4737	5.56533	1.363009	0.01349	0.001599	2.71E-06	0.001065	2.06E-06	1.2E-05	1.41E-06	2.03E-05	3.99E-06	4.97E-07	4.63E-08
E1	0.629905651	0.00419033	29.76969	2.282019	1.367109	0.009096	0.0031	2.63E-06	0.002097	2.89E-06	2.79E-05	1.16E-06	3.7E-05	2.16E-06	7.84E-07	6.18E-08
F2	0.630488854	0.01099369	28.10666	6.801224	1.368375	0.023864	0.000983	2.78E-06	0.000676	2.07E-06	8.37E-06	1.03E-06	1.26E-05	2.99E-06	1.95E-07	5.24E-08
E11	0.631483546	0.00268604	29.05997	1.755027	1.370534	0.005831	0.006735	5.56E-06	0.004513	5.44E-06	5.67E-05	1.2E-06	8.15E-05	2.81E-06	1.85E-06	8.22E-08
D8	0.63397673	0.00759204	39.73653	8.481526	1.375946	0.01648	0.001433	1.84E-06	0.000997	1.97E-06	1.12E-05	9.87E-07	1.32E-05	2.73E-06	2.05E-07	5.39E-08
E6	0.635141318	0.00588191	25.15464	1.759462	1.378474	0.012768	0.003663	4.03E-06	0.0024	2.9E-06	3.26E-05	9.8E-07	5.01E-05	2.47E-06	1.19E-06	1.01E-07
E12	0.63928807	0.01088658	25.39017	2.288197	1.387476	0.023632	0.003381	2.86E-06	0.001439	3.39E-06	2.03E-05	1.2E-06	2.97E-05	2.24E-06	4.64E-06	1.12E-07
D12	0.639562493	0.01156671	22.89615	4.618434	1.388071	0.025108	0.000898	2.78E-06	0.000591	1.9E-06	8.51E-06	1.14E-06	1.35E-05	2.65E-06	2.61E-07	4.8E-08
D11	0.642484402	0.00933074	23.055	5.076934	1.394414	0.020255	0.000949	2.03E-06	0.000666	2.12E-06	9.56E-06	1.27E-06	1.52E-05	3.25E-06	7.12E-08	4.35E-08
F6	0.643151074	0.033775	-79.9274	132.2723	1.395861	0.073317	0.000387	1.47E-06	0.000265	1.34E-06	5.53E-06	8.32E-07	-1.7E-06	-2.9E-06	5.74E-08	6.45E-08
E5	0.644451573	0.00794934	27.4549	3.273425	1.398684	0.017256	0.002587	3.99E-06	0.001473	2.62E-06	1.73E-05	1.02E-06	2.82E-05	3.05E-06	1.77E-06	8.31E-08
E9	0.644868179	0.02565864	5.444401	0.579842	1.399589	0.055698	0.001319	1.93E-06	0.000426	1.5E-06	4.66E-06	1.39E-06	4.11E-05	3.87E-06	2.43E-06	7.89E-08
E4	0.646657488	0.00944928	23.94689	2.822718	1.403473	0.020512	0.002262	4.21E-06	0.001305	1.95E-06	1.63E-05	9.21E-07	2.86E-05	3.06E-06	1.44E-06	8.8E-08
D9	0.648024579	0.00672001	23.1318	2.382966	1.40644	0.014587	0.003133	2.9E-06	0.001476	2.92E-06	1.66E-05	9.48E-07	3.35E-05	3.02E-06	3.54E-06	7E-08
F5	0.649218064	0.0152217	24.3573	6.837944	1.409031	0.033042	0.000808	2.51E-06	0.000522	2.35E-06	6.19E-06	7.94E-07	1.12E-05	3.1E-06	2.47E-07	5.6E-08
D10	0.653575987	0.00682434	23.69033	3.131842	1.418491	0.014814	0.001595	1.52E-06	0.001073	2.3E-06	1.36E-05	9.82E-07	2.38E-05	2.91E-06	2.5E-07	5.18E-08
D7	0.674279137	0.01041226	12.82347	0.945799	1.463433	0.022603	0.003965	2.2E-06	0.001341	2.13E-06	1.76E-05	1.17E-06	5.49E-05	3E-06	6.72E-06	1E-07

Table 1. ⁴⁰Ar/³⁹Ar data for YELL20-0912-BC001.

Analysis	Age (Ma)	± 1 sig. (Ma)	K/Ca	± 1 sig.	40Ar*/39Ar	± 1 sig.	40Ar (V)	± 1 sig. (V)	39Ar (V)	± 1 sig. (V)	38Ar (V)	± 1 sig. (V)	37Ar (V)	± 1 sig. (V)	36Ar (V)	± 1 sig. (V)
SCD220623-005A	J = 0.000505659	IRR391-EV	44962.6													
Total Gas Age (Ma)	Bulk K/Ca = 20.103 ± 1.038 (1 sig.)															
I10	0.003472621	0.00351721	18.17933	1.539216	0.689924	0.003808	0.004314	3.59E-06	0.005704	8.53E-06	7.3E-05	3.57E-06	0.000165	1.13E-05	1.3E-06	6.85E-08
I4	0.001853888	0.00193669	28.55828	1.743269	0.69236	0.002033	0.013208	4.94E-06	0.017112	2.36E-05	0.000212	3.43E-06	0.000314	1.12E-05	4.59E-06	9.91E-08
I12	0.002176754	0.00224791	32.61943	3.035381	0.69342	0.002387	0.005835	3.81E-06	0.008189	1.19E-05	0.000105	3.26E-06	0.000132	1.04E-05	5.34E-07	5.69E-08
I9	0.003303812	0.00335146	17.51041	1.382989	0.695913	0.003623	0.004718	3.85E-06	0.006113	9E-06	7.65E-05	3.37E-06	0.000183	1.13E-05	1.59E-06	6.94E-08
I6	0.001940989	0.00202139	16.55102	1.029921	0.697521	0.002128	0.006778	4E-06	0.009596	1.35E-05	0.000121	3.09E-06	0.000304	1.14E-05	3.35E-07	5.79E-08
I11	0.002321081	0.00239226	17.83458	1.122106	0.715827	0.002545	0.007858	4.15E-06	0.009735	1.37E-05	0.000126	3.24E-06	0.000286	1.11E-05	3.03E-06	7.38E-08
I7	0.002249757	0.00232875	15.43198	0.972039	0.74324	0.002467	0.006576	4.16E-06	0.008683	1.24E-05	0.000114	3.11E-06	0.000295	1.15E-05	4.65E-07	6.22E-08
I5	0.002219686	0.00229994	18.4801	1.245698	0.744293	0.002434	0.00634	3.95E-06	0.008382	1.2E-05	0.000104	3.2E-06	0.000238	1.09E-05	3.8E-07	5.89E-08
I8	0.001648692	0.00175701	20.05199	1.161865	0.750631	0.001808	0.010924	4.85E-06	0.014214	1.96E-05	0.000179	3.66E-06	0.000372	1.12E-05	9.09E-07	6.62E-08
SCD220628-003A	J = 0.000505048	IRR391-EW	44962.72													
Total Gas Age (Ma)	Bulk K/Ca = 23.402 ± 1.219 (1 sig.)															
J6	0.002105701	0.00217282	26.47249	1.800589	0.68922	0.002312	0.00927	5.1E-06	0.012098	1.69E-05	0.000154	3.35E-06	0.00024	1.12E-05	3.15E-06	8.19E-08
J7	0.005129074	0.00515714	23.57704	2.497833	0.691037	0.005631	0.005189	4.16E-06	0.005587	8.44E-06	7.19E-05	3.17E-06	0.000124	1.16E-05	4.47E-06	1.02E-07
I13	0.002353096	0.00241395	27.45863	1.713201	0.692699	0.002583	0.012447	5.39E-06	0.015298	2.11E-05	0.000195	3.05E-06	0.000292	1.11E-05	6.23E-06	1.2E-07
J2	0.004878754	0.00490842	22.17979	3.02908	0.693039	0.005356	0.002522	3.25E-06	0.003495	5.92E-06	4.71E-05	3.19E-06	8.27E-05	1.05E-05	3.43E-07	6E-08
J5	0.00230121	0.00236389	20.72733	1.16168	0.695451	0.002527	0.013644	5.69E-06	0.015819	2.17E-05	0.0002	2.96E-06	0.0004	1.05E-05	8.91E-06	1.2E-07
J9	0.002287943	0.00235118	22.27678	1.378809	0.696582	0.002512	0.009312	4.89E-06	0.011802	1.65E-05	0.000148	3.46E-06	0.000278	1.03E-05	3.69E-06	8.86E-08
J8	0.003478328	0.00352071	27.88907	2.595574	0.700485	0.003819	0.006216	3.98E-06	0.00728	1.06E-05	9.21E-05	3.62E-06	0.000137	1.08E-05	3.75E-06	8.81E-08
J3	0.002235523	0.00230293	18.45104	1.234058	0.711362	0.002454	0.005953	4.05E-06	0.00816	1.16E-05	0.000109	3.35E-06	0.000232	1.04E-05	5.35E-07	5.86E-08
J4	0.003124964	0.00317366	23.71168	1.596637	0.712309	0.003431	0.009784	4.84E-06	0.010952	1.54E-05	0.000139	3.24E-06	0.000242	1.1E-05	6.67E-06	1.18E-07
SCD220629-004A	J = 0.000504352	IRR391-EX	44962.84													
Total Gas Age (Ma)	Bulk K/Ca = 21.333 ± 1.138 (1 sig.)															
J12	0.002793362	0.00284039	19.75136	1.453515	0.692994	0.003071	0.005223	3.96E-06	0.007031	1.02E-05	8.85E-05	3.45E-06	0.000187	1.02E-05	1.2E-06	6.64E-08
K5	0.002462029	0.00251547	27.40143	2.14947	0.694345	0.002707	0.007022	4.19E-06	0.008937	1.25E-05	0.000111	3.48E-06	0.000171	1.04E-05	2.75E-06	7.33E-08
J11	0.005051798	0.00507831	26.12097	3.186631	0.69765	0.005554	0.004348	3.85E-06	0.004682	7.24E-06	6.29E-05	3.26E-06	9.4E-05	1.05E-05	3.63E-06	8.41E-08
K3	0.002250199	0.00230911	24.96956	1.886356	0.697755	0.002474	0.006097	4.12E-06	0.008392	1.21E-05	0.000105	3.39E-06	0.000176	1.01E-05	8.32E-07	6.1E-08
K4	0.002699391	0.00274932	22.44507	1.736606	0.702229	0.002968	0.005427	3.88E-06	0.007257	1.07E-05	8.74E-05	3.51E-06	0.00017	1.01E-05	1.13E-06	6.56E-08
K7	0.003575303	0.00361324	16.78829	1.384983	0.703073	0.003931	0.004159	3.77E-06	0.005436	8.11E-06	7.18E-05	3.32E-06	0.00017	1.12E-05	1.16E-06	6.74E-08
K2	0.002365308	0.00242253	17.60806	1.149498	0.704665	0.0026	0.005846	3.99E-06	0.007966	1.14E-05	0.000106	3.29E-06	0.000237	1.01E-05	8.19E-07	6.17E-08
J10	0.002925432	0.00297244	24.50088	2.294695	0.708847	0.003216	0.00442	3.69E-06	0.006143	9.08E-06	7.72E-05	3.2E-06	0.000132	1.05E-05	2.36E-07	6.08E-08
K6	0.002337124	0.00240109	18.02849	1.189841	0.741199	0.00257	0.006307	4.3E-06	0.008144	1.16E-05	0.000102	3.39E-06	0.000237	1.03E-05	9.46E-07	6.13E-08

Table 2. $^{40}\text{Ar}/^{39}\text{Ar}$ data for samples SCD220623-005A, SCD220628-003A, and SCD220629-004A.

Analysis	Age (Ma)	± 1 sig. (Ma)	K/Ca	± 1 sig.	40Ar*/39A	± 1 sig.	40Ar (V)	± 1 sig. (V)	39Ar (V)	± 1 sig. (V)	38Ar (V)	± 1 sig. (V)	37Ar (V)	± 1 sig. (V)	36Ar (V)	± 1 sig. (V)
SCD220706-022	J = 0.000503358	IRR391-EY	44962.95													
Total Gas Age (Ma)	Bulk K/Ca = 26.306 ± 1.377 (1 sig.)															
L5	0.001634136	0.00170787	26.44316	1.657092	0.6915	0.0018	0.010313	4.63E-06	0.014198	1.97E-05	0.000178	3.34E-06	0.000282	1.08E-05	1.69E-06	6.83E-08
K8	0.002601994	0.00264906	29.00938	2.511428	0.692524	0.002866	0.006409	4.65E-06	0.008479	1.22E-05	0.000109	3.18E-06	0.000153	1.09E-05	1.81E-06	7.39E-08
L6	0.002583421	0.00263098	24.37961	1.792906	0.693703	0.002846	0.006839	4.17E-06	0.008829	1.27E-05	0.000115	3.19E-06	0.00019	1.03E-05	2.42E-06	7.66E-08
L4	0.003102901	0.00314274	31.6176	2.542782	0.694836	0.003418	0.007679	4.06E-06	0.008971	1.27E-05	0.000116	2.54E-06	0.000149	9.43E-06	4.85E-06	9.66E-08
K11	0.004887852	0.00491324	27.66782	3.401741	0.694879	0.005384	0.005095	3.85E-06	0.00556	8.57E-06	6.79E-05	3.17E-06	0.000105	1.19E-05	4.14E-06	9.7E-08
L3	0.001978551	0.00204067	27.18145	1.805808	0.696056	0.00218	0.007172	4.03E-06	0.009727	1.36E-05	0.000121	2.4E-06	0.000188	8.3E-06	1.36E-06	6.08E-08
K9	0.002043329	0.0021039	28.51552	2.081894	0.698185	0.002251	0.008755	4.76E-06	0.011633	1.63E-05	0.000144	3.35E-06	0.000214	1.15E-05	2.14E-06	7.59E-08
K10	0.001749118	0.00181971	27.60631	1.680134	0.699168	0.001927	0.0114	4.69E-06	0.015259	2.11E-05	0.000191	3.36E-06	0.00029	1.02E-05	2.48E-06	8.13E-08
K12	0.008965738	0.00898043	18.0017	1.074905	0.715364	0.009877	0.020148	6.4E-06	0.008413	1.17E-05	0.000117	2.4E-06	0.000245	8.16E-06	4.74E-05	2.71E-07
SCD220706-026	J = 0.000502611	IRR391-EZ	44963.07													
Total Gas Age (Ma)	Bulk K/Ca = 25.586 ± 1.371 (1 sig.)															
M7	0.003026579	0.00306606	29.69556	2.817901	0.688254	0.003339	0.006265	3.89E-06	0.007922	1.15E-05	9.9E-05	2.94E-06	0.00014	1.13E-05	2.73E-06	8.28E-08
L10	0.002151152	0.00220639	26.07492	1.947991	0.688509	0.002373	0.00663	4.93E-06	0.009278	1.32E-05	0.000114	3.1E-06	0.000187	1.04E-05	8.32E-07	6.39E-08
L9	0.001866094	0.00193017	20.80018	1.324282	0.692142	0.002059	0.007802	4.68E-06	0.01099	1.55E-05	0.000135	3.36E-06	0.000277	1.11E-05	6.96E-07	6.33E-08
M6	0.005594496	0.00561633	29.82464	6.979924	0.694271	0.006172	0.002016	2.92E-06	0.002856	5.1E-06	3.77E-05	3.44E-06	5.02E-05	1.15E-05	1.16E-07	5.68E-08
L11	0.002209699	0.00226442	27.59836	2.089465	0.694387	0.002438	0.00794	4.17E-06	0.010617	1.48E-05	0.000138	3.29E-06	0.000202	1.16E-05	1.92E-06	7.7E-08
M8	0.002438328	0.00248816	25.11333	1.566686	0.695328	0.00269	0.011789	4.41E-06	0.013863	1.91E-05	0.000177	3.05E-06	0.00029	1.1E-05	7.24E-06	1.14E-07
M5	0.002679373	0.00272512	22.33753	1.803866	0.697815	0.002956	0.005568	4.09E-06	0.007557	1.1E-05	9.75E-05	3.48E-06	0.000178	1.13E-05	1.01E-06	6.81E-08
L8	0.00318757	0.00322633	31.08766	2.588867	0.699747	0.003517	0.008263	4.33E-06	0.009377	1.33E-05	0.000119	2.88E-06	0.000158	1.06E-05	5.71E-06	1.04E-07

Table 3. 40Ar/39Ar data for samples SCD220706-022 and SCD220706-026.