

THESIS

UNCOVERING YELLOWSTONE'S HIDDEN ERUPTIVE HISTORY THROUGH CORE-  
BASED GEOCHRONOLOGY

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## ABSTRACT

### UNCOVERING YELLOWSTONE'S HIDDEN ERUPTIVE HISTORY THROUGH CORE- BASED GEOCHRONOLOGY

In the late 1960s, the U.S. Geological Survey drilled a series of cores throughout Yellowstone National Park to investigate the subsurface beneath major hydrothermal basins. These cores were logged prior to development of the modern geologic map of the Yellowstone Plateau Volcanic Field (YPVF) and before most modern studies of the geochronology, geochemistry, and petrology of Yellowstone rhyolites. Consequently, some volcanic units may be misidentified in the logs and sedimentary intervals remain poorly characterized. This study revisits the Y-2 core from the Lower Geyser Basin using detailed core logging, petrography, geochemistry, and geochronology to refine the volcanic and sedimentary stratigraphy.

Results indicate that several original stratigraphic interpretations are inconsistent with the geochronologic and petrologic data presented in this study. New zircon  $^{238}\text{U}$ - $^{230}\text{Th}$  and sanidine  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology provide the first direct age constraints for volcanic units within the Y-2 core. These results demonstrate that portions of the original core log require revision as radiometric ages are inconsistent with the original core logging interpretations, including identification of a previously unrecognized lava flow. Geochronologic, geochemical, and petrographic evidence further identifies a rhyolitic interval that does not correlate cleanly with currently mapped post-Lava Creek Tuff eruptive units, suggesting the presence of a previously unrecognized rhyolitic unit within Lower Geyser Basin. Detailed investigation of sedimentary intervals identifies primary to near-primary ash deposits, glaciofluvial deposits, paleosols, and

hydrothermal deposits that records the evolution of the Lower Geyser Basin from a proglacial lake, to glacial outwash from recession of Pinedale and Bull Lake glaciations, and development of the modern hydrothermal system.

Legacy drill cores preserve volcanic and paleoenvironmental records not evident from surface exposures, and this study demonstrates the value of integrating modern analytical techniques with archived subsurface materials to refine the geologic history of Yellowstone.

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## TABLE OF CONTENTS

|                                                                    |      |
|--------------------------------------------------------------------|------|
| ABSTRACT.....                                                      | ii   |
| ACKNOWLEDGEMENTS.....                                              | iv   |
| LIST OF TABLES .....                                               | viii |
| LIST OF FIGURES .....                                              | ix   |
| 1. INTRODUCTION .....                                              | 1    |
| 1.1 Introduction to Thesis .....                                   | 1    |
| 1.2 Geologic Background .....                                      | 1    |
| 1.3 Upper Basin Member vs Central Plateau Member .....             | 4    |
| 1.4 Glacial history .....                                          | 6    |
| 1.5 Geochronology.....                                             | 7    |
| 1.6 Research Focus and Objectives .....                            | 7    |
| 2. METHODS .....                                                   | 11   |
| 2.1 Core logging and sampling .....                                | 11   |
| 2.2 Thin section petrography .....                                 | 11   |
| 2.3 Whole Rock Geochemistry .....                                  | 12   |
| 2.3.1 X-Ray Fluorescence (XRF) .....                               | 12   |
| 2.3.2 Inductively coupled mass spectrometry (ICP-MS).....          | 13   |
| 2.4 Mineral Separation.....                                        | 13   |
| 2.5 Geochronology.....                                             | 14   |
| 2.5.1 $^{230}\text{Th}/^{238}\text{U}$ Zircon Geochronology.....   | 14   |
| 2.5.2 $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine geochronology ..... | 15   |
| 2.5.3 Statistical analysis and data reduction .....                | 16   |
| 2.5.4 U-series Geochronology of Hydrothermal Deposits.....         | 17   |
| 2.6 Electron Microprobe Analysis .....                             | 18   |
| 3. RESULTS.....                                                    | 20   |
| 3.1 Core Logging Results .....                                     | 20   |
| 3.1.1 Volcanic Units (515.5 - 110 ft).....                         | 20   |
| 3.1.2 Sedimentary Units (110 - 0 ft) .....                         | 25   |
| 3.2 Geochronology.....                                             | 29   |
| 3.2.1 Zircon $^{238}\text{U}$ - $^{230}\text{Th}$ Ages .....       | 29   |
| 3.2.2 Sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ Ages.....           | 31   |
| 3.2.3 U-Series Geochronology of Hydrothermal Deposits.....         | 33   |
| 3.3 Whole Rock Geochemistry .....                                  | 34   |

|                                                                                |    |
|--------------------------------------------------------------------------------|----|
| 3.3.1 Major Elements.....                                                      | 34 |
| 3.3.2 Trace Elements.....                                                      | 35 |
| 3.3.3 Major, Minor, and Trace Element Chemostratigraphy .....                  | 37 |
| 3.4 Electron Microprobe Analysis (EPMA).....                                   | 39 |
| 4. DISCUSSION.....                                                             | 46 |
| 4.1 Volcanic Stratigraphy in the Y-2 Core .....                                | 46 |
| 4.2 Limitations of Whole Rock and Geochronologic Interpretations.....          | 51 |
| 4.3 Geochronologic Constraints on Emplacement of Rhyolite Unit #1 .....        | 53 |
| 4.3.1 Inconsistent $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Th ages.....          | 53 |
| 4.3.2 Evidence for a Distinct Post-LCT Unit.....                               | 57 |
| 4.4 Sedimentary Deposition and Paleodrainage Evolution.....                    | 60 |
| 4.4.1 Evidence of a Proglacial Lake Associated with Bull Lake Glaciation ..... | 60 |
| 4.4.2 Evidence of Bull Lake and Pinedale Glaciation Events .....               | 61 |
| 4.4.3 Modern Hydrothermal System.....                                          | 66 |
| 4.5 Alternate Hypothesis.....                                                  | 68 |
| 5. CONCLUSIONS .....                                                           | 70 |
| 6. REFERENCES .....                                                            | 73 |
| 7. APPENDIX.....                                                               | 77 |

## LIST OF TABLES

|                                                                                                                        |    |
|------------------------------------------------------------------------------------------------------------------------|----|
| Table 1: Analytical conditions for sanidine and plagioclase EPMA analyses .....                                        | 18 |
| Table 2: Zircon weighted mean ages .....                                                                               | 30 |
| Table 3: Sanidine weighted mean ages from sample depths in the Y-2, core .....                                         | 32 |
| Table 4: U-series ( $^{234}\text{U}$ - $^{230}\text{Th}$ ) ages of hydrothermal deposits from the Y-2 drill core. .... | 33 |
| Table 5 ICP-MS trace-element concentrations .....                                                                      | 78 |
| Table 6: XRF major- and minor-element concentrations normalized.....                                                   | 79 |
| Table 7: Unnormalized XRF major- and minor-element concentrations.....                                                 | 79 |
| Table 8: Accuracy estimated from XRF & ICP-MS analysis.....                                                            | 80 |

## LIST OF FIGURES

|                                                                                                               |    |
|---------------------------------------------------------------------------------------------------------------|----|
| Figure 1: Regional map of calderas across the Snake River plain.....                                          | 2  |
| Figure 2: Location map of the three caldera-forming eruptions .....                                           | 3  |
| Figure 3: Geologic Map of Yellowstone National Park modified from Christensen 2001 .....                      | 9  |
| Figure 4: Thin section photos (PPL) from each sample taken in Rhyolite unit #1 .....                          | 21 |
| Figure 5: Sample depth 395 & 402.5 ft photographs.....                                                        | 22 |
| Figure 6: Thin section photo (XPL) of 380 ft depth. ....                                                      | 23 |
| Figure 7: Altered sedimentary breccia photographs .....                                                       | 24 |
| Figure 8: Thin section photos of Rhyolite Unit #2 of sample depths (262, and 254 ft).....                     | 25 |
| Figure 9: SEM images from the 106.5 ft interval within laminated sandstones .....                             | 27 |
| Figure 10: Thin section photomicrographs of laminated sandstones and siltstones #1 .....                      | 27 |
| Figure 11: Kernel density estimates (KDEs) of single-grain zircon U–Th model ages .....                       | 30 |
| Figure 12: Kernel density estimates (KDEs) of single grain sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ ages..... | 32 |
| Figure 13: Total alkali silica (TAS) plot of all Y-2 volcanic samples .....                                   | 35 |
| Figure 14: Spider diagrams of all volcanic samples in Y-2 .....                                               | 36 |
| Figure 15: Spider diagrams of all volcanic samples in Y-2 normalized to unaltered CPM.....                    | 36 |
| Figure 16: Spider diagrams of Rhyolite Unit #1 (501.5, 450, and 415 ft).....                                  | 37 |
| Figure 17: Chemostratigraphic profiles of major- and minor-element concentrations (wt%).....                  | 38 |
| Figure 18: Chemostratigraphic profiles of trace-element concentrations.....                                   | 38 |
| Figure 19: Feldspar compositional ternary diagram of feldspars .....                                          | 40 |
| Figure 20: Box and whisker plot of sanidine and plagioclase feldspar BaO (wt%) .....                          | 41 |
| Figure 21: Comparison of the original stratigraphic log of the Y-2 drill core .....                           | 42 |
| Figure 22: Expanded stratigraphic column of the sedimentary interval .....                                    | 43 |
| Figure 23: Expanded stratigraphic column .....                                                                | 44 |
| Figure 24: Schematic cross section of a rhyolite lava flow .....                                              | 47 |
| Figure 25: Perlitic textures in the groundmass of rhyolite unit #2 .....                                      | 48 |
| Figure 26: Chemical Index of Alteration (CIA) and Loss on Ignition (LOI) .....                                | 52 |
| Figure 27: Comparison of zircon U–Th weighted mean ages from the Y-2 drill core .....                         | 54 |
| Figure 28: Reverse isochron plots for sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ analyses .....                 | 56 |
| Figure 29: Ba concentration (wt%) versus orthoclase content (Or mol%).....                                    | 57 |
| Figure 30: Whole rock trace element compositions of rhyolitic units from the Y-2 drill core .....             | 59 |
| Figure 31: Paleoreconstruction of Lower Geyser Basin during deposition of the ash beds .....                  | 62 |
| Figure 32: Paleoreconstruction of Lower Geyser Basin during recession of Bull Lake .....                      | 64 |
| Figure 33: Paleoreconstruction of Lower Geyser Basin during recession of Pinedale.....                        | 66 |
| Figure 34: U-series ( $^{234}\text{U}$ – $^{230}\text{Th}$ ) ages of travertine and calcite samples.....      | 67 |



# 1. INTRODUCTION

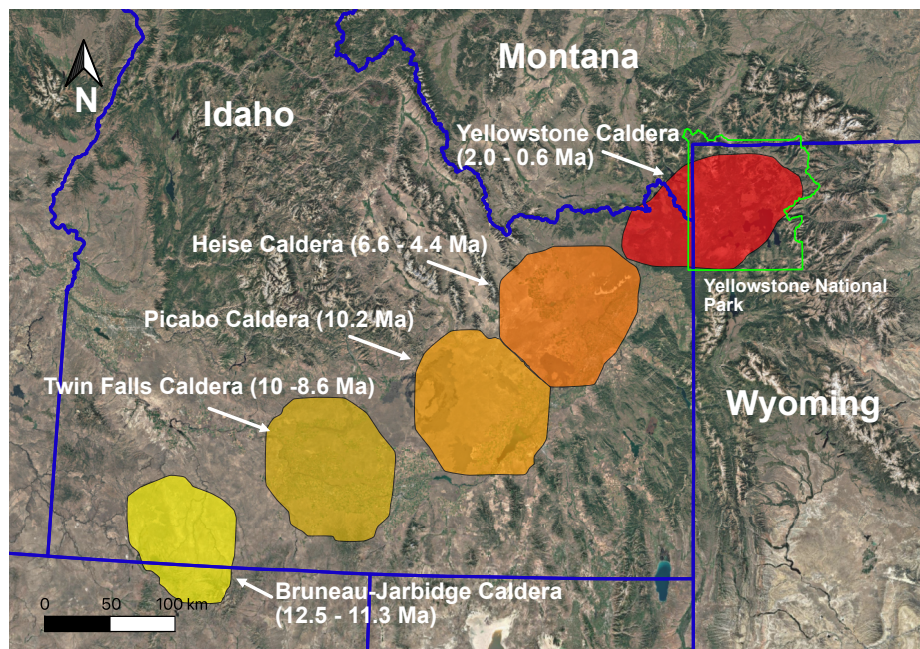
## 1.1 Introduction to Thesis

This study aims to refine the subsurface volcanic stratigraphy of the Yellowstone Plateau Volcanic Field (YPVF), where many volcanic units remain poorly constrained and difficult to correlate to the known eruptive units (Christiansen, 2001). The geologic history of the YPVF is complex and difficult to elucidate due to glacial deposits that obscure surficial geologic unit exposures and contacts, limiting the ability to reconstruct eruptive sequences from outcrop alone. Therefore, subsurface records preserved in drill cores provide an opportunity to better understand the timing and evolution of volcanic activity. In this study, rhyolitic units recovered from the Y-2 drill core in the Lower Geyser Basin (LGB) are investigated using geochronological, geochemical, and stratigraphic (core logging and lithological) approaches to evaluate their origins and relationships to established YPVF eruptive units. Additionally, volcanoclastic and sedimentary intervals are logged in detail for the first time, providing greater insight into the surficial evolution since the last caldera forming eruption and the sedimentary rocks which host one of the largest hydrothermal systems in the world.

## 1.2 Geologic Background

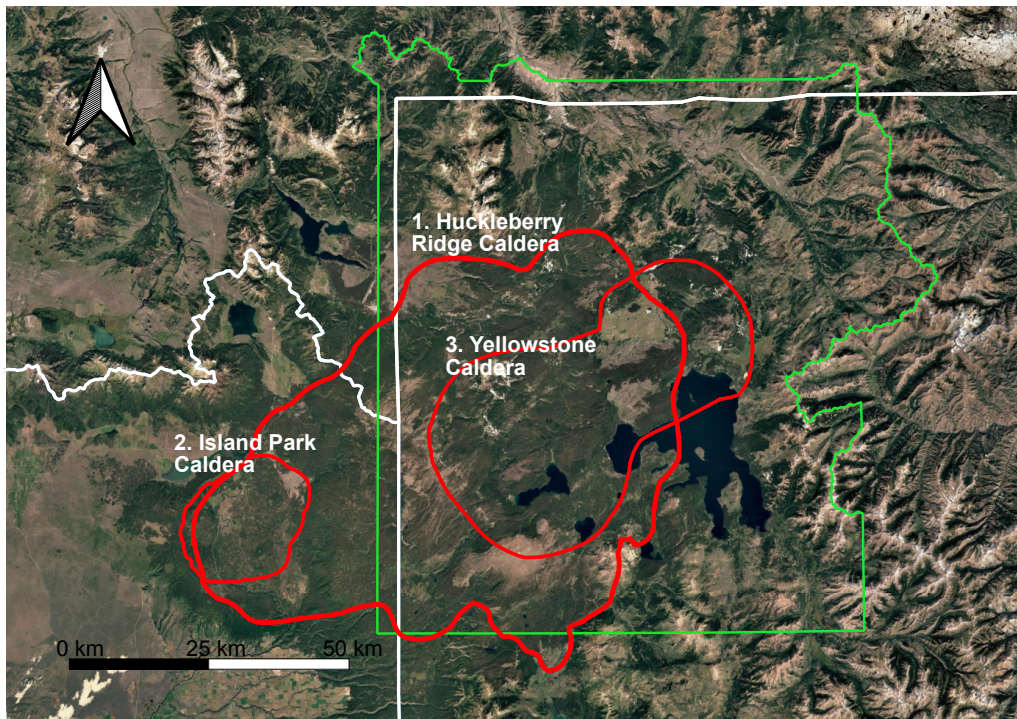
Yellowstone National Park is the location of a large, currently active, and complex volcanic system, making it both a globally recognized landmark and a premier site for geologic research. Volcanism originates from a continental hotspot, hereafter referred to as the Yellowstone hotspot, which is responsible for the current landscape and spectacular hydrothermal system (Pierce and Morgan, 1990, 2009). Volcanic activity associated with the Yellowstone hotspot started approximately 16 Ma at the junction of Nevada, Oregon, and Idaho

and has tracked east-northeast across ~400 miles to the present location beneath northwestern Wyoming and southern Montana (Pierce and Morgan, 1990, 2009; Christiansen, 2001). As the North American plate has moved west-southwest over the Yellowstone hotspot, the hotspot has erupted a series of silicious calderas that are now buried by voluminous basalts which comprise the Snake River Plain, with progressively younger volcanic rocks to the east (Figure 1) (Pierce and Morgan, 2009). Volcanism started ~2.1 Ma in its present location and this physiographic province is referred to as the Yellowstone Plateau Volcanic Field (YPVF). The YVPF is one of the largest silicic volcanic provinces in the world; it covers an area of ~6,500 km<sup>2</sup> and has erupted magma during repeated caldera cycles throughout the Quaternary. This volcanic field erupts bimodal basalt-rhyolite compositions, but 95% of the lava flows within the field are rhyolite (Christiansen, 2001).



*Figure 1: Regional map of calderas across the Snake River Plain modified from (Kumar 2017) showing past caldera centers as the North American Plate moved over the Yellowstone Hotspot Modified from (Kumar 2017)*

The Yellowstone Plateau Volcanic Field (YVPF) has had three major caldera cycles. Each of these cycles starts with pre-caldera effusive volcanism of high silica rhyolites and basalts, followed by an explosive large caldera-forming eruption that deposits thick ignimbrite sheets locally and disburse ash over large areas of the continental United States. The caldera-forming eruption is followed by smaller, post-caldera-forming eruptions of basalt and rhyolite (Christiansen, 2001). Outlines of the 3 caldera boundaries are show in Figure 2.



*Figure 2: Location map of the three caldera-forming eruptions of the Yellowstone Plateau Volcanic Field. The Huckleberry Ridge, Island Park, and Yellowstone calderas correspond to eruption of the Huckleberry Ridge Tuff, Mesa Falls Tuff, and Lava Creek Tuff, respectively.*

The caldera-forming eruption of the first cycle produced the Huckleberry Ridge Tuff at approximately  $2.059 \pm 0.004$  Ma (Lanphere et al., 2002). The second cycle, the smallest of Yellowstone's three major caldera forming events, culminated in the eruption of the Mesa Falls Tuff at  $1.285 \pm 0.004$  Ma (Christiansen, 2001; Lanphere et al., 2002). The third and most recent

cycle erupted the Lava Creek Tuff (LCT) at  $631.3 \pm 4.3$  ka (Matthews et al., 2015), which formed the present-day Yellowstone Caldera. Any eruptive events after the third caldera collapse are referred to as post-caldera rhyolitic volcanism or specifically, post-Lava Creek Tuff volcanism. These are the focus of this study. In the YPVF, post-LCT volcanism includes the Upper Basin Member (UBM) and Central Plateau Member (CPM) rhyolites.

### **1.3 Upper Basin Member vs Central Plateau Member**

After the collapse of the third caldera, a series of rhyolites erupted, beginning with the Upper Basin Member, composed of five rhyolite flows, and followed by the Central Plateau Member, containing at least 25 rhyolite flows. The post-LCT rhyolites are divided into these two members based on location, age, and composition; each member can be further divided into individual flows. The texture and composition of these two members are broadly similar, but diverge in eruption age, trace element geochemistry, and minor mineralogical differences. Both members are thought to be derived from crystal-rich, silicic-mush reservoirs that were incrementally remobilized through time (Girard and Stix, 2009, 2010; Stelten et al., 2023).

The Upper Basin Member rhyolites (UBM) erupted in two main episodes. The first was from  $516 \pm 7$  to  $473 \pm 9$  ka and the second began  $257 \pm 13$  ka (Gansecki et al., 1996; Girard and Stix, 2009; Till et al., 2019). Most Upper Basin Member rhyolites erupted along the margins of two resurgent domes within the  $\sim 631$ ka caldera, the Mallard Lake Dome to the west and the Sour Creek Dome to the east. UBM rhyolite flows include the Biscuit Basin flows (North, South, East, and Middle) and the Scaup Lake flow (Christiansen, 2001; Girard and Stix, 2009). These rhyolites are high silica (73–76 wt.%  $\text{SiO}_2$ ) and are interpreted as effusive (Smith and Bailey, 1968; Christiansen, 2001). The mineralogy is dominated by plagioclase but also contains sparse sanidine, quartz, and small amounts of pyroxene and Fe-Ti oxides. High concentrations ( $\sim 2300$

ppm) of Ba in plagioclase rims with low concentrations (~860 ppm) of Ba in the cores (Girard and Stix, 2009) are distinctive of UBM rhyolites and suggest that rejuvenation of the magma reservoir with a more primitive magma initiated the eruption of these flows. Other petrographic observations that are unique to the UBM rhyolites are the presence of sieved textures in plagioclase grains and polymineralic glomerocrysts of Fe-Ti Oxides and plagioclase.

The Central Plateau Member rhyolites (CPM) are the youngest post-collapse rhyolites of the third caldera cycle, erupting between 173 and 70 ka (Christiansen et al., 2007; Stelten et al., 2023). This member is comprised of at least 25 voluminous high-silica rhyolite lava flows originating from vents on two NNW lineaments likely aligned with preexisting regional faults (Christiansen, 2001; Girard and Stix, 2009). While most CPM flows are compositionally and texturally similar, several show evidence such as perlitic textures of interaction with surface water or ice during emplacement (Richmond, 1986; Christiansen, 2001; Bindeman and Lowenstern, 2016). Chemically, the CPM rhyolites are highly evolved, crystal-poor, and compositionally uniform high-silica rhyolites (76–78 wt.% SiO<sub>2</sub>). The dominant mineral phases are sanidine and quartz which appear in about equal modal percentages. They also contain clinopyroxene and sparse fayalite (Girard and Stix, 2010). A ubiquitous feature in all CPM and UBM rhyolites is the absence of biotite and hornblende (Christiansen, 2001).

Together, the UBM and CPM rhyolites represent temporally distinct stages of post-caldera volcanism separated by a period of quiescence ~97 ka long (Stelten et al., 2023). While both are derived from crystal-rich mush reservoirs, UBM units show greater geochemical and mineralogical heterogeneity, whereas CPM rhyolites are generally more compositionally uniform. These distinctions provide a framework for correlating rhyolitic units recovered in the Y-2 core with established post-LCT eruptive units.

## 1.4 Glacial history

Glaciation plays a major role in the geologic history of the YPVF and must be considered when interpreting subsurface core records. There has been many glaciations in the Pleistocene and Holocene. However, Two main episodes of glaciation are considered in this study, The Bull Lake (~150-140 ka) and the Pinedale (~22-16 ka). These have taken place during and after the emplacement of the post-LCT rhyolites: The Bull Lake and the Pinedale, which occurred from ~150-140 ka and from ~22-16 ka, respectively (Licciardi and Pierce, 2018). The modern landscape was shaped by these glaciations, which accomplished extensive erosion and left a thick mantle of glacial till and outwash burying exposures of many volcanic units. This drift infills the major geyser basins in the Park, including Lower Geyser Basin (LGB), obscuring the volcanic history of the basin. Additionally, younger glacial episodes tend to erase or overprint deposits from earlier glaciations, especially on the central Yellowstone Plateau where a ~1 km thick Pinedale Last Glacial Maximum (LGM) Pinedale ice sheet extensively redistributed pre-existing sediment (Licciardi and Pierce, 2018). Indeed, direct evidence for the presence of Bull Lake glaciers in the Yellowstone region is only from terminal moraines of some valley glaciers preserved where Bull Lake ice extended farther than Pinedale glaciers. At its maximum extent in the Pleistocene, the Greater Yellowstone Glacial System (GYGS) covered around 20,000 km<sup>2</sup>. Notably, there is overlap between post-LCT eruptions and glaciations (Christiansen, 2001; Bindeman and Lowenstern, 2016; Stelten et al., 2023). The greatest extent of overlap between glaciation and volcanism is during the Bull Lake glaciation, where some of the earlier CPM eruptions (Group 1:  $160.3 \pm 1.0$  ka and Group 2:  $149.8 \text{ ka} \pm 4.0$  ka; groups from Stelten et al., 2023) might have overlapped with this glacial period. Subsurface drill cores provide a unique



opportunity to investigate this poorly understood time in the YPVF eruptive and depositional history, especially the period before the LGM.

## **1.5 Geochronology**

Since publication of the YPVF geologic map (Christiansen, 2001), many studies have focused on providing high-precision geochronology of YVPF lava flows and ignimbrites, which is essential for reconstructing the evolution of the magmatic system, establishing the reoccurrence interval of post-caldera volcanism, and therefore, quantifying the ongoing volcanic hazard (White et al., 1975; Bargar and Beeson, 1981; Christiansen, 2001). The estimated age of an eruption dictates which geochronologic method is most appropriate. U-Th disequilibrium dating of zircon is effective for constraining Quaternary volcanism, whereas U-Pb geochronology is typically applied to eruptions older than ~350 ka (Dickin, 2018).  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology of minerals such as sanidine has also been widely used in Yellowstone because of its utility for dating eruptions spanning a broad age range, from tens of thousands to millions of years old (Dickin, 2018). However, all of the mentioned methods are subject to complexities that can complicate age interpretations. Zircon populations may contain inherited or antecrystic grains that predate eruption, while  $^{40}\text{Ar}/^{39}\text{Ar}$  ages can be influenced by excess argon, incomplete degassing at the time of eruption, or post-eruptive thermal histories. Nevertheless, geochronology, paired with other tools like petrography, whole rock chemistry, and mineral chemistry, is important for correlating unknown subsurface units with mapped surficial equivalents.

## **1.6 Research Focus and Objectives**

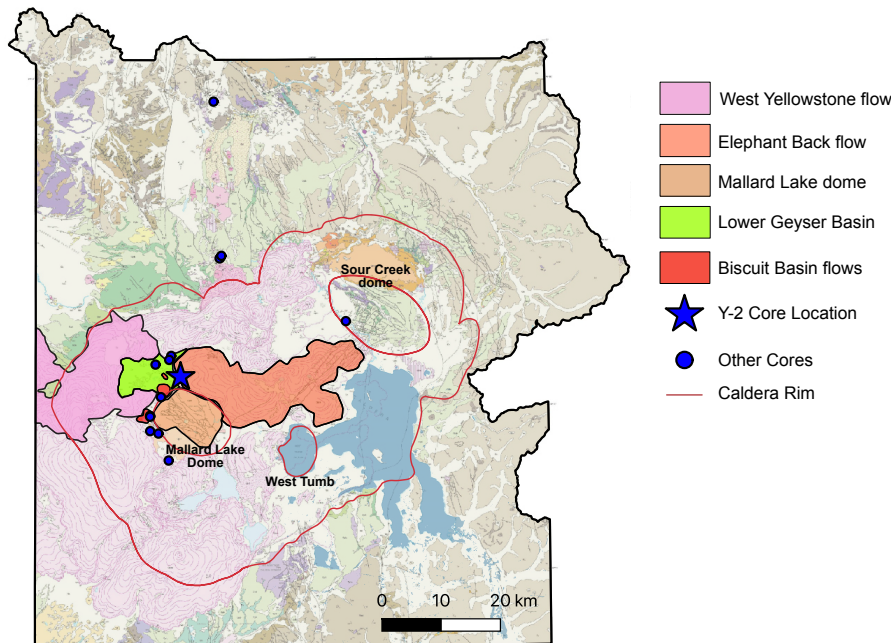
In the late 1960s, the U.S. Geological Survey drilled a series of continuous drill cores in the major geyser basins within Yellowstone National Park with the aim of studying hydrothermal

alteration and temperature gradients (White et al., 1975; Bargar and Beeson, 1981). Core Y-2 was drilled on the eastern edge of Lower Geyser Basin (LGB) about 134 meters east of Hot Lake in very close proximity to active hydrothermal features and a rare deposit of travertine located within the caldera (Harrison et al., 2024). The Y-2 core recovered 515.5 feet of material, revealing sequences of rhyolitic lava flows, volcaniclastic deposits, volcanic ashes, and glacial-fluvial deposits that offer insight into subsurface volcanic and sedimentary history within LGB. Drilling intersected a hot aquifer with temperatures of about 170° C, and a bottom hole temperature registered 203.1° C (Bargar and Beeson, 1981). Therefore, the core has been mildly to moderately hydrothermally altered, which must be taken into account when investigating the textures and chemistry of core samples (White et al., 1975; Bargar and Beeson, 1981; Christiansen, 2001). In the immediate area surrounding Y-2, there are deposits of glacial till and kame deposits and steep flow-fronts of the CPM Elephant Back ( $161.7 \pm 2.7$  ka; Stelten et al., 2023) and Nez Perce rhyolite flows ( $160.8 \pm 1.1$  ka; Stelten et al., 2023) (Waldrop and Pierce, 1975; Christiansen, 2001)

The original core log and stratigraphic interpretations were completed before the modern geologic map of the YVPF (Bargar and Beeson, 1981; Christiansen, 2001) shown in Figure 3 and before most modern geochronology studies of these units were published (Christiansen, 2001; Bindeman et al., 2001; Lanphere et al., 2002; Vazquez and Reid, 2002; Watts et al., 2012; Stelten et al., 2014a, 2023; Till et al., 2015, 2019; Matthews et al., 2015). Because the primary objective of the original study by Bargar and Beeson (1981) was to characterize hydrothermal alteration mineralogy, only a generalized stratigraphy was logged. Rhyolite flows were identified based on location and visual textures rather than geochemical or geochronological data, leading to potential misidentification of flows or volcanic stratigraphy. The generalized stratigraphy noted



the presence of pumice and tuffaceous units but did not differentiate or interpret them further. Furthermore, the sedimentary sections of the core were not logged for variations in grain size, sedimentary structures, or interpreted for sedimentary facies. This is a conspicuous omission considering these units host one of the largest hydrothermal systems in the world and are a rare record of paleoclimate and morphological conditions on the pre-LGM Yellowstone plateau. This highlights the need to investigate these cores with the benefit of modern methods and context. A thorough analysis will enhance our understanding of the YVPF's most recent eruptive events and how the surficial climate, environment, and geomorphology varied through time.



*Figure 3: Geologic Map of Yellowstone National Park with locations of USGS drill cores (modified from Christensen 2001). Core Y-2 is highlighted in the Lower Geyser Basin and lies near the Mallard Lake Flow, Elephant Back Flow, West Yellowstone Flow, and the Biscuit Basin flows.*

Specifically, this study aims 1.) refine the stratigraphic interpretation of the Y-2 core by integrating multiple data sets. 2.) refine the volcanic stratigraphy by identifying Central Plateau

Member (CPM) and Upper Basin Member (UBM) rhyolites in the core and linking these units to surficial equivalents. 3.) The recovery of approximately ~110 feet of glacial and sedimentary deposits provides an opportunity to investigate the paleoenvironmental conditions of the region during a time interval that is relatively poorly constrained. These deposits include interpreted primary or near primary ash beds interbedded between deposits, which offer potential chronostratigraphic markers.

## 2. METHODS

### 2.1 Core logging and sampling

Core logging was conducted at the U.S. Geological Survey Core Research Center (CRC) in Lakewood, Colorado, where several archived drill cores from the YPVF were examined and described. This study focuses on the core Y-2, where volcanic and sedimentary units were described in detail. In volcanic units, phenocryst content and composition, vesicularity, spherulitic textures, and zones of devitrification were noted and volcanic flow contacts were interpreted based on physical features such as the presence of lava flow autobreccia. The sedimentary section was described for the first time in detail based on composition, grain size, sorting, grading, color and sedimentary structures. Stratigraphic units were identified and depositional environments were interpreted for each bed. Each core interval was photographed, measured, and digitized into a stratigraphic column that is the foundation for lithologic interpretation of subsurface volcanic and sedimentary units. A total of 30 representative samples were taken from the core of both volcanic and sedimentary lithologies and select samples were analyzed for petrography, whole rock geochemistry, geochronology, and in-situ mineral chemistry. The methods of these analyses are outlined in the subsections that follow.

### 2.2 Thin section petrography

Representative samples were cut into billets approximately 2-3 cm thick and were made into thin sections by Wagner Petrographic. Each billet face was polished and mounted to a glass slide using epoxy, then was ground to a standard thickness of around 30 microns. Each thin section was polished smooth using a progressively finer grit until the surface was free of

scratches and was optically smooth for use in electron microscopy. Thin sections were then described and characterized using a petrographic microscope.

Minerals and volcanic textures were identified in volcanic units, which guided in-situ electron microprobe analysis. In sedimentary units, angularity, sorting, and grain size were characterized. These descriptions aided in discriminating between primary ashes and fluvial sediments.

## **2.3 Whole Rock Geochemistry**

After billets were prepared for thin sections, the remaining material was cut and weighed into 3.5 to 4 gram pieces and sent to the Washington State University GeoAnalytical Lab. Here samples were prepared for X-ray fluorescence (XRF) and inductively coupled mass spectrometry (ICP-MS) analysis to determine major, minor, and trace element concentrations. Methods for these analyses can be found on the WSU GeoAnalytical lab's website here:

(<https://environment.wsu.edu/facilities-labs/geoanalytical-lab/>). Each sample was ground in a tungsten carbide (WC) mill which marginally contaminates samples with W, Co, and Ni.

### ***2.3.1 X-Ray Fluorescence (XRF)***

Part of each sample was crushed into a very fine powder and weighed with di-lithium tetraborate flux 2:1 (flux:rock) before fusion in a muffle oven at 1000°C into glass beads. The samples were then polished on a diamond lap to make a smooth surface for analysis. Ten major and minor elements and 20 trace elements were analyzed using a ThermoARL Advant'XP+ sequential X-ray fluorescence spectrometer. Geologic standards AGV-2, CRM-1, BCR-2, CRM-2, GSP-2, CRM-3 were used for instrument calibration and quality control assessment of analytical accuracy and precision. Loss on ignition (LOI) values were determined on all samples

and reported by the analytical laboratory. LOI measures the mass loss when the sample is heated to extreme temperatures (950-1100°C) and is an indicator of volatile and water content.

### *2.3.2 Inductively coupled mass spectrometry (ICP-MS)*

Trace element concentrations were measured on an Agilent 7700 ICP-MS quadrupole inductively coupled mass spectrometry (ICP-MS). Geologic reference material BHVO-2 and BCR-2 were analyzed as internal standards for calibration and quality control procedures.

## **2.4 Mineral Separation**

Intervals of primary igneous deposits from four depths (ash, rhyolite breccias and flows) (501.5, 415, 254, and 151 ft) were targeted for geochronology on zircon and sanidine. The samples were crushed using a jaw crusher into a coarse crush composed of >800 µm grain sizes. From the coarse crush, sanidine grains were picked for  $^{40}\text{Ar}/^{39}\text{Ar}$  analysis. The remaining sample was crushed to a grain size of <250 µm for zircon separation (fine crush). The fine crush was washed to remove fine grained, light sediment. Zircons were separated from the rest of heavy grains by density using methylene iodide (MEI) that has a specific gravity of ~3.3. Both the separated zircons and sanidine grains were acid leached to remove adhering glass that would interfere with the analysis, following the method of Stelten et al. (2014). In brief, mineral grains were immersed in concentrated hydrofluoric acid (HF) and sonicated for 3 minutes. The sample was then rinsed using ultra-pure water three times and placed under a heat lamp to dry. Final grains were hand-picked under a binocular microscopic, prioritizing grains that were euhedral, unbroken, and free of adhering glass.

## 2.5 Geochronology

Geochronology provides the temporal framework necessary to interpret subsurface stratigraphy in the Y-2 drill core. Two geochronology systems were chosen, U-series ( $^{230}\text{Th}/^{238}\text{U}$ ) disequilibrium geochronology in zircons and total fusion  $^{40}\text{Ar}/^{39}\text{Ar}$  in sanidine; both zircon and sanidine are present in most Yellowstone post-LCT caldera rhyolites.

Obtaining eruption ages of rhyolitic eruptive materials in hydrothermally altered rocks is non-trivial. Zircons are very resistant to alteration, but they can also record a magmatic history of crystallization that started long before eruption. In past geochronology studies of Yellowstone rhyolites, the rims of zircon grains have been shown to more closely agree with sanidine  $^{40}\text{Ar}/^{39}\text{Ar}$  ages, suggesting that the outermost zircon growth (the rim) crystalized shortly before eruption (Watts et al., 2012; Stelten et al., 2014). Therefore, in this study the unpolished rims of zircon grains were targeted to best constrain the age of the youngest zircon growth immediately preceding eruption.  $^{40}\text{Ar}/^{39}\text{Ar}$  in sanidine is better suited to constrain eruption age directly, so by integrating the two age-data sets, interpretations can be drawn to the eruptive history of the Y-2 core.

### 2.5.1 $^{230}\text{Th}/^{238}\text{U}$ Zircon Geochronology

$^{230}\text{Th}/^{238}\text{U}$  disequilibrium analyses were completed using a secondary ion mass spectrometry (SIMS), at the USGS-Stanford Sensitive High-Resolution Ion Microprobe–Reverse Geometry (SHRIMP-RG). Zircon separates were mounted in indium and washed using a series of industrial cleaners and hydrochloric acid (HCl) to ensure no organic material remained on samples. Mounts were coated in gold before being loaded into the SHRIMP-RG. One spot was measured on each of 134 zircon grains, from 7 rhyolite samples in the Y-2 core, using an  $\text{O}_2^-$  primary beam with a beam current of 13-14 nA focused to a  $\sim 50\text{ }\mu\text{m}$  diameter beam size. The

primary oxygen ion beam ablates the surface of the zircon to produce secondary ions of U, Th, and oxide species that were used to calculate corrected activity ratios of  $^{230}\text{Th}/^{232}\text{Th}$  and  $^{238}\text{U}/^{232}\text{Th}$  for each zircon grain.

Single-grain model ages were calculated from corrected activity ratios using Equation 1. Where  $t$  is the model age,  $\lambda$  is the decay constant for  $^{230}\text{Th}$  (Steiger and Jager, 1977),  $(^{230}\text{Th}/^{232}\text{Th})$  and  $(^{238}\text{U}/^{232}\text{Th})$  are the corrected activity ratios, and  $(^{230}\text{Th}/^{232}\text{Th})_0$  is the initial  $^{230}\text{Th}$  component, assumed to be negligible ( $=0$ ) at the time of crystallization.

Equation 1

$$\left(\frac{^{230}\text{Th}}{^{232}\text{Th}}\right) = \left(\frac{^{230}\text{Th}}{^{232}\text{Th}}\right)_0 + \left(\frac{^{238}\text{U}}{^{232}\text{Th}}\right)(1 - e^{-\lambda_{230}t})$$

The individual grain model ages and associated uncertainties for each zircon were calculated using IsoplotR, an open source R package for geochronology (Vermeesch, 2018). Zircon analyses that failed to yield valid ages, approached secular equilibrium from age calculations, or produced geologically implausible ages inconsistent with Yellowstone volcanic history were excluded from weighted mean calculations and corresponding MSWD values.

### 2.5.2 $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine geochronology

Sanidine separated from the coarse crush fraction ( $>800\text{ }\mu\text{m}$ ) of three Y-2 core samples (501.5, 415, 254 ft) were irradiated to convert  $^{39}\text{K}$  to  $^{39}\text{Ar}$  through neutron capture, enabling the analysis of both the parent ( $^{40}\text{K}$ ) and daughter ( $^{40}\text{Ar}$ ) isotopes in the same sample and analysis. Total fusion analyses were performed at the U.S. Geological Survey Volcano Science Center Argon Geochronology Lab in Moffett Field, CA using a laser heating system, releasing all argon isotopes from each grain in a single heating step. The isotopes were measured on a Isotopx

NGX-600 mass spectrometer and ages were calculated on each grain using the standard age equation (Equation 2) (Dickin, 2018).

Equation 2

$$t = \frac{1}{\lambda} \ln (1 + J(^{40}\text{Ar}^*/^{39}\text{Ar}))$$

Where  $\lambda$  is the decay constant of  $^{40}\text{K}$  (Steiger and Jager, 1977),  $J$  is the irradiation parameter determined relative to neutron flux monitors, and  $^{40}\text{Ar}^*/^{39}\text{Ar}$  represents the ratio of radiogenic argon to potassium derived argon. For these analyses, ages were calibrated relative to the Bodie Hills sanidine ( $9.7946 \pm 0.0031$  Ma; Fleck et al., 2019). Weighted mean  $^{40}\text{Ar}/^{39}\text{Ar}$  ages from individual sanidine grains were used as the reported age in this thesis. Inverse isochron regressions were evaluated for each sample to assess argon systematics through determination of initial  $^{36}\text{Ar}/^{40}\text{Ar}$  ratios and comparison with the atmospheric ratio of 295.5 (Lee et al., 2006; Dickin, 2018). This approach allowed for evaluation of potential excess argon, inherited argon, or argon loss within sanidine populations. No samples in this study showed signs of these processes. Although inverse isochron regressions also yield independent age estimates, they were used in this thesis primarily as a validation tool for argon system behavior rather than the principal reported eruption ages.

### *2.5.3 Statistical analysis and data reduction*

For this study, weighted mean ages (Equation 3) and mean square of weighted deviates (MSWD) values (Equation 4) for both U-Th zircon data and  $^{40}\text{Ar}/^{39}\text{Ar}$  sanidine grains were determined following (Ludwig, 2003).



Equation 3

$$\bar{t} = \frac{\sum_{i=1}^n \frac{t_i}{\sigma_i^2}}{\sum_{i=1}^n \frac{1}{\sigma_i^2}}$$

Equation 4

$$MSWD = \frac{1}{n-1} \sum_{i=1}^n \frac{(t_i - \bar{t})^2}{\sigma_i^2}$$

Where  $\bar{t}$  is the weighted mean,  $t_i$  is the individual grain age,  $\sigma_i$  is the associated analytical uncertainty, and  $n$  is the number of analyses. Weighted mean ages were determined using inverse-variance weighting so that grains with smaller uncertainty contributed more weight in the reported mean age calculated. All reported uncertainties are presented at the  $2\sigma$  confidence level unless otherwise specified.

#### *2.5.4 U-series Geochronology of Hydrothermal Deposits*

Travertine and calcite were collected from hydrothermal deposits within the upper portion of the Y-2 drill core. Small aliquots (40–150 mg) were excavated from individual layers using a Dremel hand held drill under a binocular microscope while avoiding areas of visible alteration and detrital contamination.

U-series geochronology was conducted at the U.S. Geological Survey Denver Radiogenic Isotope Laboratory. Approximately 20–40 mg aliquots were spiked with a high-purity  $^{233}\text{U}$ – $^{236}\text{U}$ – $^{229}\text{Th}$  tracer solution prior to digestion in ultra-pure acids. Uranium and thorium were separated using ion-exchange chromatography with Bio-Rad AG1×8 anion resin and analyzed on a Thermo-Finnigan Triton multicollector thermal ionization mass spectrometer (TIMS). Analytical

procedures, standards, and reference materials follow those described by Paces et al. (2022) and Harrison et al. (2023). Ages were calculated using  $^{234}\text{U}$ – $^{230}\text{Th}$  disequilibrium geochronology.

## 2.6 Electron Microprobe Analysis

Seven samples from volcanic units at depths (501.5, 415, 395, 254, and 151 ft) were analyzed for feldspar chemistry on a JEOL JXAiHP200F Field Emission Electron Probe Microanalyzer (EPMA) at Colorado State University for in-situ analysis on polished thin sections. Specifically, sanidine was targeted in order to compare to available published EPMA data (Till et al., 2019) and utilize mineral chemistry to identify flows. In samples where sanidine was absent, plagioclase was analyzed with the same analytical conditions. Elements analyzed including count times, crystal and spectrometer assignments are listed in Table 1.

A large beam size of 10  $\mu\text{m}$  was selected to minimize alkali migration and time-dependent intensity (TDI) effects while maintaining sufficient count rates, to result in more accurate analyses of trace elements like Ba. Repeated analyses at the beginning and end of each analytical session of Smithsonian reference materials MAC Sanidine and NMNH Plagioclase were used to assess instrument accuracy. All standard analyses were within the accepted tolerance of 2% variance on major elements (element concentrations > 5%), 5% variance for minor elements (element concentrations 1% - 5%), and 20% variance for trace elements (element concentrations < 1%).

*Table 1: Analytical conditions for sanidine and plagioclase EPMA analyses, showing elements analyzed with their count times in seconds, crystal and spectrometer assignments, accelerating voltage, beam current, and beam size.*

| Phase analyzed | Spectrometers |         |          |          |          | Accelerating Voltage (kV) | Beam Current (nA) | Beam Size ( $\mu\text{m}$ ) |
|----------------|---------------|---------|----------|----------|----------|---------------------------|-------------------|-----------------------------|
|                | 1 – TAP       | 2 - TAP | 3 – PETJ | 4 – LiFL | 5 – PETJ |                           |                   |                             |

|             |         |         |         |         |         |    |    |    |
|-------------|---------|---------|---------|---------|---------|----|----|----|
| Sanidine    | Si (30) | Na (40) | K (60)  | Fe (60) | Ba (60) | 20 | 15 | 10 |
| Plagioclase | Mg (60) | Al (30) | Ca (40) | Mn (60) | Sr (60) |    |    |    |

## 3. RESULTS

### 3.1 Core Logging Results

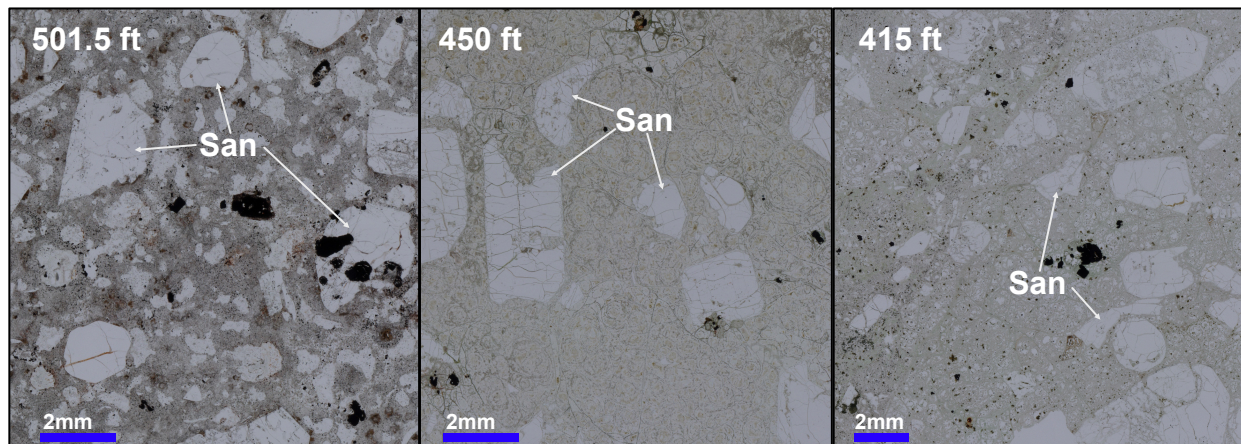
Observations from the Y-2 core at the U.S. Geological Survey Core Research Center in Lakewood, Colorado provide insight into subsurface volcanic and sedimentary units within the YPVF. The Y-2 core recovered a total of 515.5 ft (160.3 m) of material. Descriptions below are presented from the bottom of the core upward (Figures 21, 22, and 23).

#### *3.1.1 Volcanic Units (515.5 - 110 ft)*

##### *Rhyolite Unit #1 (515.9 to 403 ft)*

From 515.9 - 403 ft, the core consists of a single, crystal-rich, rhyolite flow. This unit is autobrecciated at the base (515.9 - 456 ft) before transitioning into the stony crystalline core of the flow (456 - 403 ft). Vesiculation starts at ~417 ft and becomes more concentrated towards the top of the unit as the lithology transitions gradationally into a more pumice-rich texture. No sharp contact is observed between the stony rhyolite and pumice-rich rhyolite. Perlitic textures are present in the groundmass beginning at approximately 460 ft and continue upward to the top of the unit. Samples collected from this interval at 501.5 and 415 ft were analyzed for geochronology and whole rock geochemistry. Zircon U–Th ages from this unit are ~220 ka, whereas  $^{40}\text{Ar}/^{39}\text{Ar}$  ages from sanidine yield significantly older values of ~633 - 640 ka. Thin sections from this interval at 501.5, 450, and 415 ft are dominated by fractured sanidine phenocrysts within a pervasively altered microcrystalline groundmass (Figure 4). Sanidine crystals are typically subhedral and commonly display resorbed cores and inclusions of opaque oxides. Sparse plagioclase phenocrysts are also present and are commonly fractured and fragmented. Quartz phenocrysts are comparatively rare and typically rounded and anhedral.

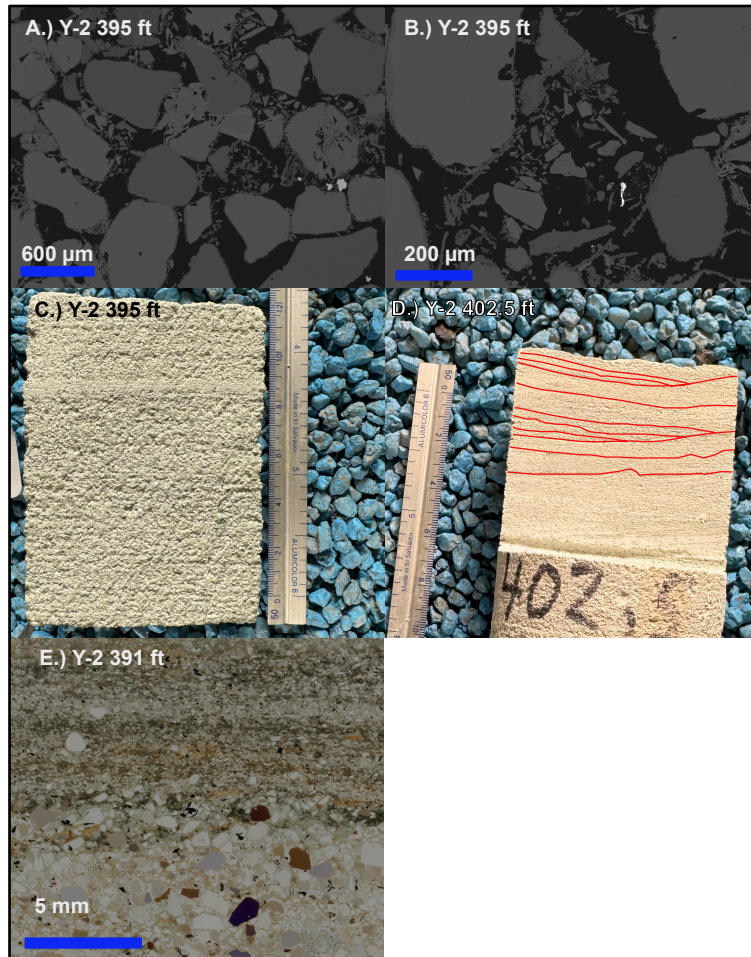
Groundmass alteration is particularly pronounced in sample 501.5 ft, whereas samples from 450 ft and 415 ft preserve well developed perlitic textures.



*Figure 4: Thin section photos (PPL) from each sample taken in Rhyolite unit #1. 501.5: altered ground mass and fractured sanidine grains. 450 ft: Fractured sanidine with perlite texture in the glass. 415 ft: Fractured sanidine grains with a more altered perlite glass, and a higher abundance of opaque oxides than sample 450 ft.*

#### *Volcaniclastic Sandstone (403 to 388.1 ft)*

The contact between Rhyolite Unit #1 and the overlying volcaniclastic sandstone is sharp and occurs at a depth of 403 ft. This unit exhibits two upward coarsening sequences from 403 - 391 ft and a finer-grained sandstone sequence between 391 and 388.1 ft. Sedimentary structures are mostly planar beds, but there is a cross-bedded interval in the first 15 cm of this interval. Thin sections of sandstone from 395 ft and 391 ft depths show rounded, poorly sorted grains of mostly quartz and sanidine with minor plagioclase, surrounded by population of a smaller, poorly sorted, subangular grains in the interstitial space (Figure 5). A sample was collected at 395 ft for geochronology to assess its temporal relationship with the overlying and underlying units and yielded a weighted mean zircon U–Th age of ~219 ka, within error of the age of Rhyolite Unit #1.



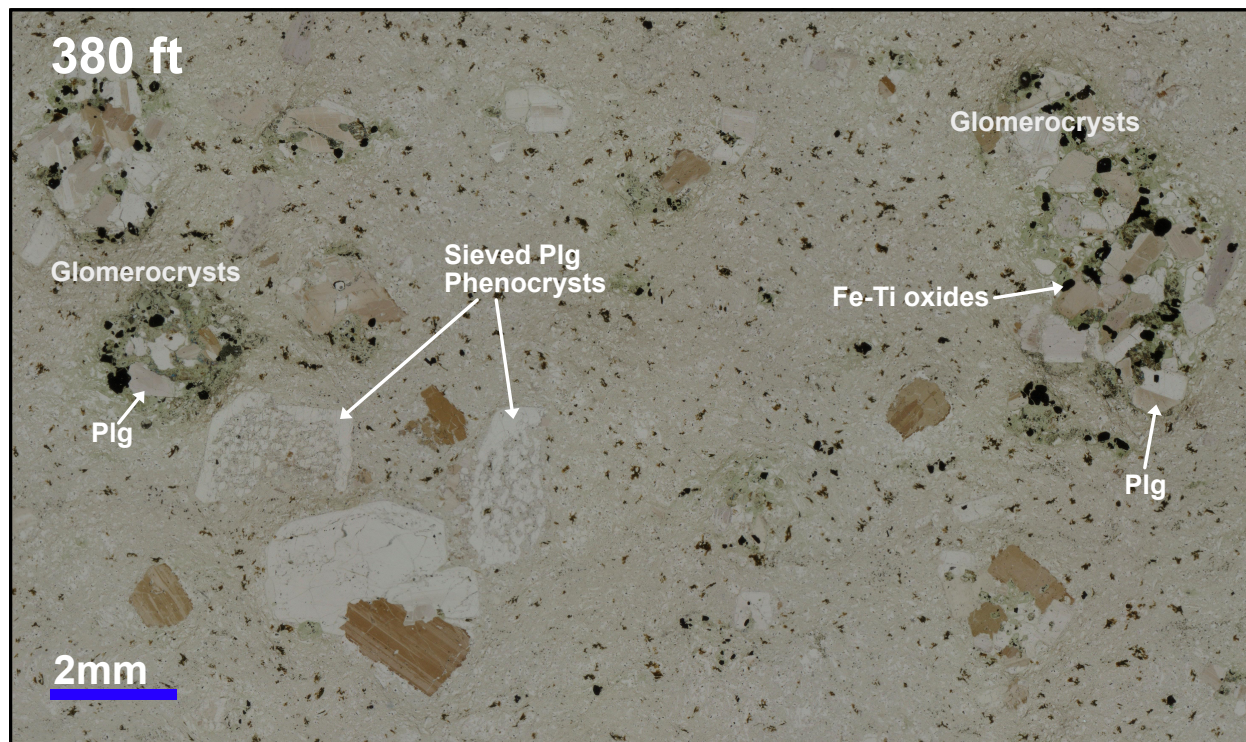
*Figure 5: A)/B) Sample depth 395 ft: SEM images of rounded larger grain size of 0.6mm and 0.4 mm with smaller more angular interstitial grains. C.) Planar bedding features dominate a majority of this unit. D) 402.5 ft: Outline of cross bedding present in the lowermost portion of the core. E) 391 ft: Thin section image (XPL) showing the contact between two coarsening upward sequences in this interval.*

#### *Pumice Unit #1 (388.1 to 373 ft)*

The interval from 388.8–373 ft is a heavily altered green pumice with glass altered to hydrothermal opal. The contact with the underlying unit is sharp and wavy. This unit is crystal-poor relative to the pumice-rich top of Rhyolite Unit #1. Pumice Unit #1 contains abundant oxide phases, and plagioclase occurs as large sieved-textured phenocrysts and as glomerocrysts with Fe-

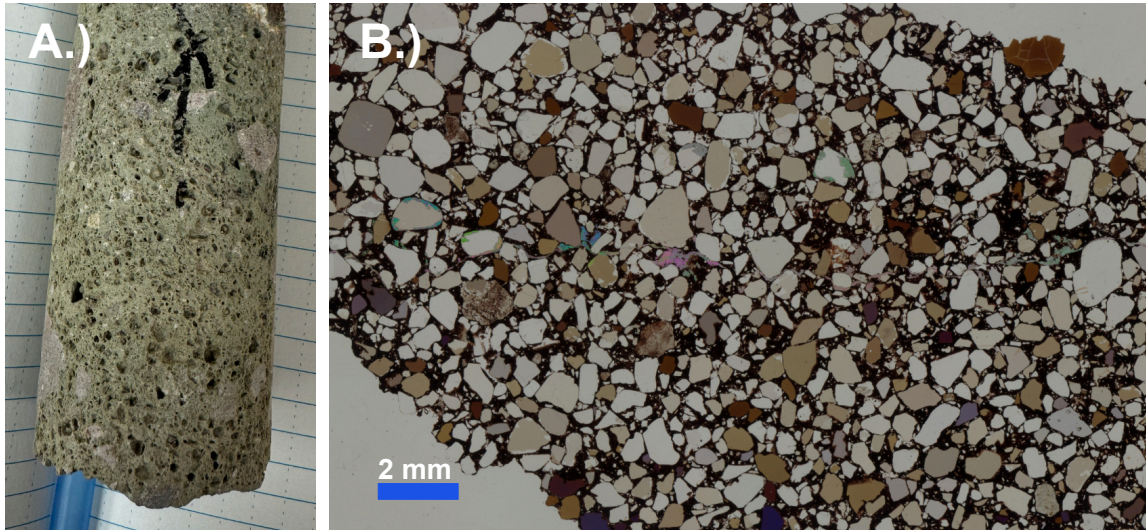


Ti oxides. Notably, sanidine is absent (Figure 6). The groundmass is pervasively altered into hydrothermal opal and many original textures are not preserved.



*Figure 6: Thin section photo (XPL) of 380 ft depth. Sieved plagioclase phenocrysts show a honeycomb like texture in the center of the phenocryst surrounding by a new rim growth. Polymineralic glomerocrysts are present that contain grains of plagioclase and Fe-Ti oxides.*  
*Sedimentary Breccia #2 (373–364 ft)*

From approximately 373 - 364 ft is an altered sedimentary breccia. The interval is poorly sorted, fines upward (normal grading), and has no apparent bedding or sedimentary structures, with 20-70 mm clasts of rhyolite suspended within the sand matrix. Thin section observations from 373.5 ft show the matrix is dominated by ~1mm grains, with a wide range of grain compositions that include sanidine, quartz, sparse plagioclase, and rhyolitic fragments. The rhyolitic clasts show perlitic textures and flow banding (Figure 7). The combination of normal grading, poor sorting, matrix-supported angular clasts, and a fragmental crystal-rich matrix supports an interpretation as a sedimentary unit rather than an auto breccia.



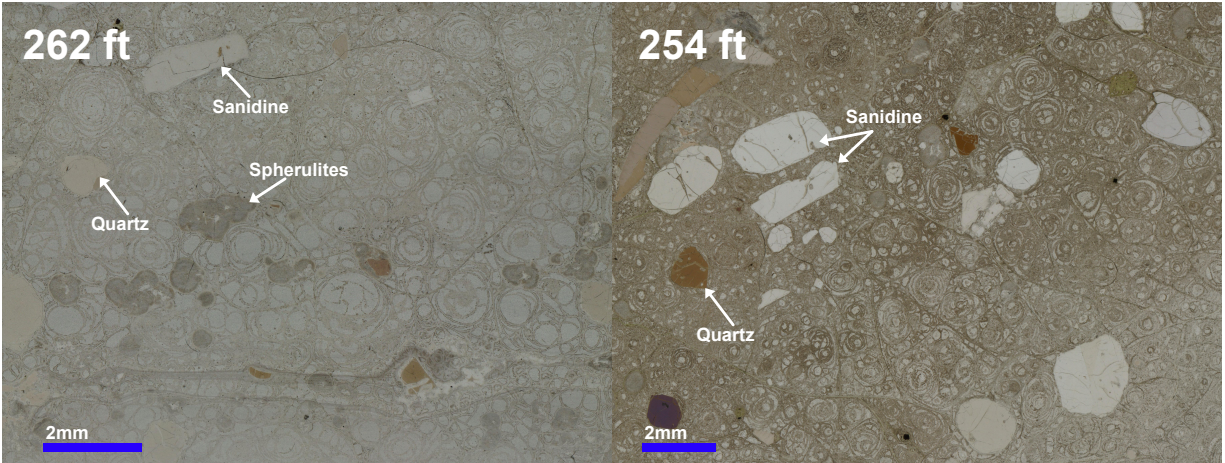
*Figure 7: A.) Altered sedimentary breccia that indicates a break in volcanic activity. Void spaces in the matrix are likely where some grains have been plucked out during drilling or dissolved during alteration. Centimeter sized rhyolite clasts are dispersed in this matrix. B.) Thin section photo (XPL) of 373.3 ft rounded poorly sorted grains of quartz, sanidine, lithics, and minor plagioclase.*

#### *Rhyolite Unit #2 (364 – 220 ft)*

The unit that begins at approximately 364 ft is a rhyolite flow with an autobrecciated basal contact from 364 – 328 ft. The stony core of the flow extends from 328 - ~220 ft where the top part of the flow has likely been removed by erosion. Clasts within this unit are composed of rhyolite with variable textures, including perlitic and flow-banded features. Vesiculation is common and alteration is pervasive.

Thin sections from this unit at 262 and 254 ft exhibit similar petrographic characteristics. Phenocrysts are sparse and consist primarily of quartz and sanidine in roughly equal proportions, while plagioclase was not observed (Figure 8). Spherulites are present throughout the interval and occur as fibrous radiating structures within the groundmass. Perlite texture is present in both thin sections.





*Figure 8: Thin section photos of Rhyolite Unit #2 of sample depths (262, and 254 ft) showing sanidine grains. Groundmass is composed of perlite textured glass which is common throughout this unit.*

#### *Rhyolite Unit #3 (220 – 120 ft)*

This unit consists of a basal autobreccia extending from 220 to 208 ft that grades upward into a coherent stony rhyolite. The top portion of the flow is not preserved and is interpreted to have been removed by erosion. Two thin sections were collected from the stony core at depths of 151 and 136.5 ft. Relative to Rhyolite Unit #2, this unit contains a higher abundance of vesicles and lacks pervasive perlitic textures within the groundmass. Phenocrysts consist primarily of sanidine and quartz, with sparse opaque oxide minerals. The contact between this unit and the underlying Rhyolite unit #2 is not directly observed and is interpreted to occur within an interval of missing core.

#### *3.1.2 Sedimentary Units (110 - 0 ft)*

The remainder of the core is composed of sedimentary units characterized by fine grained clastic material. A complete stratigraphic column of this upper sedimentary sequence is shown in Figure 22. This upper interval is broadly sandstones, siltstones, conglomerates, and sinter

interbedded with travertine. Interspersed through these sections are beds of primary ash and secondary volcaniclastic material, which provides temporal constraints of timing of deposition.

#### *Laminated Sandstones and Siltstones #1 (111.1-93 ft)*

This unit extends from 111.1 - 93 ft and consists of laminated and interbedded siltstone to medium-coarse sandstone. Sedimentary structures are well developed throughout the interval as planar beds and wavy laminations range from the sub-millimeter up to 2 millimeter scale. The texture from bed to bed varies slightly but alternates between coarse-sand and silt.

Three thin sections were prepared from this interval at 103.5 ft and 96 ft. The thin section at 103.5 ft contains banding on the millimeter scale of alternating red and white layers. Grain size within these bands alternates from very fine sand to silt (Figure 10). SEM analysis reveals elongate, angular, shard-like grains that are poorly sorted in the white laminations. These grains appear as void space (show up black on SEM images) (Figure 9) and are interpreted to be the skeletal remains of glass shards that have dissolved away from hydrothermal alteration.

The thin section at 96 ft exhibits similar laminations but without the red alternating color change like the deeper interval (Fig. 10B vs 10A). The grain size difference between laminations is smaller, but it is apparent from slight tan color changes between laminations and SEM images that show grain size variations is also present between the mentioned colors. The coarse grained laminations also show the ash shards are present in the coarser beds. Many of the same observations present in sample 103.5 are present in 96.5 ft with the exception of more lithics and larger crystal grains that are shown in figure 10B.

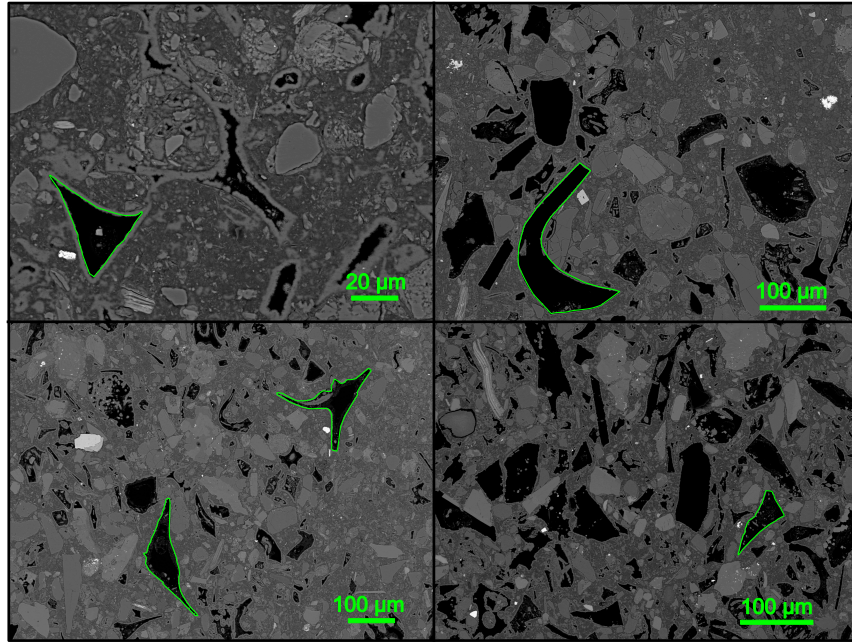


Figure 9: SEM images from the 106.5 ft interval within Laminated Sandstones and Siltstones #1. The images show intensely angular grains, including Y-shaped and U-shaped morphologies. These features are reminiscent of vesicle wall fragments produced during explosive fragmentation of volcanic glass.

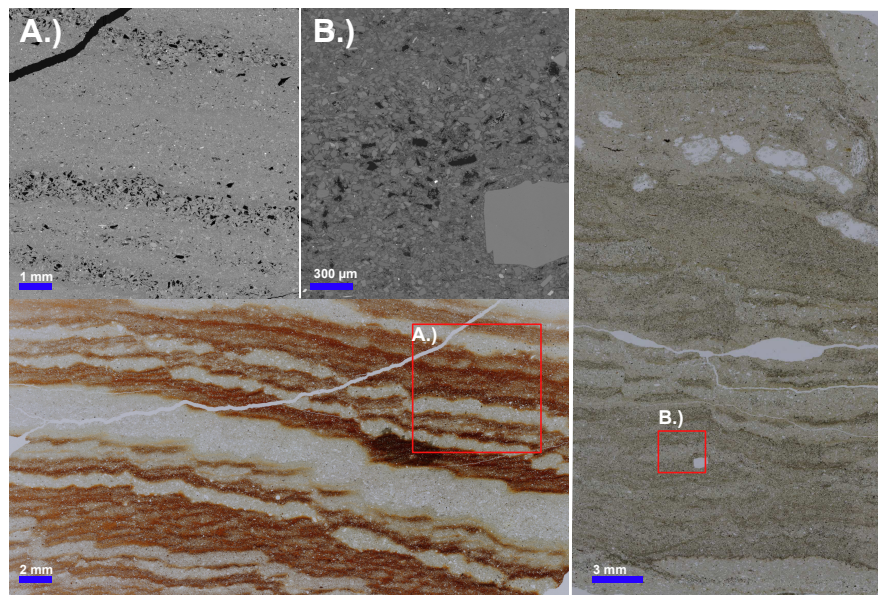


Figure 10: Thin section photomicrographs of Laminated Sandstones and Siltstones #1 with corresponding SEM insets. (A) Sample 103.5 ft showing millimeter-scale laminations and alternating grain-size populations. The SEM inset highlights bedded concentrations of angular

*grains and skeletal grain remnants. (B) Sample 96.5 ft exhibiting similar laminated textures. The SEM inset shows the layered distribution of angular grains and skeletal grain remnants within the sedimentary fabric.*

*Fluvial Gravel #1 (93 – 79.5 ft)*

The sedimentary unit from 93 – 79.5 ft is a lithified conglomerate of gravel sized clasts. The lower portion of this interval (93–88 ft) consists of a light gray, massive, clast supported pebble gravel composed of subangular to subrounded clasts ranging from 1 - 3 cm in diameter. From 88 - 87.5 ft, the gravel is overlain by a highly altered, friable ash-rich interval containing abundant pumice clasts. Core recovery within the ash rich intervals was poor, and recovered material consists primarily of loose chippings rather than intact core.

The overlying interval from 87.5 - 83 ft consists of the same-texture gravel as below, with subangular to subrounded clasts 1 - 3 cm in diameter. Beds of a medium grained sandstone occur locally within the gravel and exhibit parallel lamination. The uppermost portion of the unit from 83 - 79.5 ft consists of an additional interval of highly altered ash and pumice similar to that observed between 88 and 87.5 ft. Samples of the ash and pumice rich intervals were taken for radiometric dating to constrain deposition age; however, no zircons or sanidine were recovered from these samples. Additionally, thin section were not possible from these ash and pumice intervals due to their friable nature.

*Diatomaceous silt (79.5 – 64.5 ft)*

The interval from 79.5 – 64.5 ft is white, altered, friable silt. Primary sedimentary structures are not preserved. Core recovery was so poor that most of the material was contained within sample bags inside the core boxes. Based on lithological characteristics and this unit is correlated with the mapped “Diatomaceous silt” deposits of the Lower Geyser Basin (Muffler et al., 1982), this interval is interpreted as diatomaceous silt.

### *Fluvial Gravel #2 (64.5 – 34.5 ft)*

This interval is composed of well cemented conglomerate with poorly sorted, subangular to subrounded clasts. Most clasts are granules and small pebbles up to 6mm and a few clasts are up to 7 cm in size, generally larger than those observed in Glaciofluvial Gravel #1. The interval contains multiple thick beds ranging from approximately 5 - 15 ft in thickness with thin interbeds of sandstone that exhibit planar bedding.

### *Paleosols (34.5 – 29.7 ft)*

The unit from 34.5 to 29.7 ft is characterized by sand and silt that is pedogenically altered and mottled with horizons containing abundant root traces and possible insect burrows. This unit is partially cemented and locally replaced by travertine, indicating post depositional hydrothermal alteration.

### *Sinter and Travertine (29.7 – 0 ft)*

The uppermost 29.7 ft of the core contains hydrothermal deposits composed primarily of siliceous sinter with minor intervals of calcareous travertine. From approximately 29.5 to 26.5 ft, the interval is dominated by travertine before transitioning back into predominantly sinter. An interval enriched in precipitated Fe-Mn oxides occurs near 25 ft. The uppermost 2 ft of the core consists of bedded sinter.

## **3.2 Geochronology**

### *3.2.1 Zircon $^{238}\text{U}$ - $^{230}\text{Th}$ Ages*

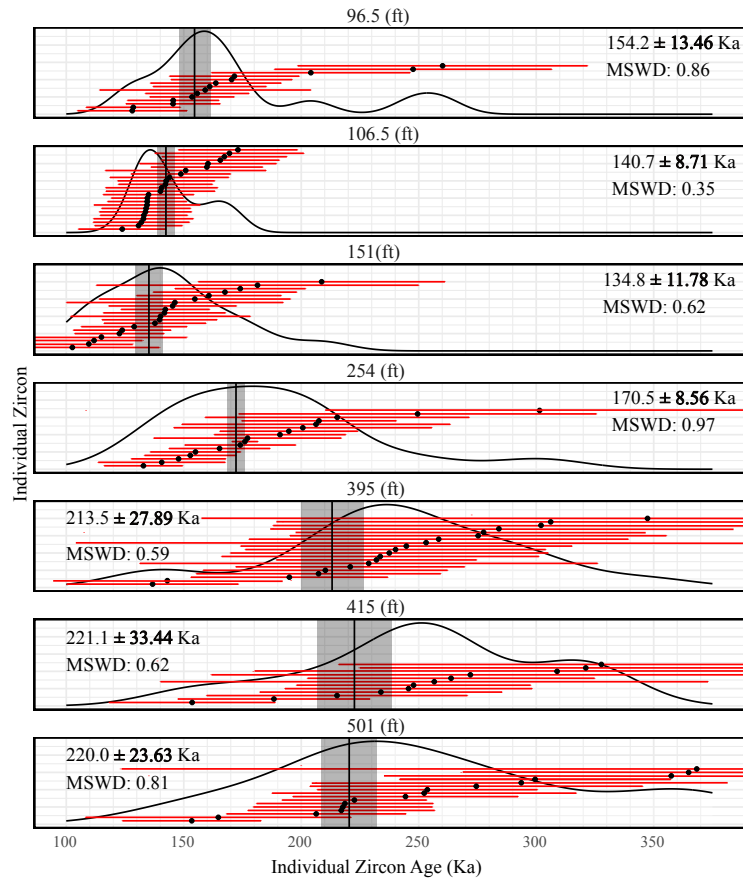
Zircon  $^{238}\text{U}$ - $^{230}\text{Th}$  disequilibrium analyses were conducted on 134 zircon grains to characterize age populations across seven depth intervals within the Y-2 core. Weighted mean



ages, uncertainties ( $2\sigma$ ), and MSWD values for each sample are reported in Table 2, and kernel density estimates (KDEs) of individual zircon model ages are shown in Figure 11.

*Table 2: Zircon weighted mean ages from sample depths in the Y-2, core respective  $2\sigma$  uncertainty and number of grains analyzed*

| Hole / Depth (ft) | $^{238}\text{U}$ - $^{230}\text{Th}$<br>Weighted mean<br>age (ka) | $\pm 2\sigma$ (ka) | MSWD | n  | Material       |
|-------------------|-------------------------------------------------------------------|--------------------|------|----|----------------|
| <b>Y2-96.5</b>    | 154.2                                                             | 13.46              | 0.86 | 14 | Sed/Ash bed    |
| <b>Y2-106.5</b>   | 140.7                                                             | 8.71               | 0.35 | 24 | Sed/Ash bed    |
| <b>Y2-151</b>     | 134.8                                                             | 11.78              | 0.62 | 20 | Rhyolite       |
| <b>Y2-254</b>     | 170.5                                                             | 8.56               | 0.97 | 17 | Rhyolite       |
| <b>Y2-395</b>     | 213.5                                                             | 27.89              | 0.59 | 23 | Volcaniclastic |
| <b>Y2-415</b>     | 221.1                                                             | 33.43              | 0.62 | 17 | Rhyolite       |
| <b>Y2-501</b>     | 219.9                                                             | 23.63              | 0.81 | 19 | Rhyolite       |



*Figure 11: Kernel density estimates (KDEs) of single-grain zircon U–Th model ages from seven depth intervals in the Y-2 core. Reported ages represent weighted mean ages, with uncertainties*

*reported as  $2\sigma$  in gray shaded region. Corresponding MSWD values are shown for each population. Sample depths are indicated on each panel.*

Samples from deeper intervals of the core (501.5 ft, 415 ft, and 395 ft) yield weighted mean ages of  $219.0 \pm 11.81$  ka,  $221.1 \pm 16.72$  ka, and  $213.5 \pm 13.94$  ka, respectively, with overlapping uncertainties and MSWD values  $<1.0$ . Individual zircon model ages within these intervals, however, span broad ranges (e.g., 584.9–153.4 ka). Overall, the weighted mean ages of zircon populations cluster around 220 ka with overlapping uncertainties.

In contrast, zircon populations from intermediate depths (254 and 151 ft) do not share a weighted mean age with each other, and both samples are younger than the underlying deeper intervals. The 254 ft interval yields a weighted mean age of  $170.5 \pm 4.28$  ka, with individual ages ranging from 301.4–132.8 ka, whereas the 151 ft interval yields a younger weighted mean age of  $134.8 \pm 5.90$  ka, with a range of 208.7–102.6 ka.

Zircon populations from the upper sedimentary intervals (96.5–106.5 ft) yield younger weighted mean ages with relatively narrow distributions. Two sample depths within the sedimentary section did not yield recoverable zircons through the mineral separation process (86.5 and 79.5 ft) and were not dateable (see section 3.1.2 *Glaciofluvial Bars #1*). The 106.5 ft interval yields a weighted mean age of  $140.7 \pm 4.35$  ka, with individual ages ranging from 123.8–170.0 ka, while the 96.5 ft interval yields a weighted mean age of  $154.1 \pm 13.46$  ka with individual ages ranging from 128.1–260 ka. Weighted mean ages from these two samples are older than the underlying rhyolitic units, despite their stratigraphic position.

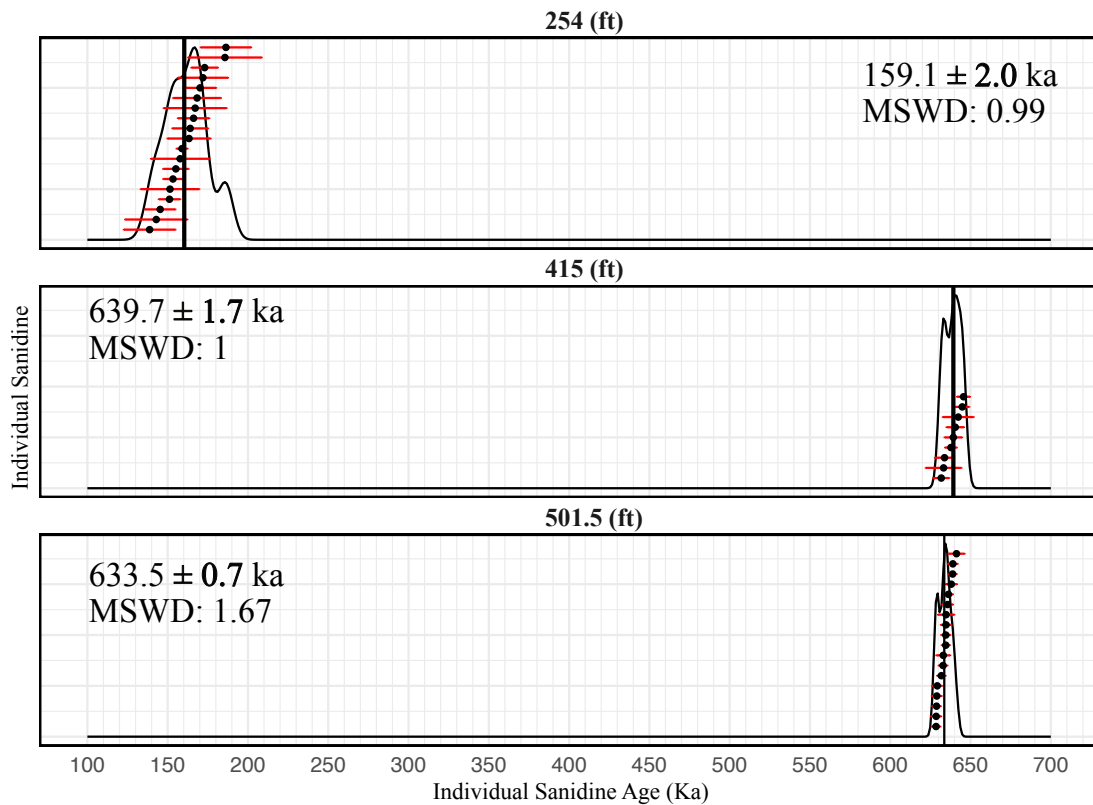
### 3.2.2 Sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ Ages

$^{40}\text{Ar}/^{39}\text{Ar}$  total fusion analyses were conducted on sanidine grains from selected intervals to further constrain eruption ages (Figure 12). The sample from 254 ft yields an age of  $159.1 \pm$

2.0 ka (MSWD = 0.99), consistent with zircon derived ages from the same depth. In contrast, samples from deeper intervals (415 ft and 501.5 ft) yield older ages of  $639.7 \pm 1.7$  ka and  $633.5 \pm 0.7$  ka, respectively, which do not overlap with zircon U–Th ages. Samples, with their weighted mean ages, uncertainty ( $1\sigma$ ), and MSWD values are reported in Table 3.

*Table 3: Sanidine weighted mean ages from sample depths in the Y-2, core respective  $1\sigma$  uncertainty and number of grains analyzed*

| Hole / Depth (ft) | $^{40}\text{Ar}/^{39}\text{Ar}$<br>Weighted mean<br>age (ka) | $\pm 1\sigma$ (ka) | MSWD | n  | Material |
|-------------------|--------------------------------------------------------------|--------------------|------|----|----------|
| Y2-254            | 159.1                                                        | 2.0                | 0.99 | 19 | Rhyolite |
| Y2-415            | 629.7                                                        | 1.7                | 1.0  | 9  | Rhyolite |
| Y2-501            | 633.7                                                        | 0.7                | 1.67 | 18 | Rhyolite |



*Figure 12: Kernel density estimates (KDEs) of single grain sanidine  $^{40}\text{Ar}/^{39}\text{Ar}$  ages from selected depth intervals in the Y-2 core. Reported ages represent weighted mean ages, with uncertainties*



reported as  $1\sigma$ , shaded region that would note this is smaller than stroke of line that is the average. Corresponding MSWD values are shown for each sample population. Sample depths are indicated on each panel

Overall, zircon U–Th ages show systematic variation with depth, with deeper intervals forming a coherent age weighted mean age  $\sim 220$  ka, intermediate intervals displaying more variable age distributions, and upper sedimentary intervals defining a distinct younger population.  $^{40}\text{Ar}/^{39}\text{Ar}$  ages partially overlap zircon results in some intervals but are inconsistent in deeper sections.

### 3.2.3 U-Series Geochronology of Hydrothermal Deposits

U-series ages obtained from travertine and calcite samples range from 8.3 to 22.7 ka with large uncertainties on all samples except Y2-4 (Table 4). Initial  $^{234}\text{U}/^{238}\text{U}$  values were near secular equilibrium and comparable to values reported from modern Yellowstone thermal waters (Paces et al., 2022). Although the ages indicate late Pleistocene to Holocene hydrothermal activity, analytical uncertainties are large and limit precise temporal constraints on the underlying sedimentary sequence.

Table 4: U-series ( $^{234}\text{U}$ - $^{230}\text{Th}$ ) ages of hydrothermal deposits from the Y-2 drill core. Reported values include estimated sample depth, material analyzed, and age with associated  $2\sigma$  uncertainty.

| Sample Name | Estimated depth (ft) | Material   | $^{234}\text{U}$ - $^{230}\text{Th}$ age | $2\sigma$ |
|-------------|----------------------|------------|------------------------------------------|-----------|
| Y2-9        | 26.6                 | calcite    | 8.3                                      | 11.2      |
| Y2-1        | 27                   | travertine | 9.0                                      | 11.5      |
| Y2-2        | 27.3                 | travertine | 9.2                                      | 15.2      |
| Y2-3        | 28.5                 | travertine | 21.5                                     | 19.8      |
| Y2-4        | 28.8                 | travertine | 22.7                                     | 7.1       |

### 3.3 Whole Rock Geochemistry

Whole rock major, minor, and trace element compositions were determined for 14 samples collected from volcanic, volcanoclastic, and sedimentary intervals within the Y-2 core. Samples selected for whole rock geochemistry were chosen based on core logging observations and interpreted stratigraphic relationships. Major element concentrations were measured by X-ray fluorescence (XRF), and trace element concentrations were determined by inductively coupled plasma mass spectrometry (ICP-MS) at the Washington State University GeoAnalytical Laboratory. Complete geochemical results are reported in Tables 5, 6, and 7. Analytical limits of determination, and precision values for XRF and ICP-MS analyses are reported in Table 8

#### 3.3.1 Major Elements

SiO<sub>2</sub> concentrations range from 69.02 to 78.54 wt.% and total alkali (Na<sub>2</sub>O + K<sub>2</sub>O) contents range from 5.99 to 10.30 wt.%. Most samples are rhyolites based on total alkali-silica (TAS) plots (Figure 13), with the exception of Rhyolite Unit #2 at sample depth 254, which is plotted as a dacite, and Rhyolite Unit #1 at sample depths 415 and 450 ft, which are interpreted as trachyte and dacite, respectively. Currently there has been no documentation of trachytes or dacites within CPM or UBM rhyolites. Thus, this is likely due to hydrothermal alteration and not a true chemical signal.

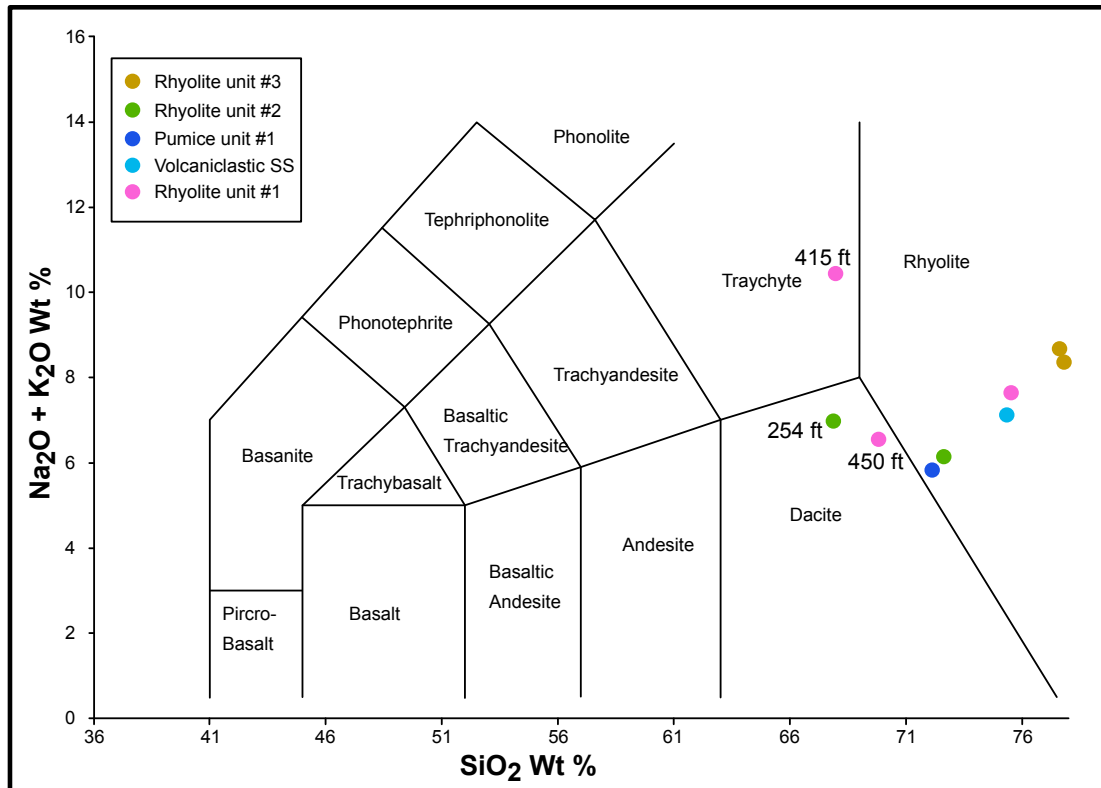


Figure 13: Total alkali silica (TAS) plot of all Y-2 volcanic samples, outliers mentioned in sub section 3.3. It above are labeled (450, 415, and 254 ft).

### 3.3.2 Trace Elements

Trace-element spider diagrams normalized to prevalent mantle (PREMA) (Figure 14) and unaltered CPM rhyolites show similar overall patterns, with the greatest variability occurring in mobile elements such as Cs, Rb, Ba, Sr, and U. In contrast, the more immobile/incompatible elements display comparatively coherent patterns between samples (Figure 15). Trace element plots of samples from Rhyolite Unit #1 normalized to unaltered UBM rhyolites show similar trends across rhyolitic samples, although volcaniclastic and sedimentary intervals display greater variability (Figure 15). These help inform the use of relatively immobile trace-element relationships for compositional comparison.

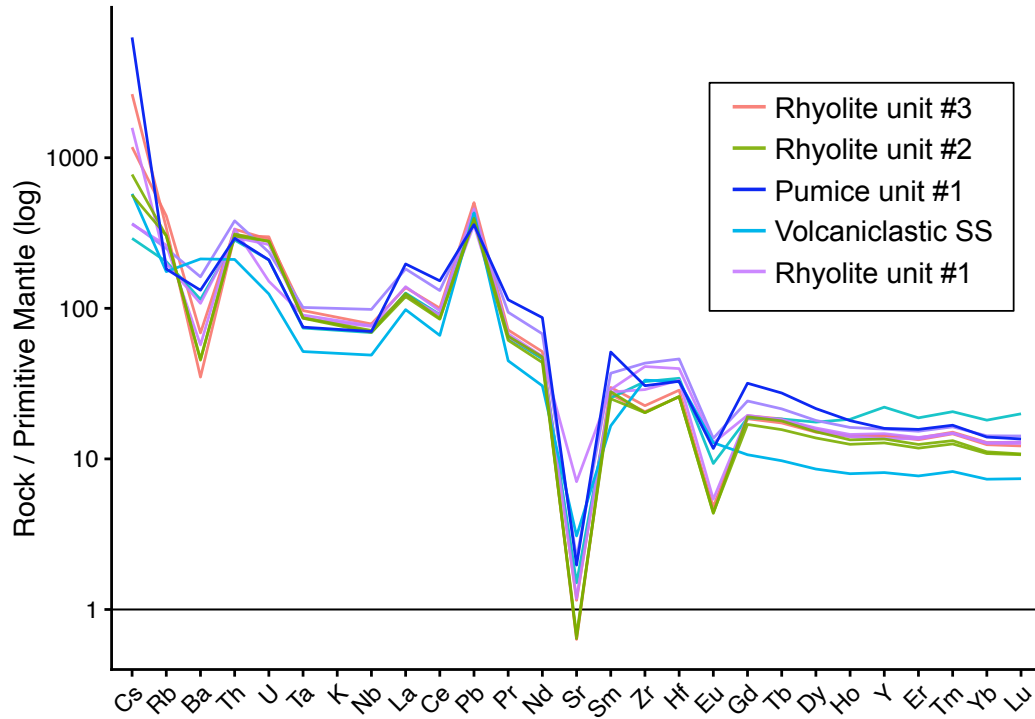


Figure 14: Spider diagrams of all volcanic samples in Y-2 normalized to prevalent mantle (PREMA) (Doe et al., 1982; Hildreth et al., 1991; Christiansen, 2001; Bindeman et al., 2001; Girard and Stix, 2009, 2010; Watts et al., 2012; Bindeman and Lowenstern, 2016; Till et al., 2019).

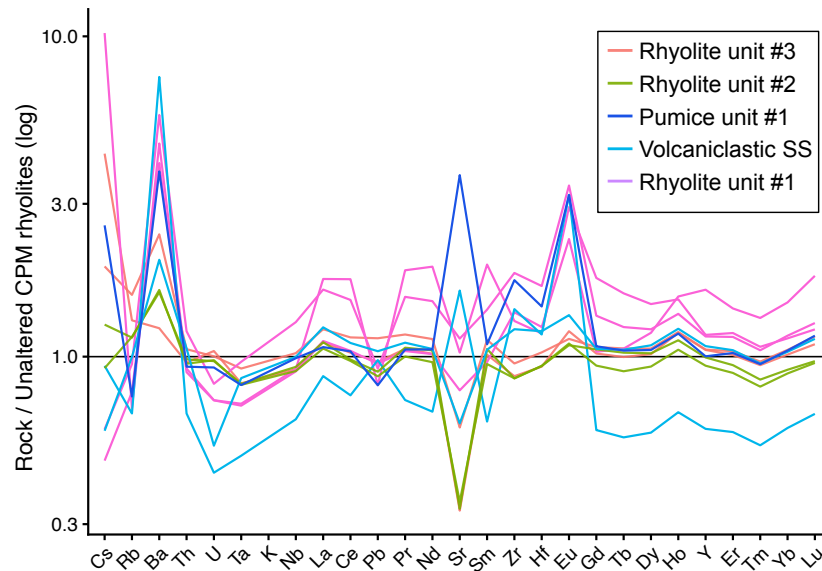


Figure 15: Spider diagrams of all volcanic samples in Y-2 normalized to unaltered CPM rhyolites (Doe et al., 1982; Hildreth et al., 1991; Christiansen, 2001; Bindeman et al., 2001; Girard and Stix, 2009, 2010; Watts et al., 2012; Loewen et al., 2017; Till et al., 2019).

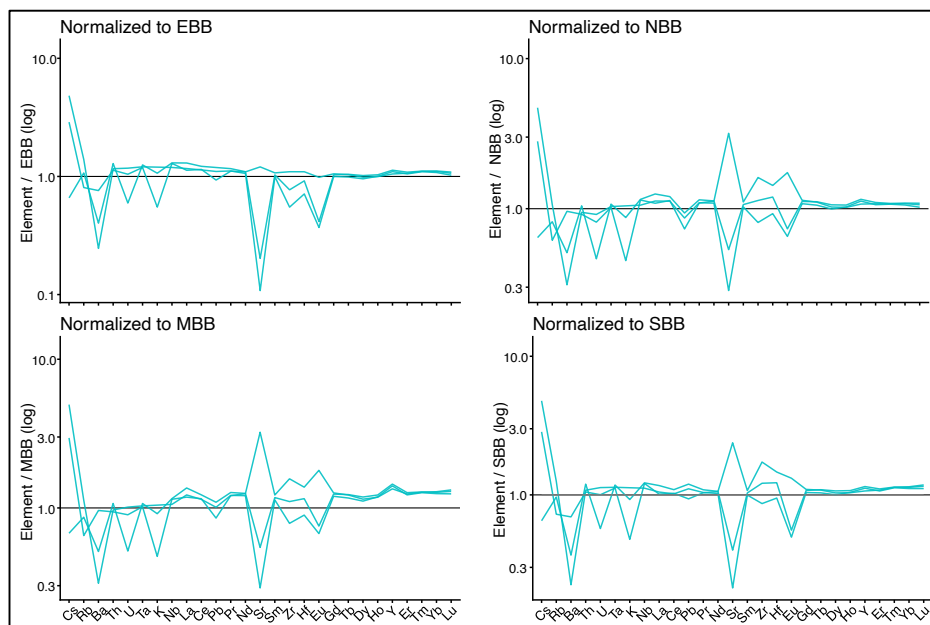


Figure 16: Spider Diagrams of Rhyolite Unit #1 (501.5, 450, and 415 ft) normalized to unaltered UBM flows that include East Biscuit Basin (EBB), North Biscuit Basin (NBB), Middle Biscuit Basin (MBB), and South Biscuit Basin (SBB) (Till et al., 2019).

### 3.3.3 Major, Minor, and Trace Element Chemostratigraphy

Major, minor, and trace element concentrations are plotted as a function of depth with loss on ignition (LOI) values as a proxy for relative hydrothermal alteration, which may affect the mobility of alkali metals and other mobile elements (Figure 17 & 18). Major, minor, and trace element concentration through depth reveal systematic geochemical variability throughout the core.

The rhyolite flows are generally more internally consistent than volcanoclastic and sedimentary intervals. The lowermost rhyolitic interval, Rhyolite Unit #1, displays broadly uniform major, minor, and trace element compositions, although La and Nd concentrations are variable between samples relative to other trace elements. An exception to this homogeneity is the 450 ft sample, which major, minor, and trace element concentrations deviates from adjacent

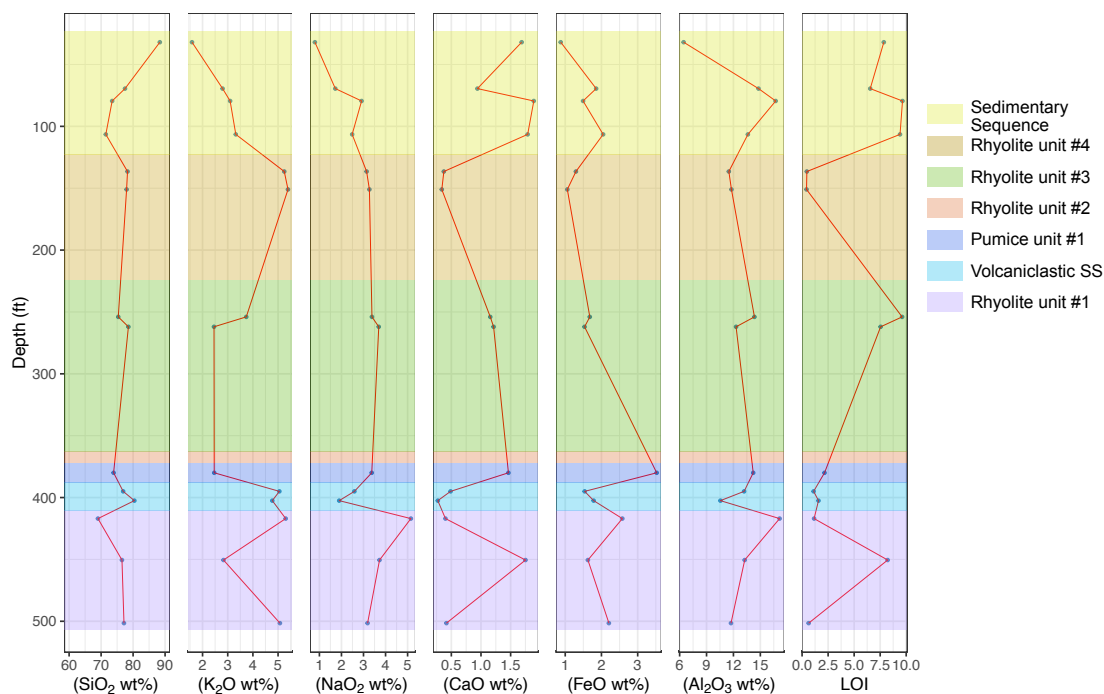


Figure 17: Chemostratigraphic profiles of major- and minor-element concentrations (wt%) and loss on ignition (LOI) versus depth in the Y-2 drill core.

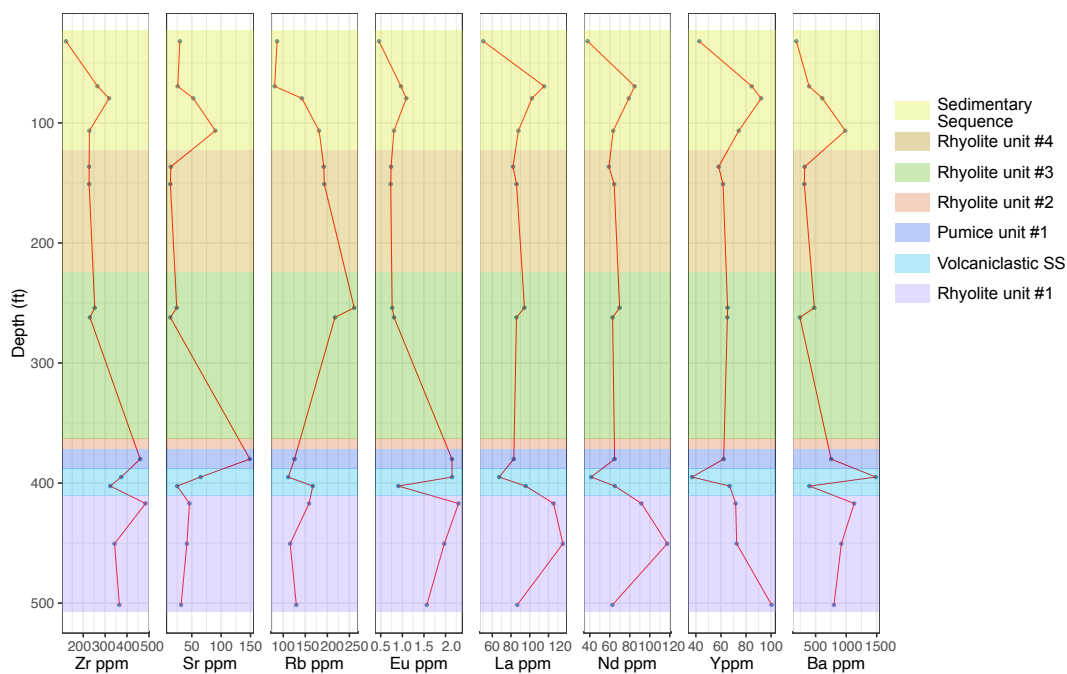


Figure 18: Chemostratigraphic profiles of trace-element concentrations (ppm) versus depth in the Y-2 drill core.

samples and exhibits elevated LOI values relative to other samples in this unit. Relative to overlying rhyolitic intervals, the lowermost rhyolite is enriched in Zr, Sr, Eu, Y, and Ba, while exhibiting lower Rb concentrations.

The overlying volcanoclastic interval exhibits substantially greater geochemical variability relative to coherent rhyolitic flows, consistent with its mixed clastic texture and multiple observed grain populations. The pumiceous interval centered near 380 ft is characterized by elevated CaO and FeO concentrations relative to surrounding samples and corresponds to the abundance of plagioclase and Fe-Ti oxides observed petrographically.

The two uppermost rhyolitic intervals (Rhyolite Unit #2 and #3) are internally uniform, concerning trace elements and do not appear to vary much between flows. The uppermost rhyolitic interval exhibits higher K<sub>2</sub>O and lower CaO concentrations relative to the underlying flow, while also displaying comparatively enriched Rb concentrations. Sedimentary and volcanoclastic intervals display the greatest overall geochemical variability and lack internally coherent chemistries compared to the rest of the core.

### **3.4 Electron Microprobe Analysis (EPMA)**

Electron microprobe analyses were conducted on feldspar phases from selected volcanic intervals within the Y-2 core to characterize compositional variability in the feldspar phase. Analyses focused primarily on sanidine within coherent rhyolitic intervals, with plagioclase analyzed in intervals where sanidine was absent. Major and minor element compositions, including Or, Ab, and An components, as well as Ba concentrations, were measured. Seven intervals were targeted for EPMA analysis to assess variability between the main volcanic units. Feldspar compositions are shown in Figure 19.

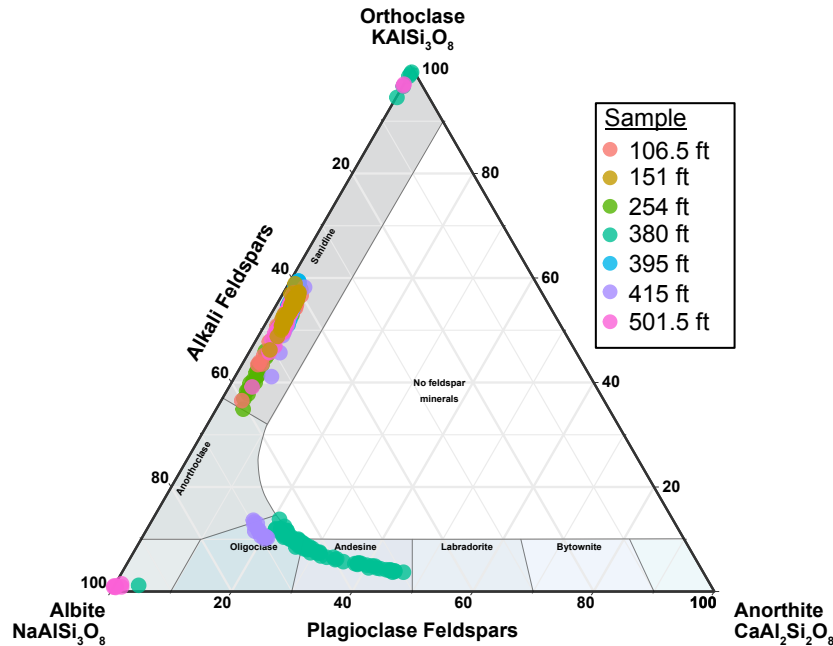


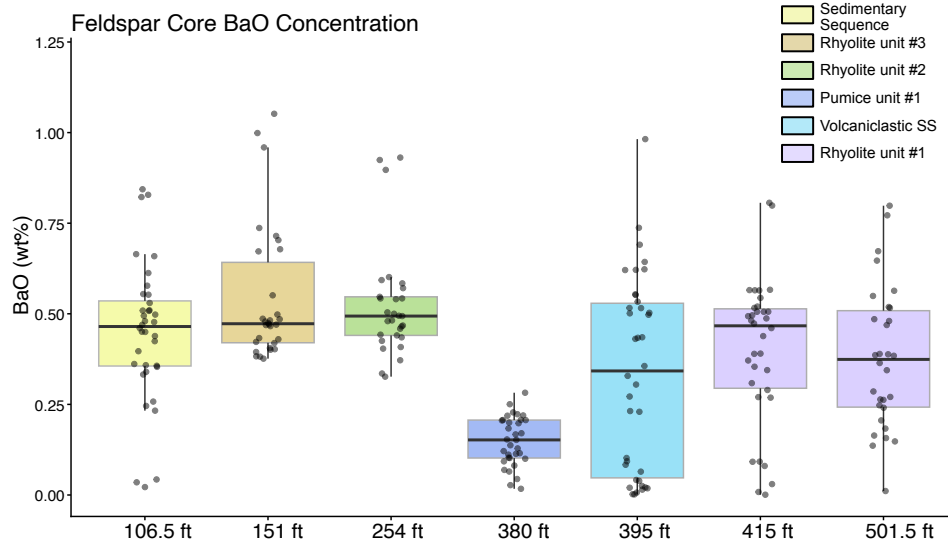
Figure 19: Feldspar compositional ternary diagram of feldspars analyzed by EPMA from selected volcanic intervals in the Y-2 core. Compositions are plotted using the albite (Ab), anorthite (An), and orthoclase (Or) end members.

Alkali feldspars analyzed are dominantly sanidine. The few grains from samples 380 ft and 501.5 ft that are albite and orthoclase correspond to the rims present on some grains. Intervals that contain plagioclase feldspars are dominantly andesine and oligoclase compositions. From sample depth 415 ft, the plagioclase analyzed in this interval are entirely oligoclase.

Sanidine grains from Rhyolite Units #1 at 501.5 and 415 ft show a consistent spread in BaO concentrations, ranging from 0.25% - 0.52% (Figure 20). The overlying Volcaniclastic Sandstone displays broader compositional variability between analyzed sanidine, ranging from 0.54% - 0.11%. In contrast, the overlying Pumice Unit #1 displays a much tighter cluster of lower BaO concentrations in analyzed plagioclase grains. The overlying Rhyolite Units #2 and #3 displays uniform sanidine Ba concentrations, similar to Rhyolite Unit#1, however, Rhyolite



Units #2 and #3 shows higher Ba concentrations relative to Rhyolite Unit #1. The sedimentary unit at 106.5 ft displays a range of sanidine BaO concentrations from 0.36% - 0.53%.



*Figure 20: Box and whisker plot of Sanidine and plagioclase feldspar BaO (wt%) from core of grains. All samples analyzed are sanidine with the exception of depth 380 ft which is entirely plagioclase because of the absence of sanidine.*

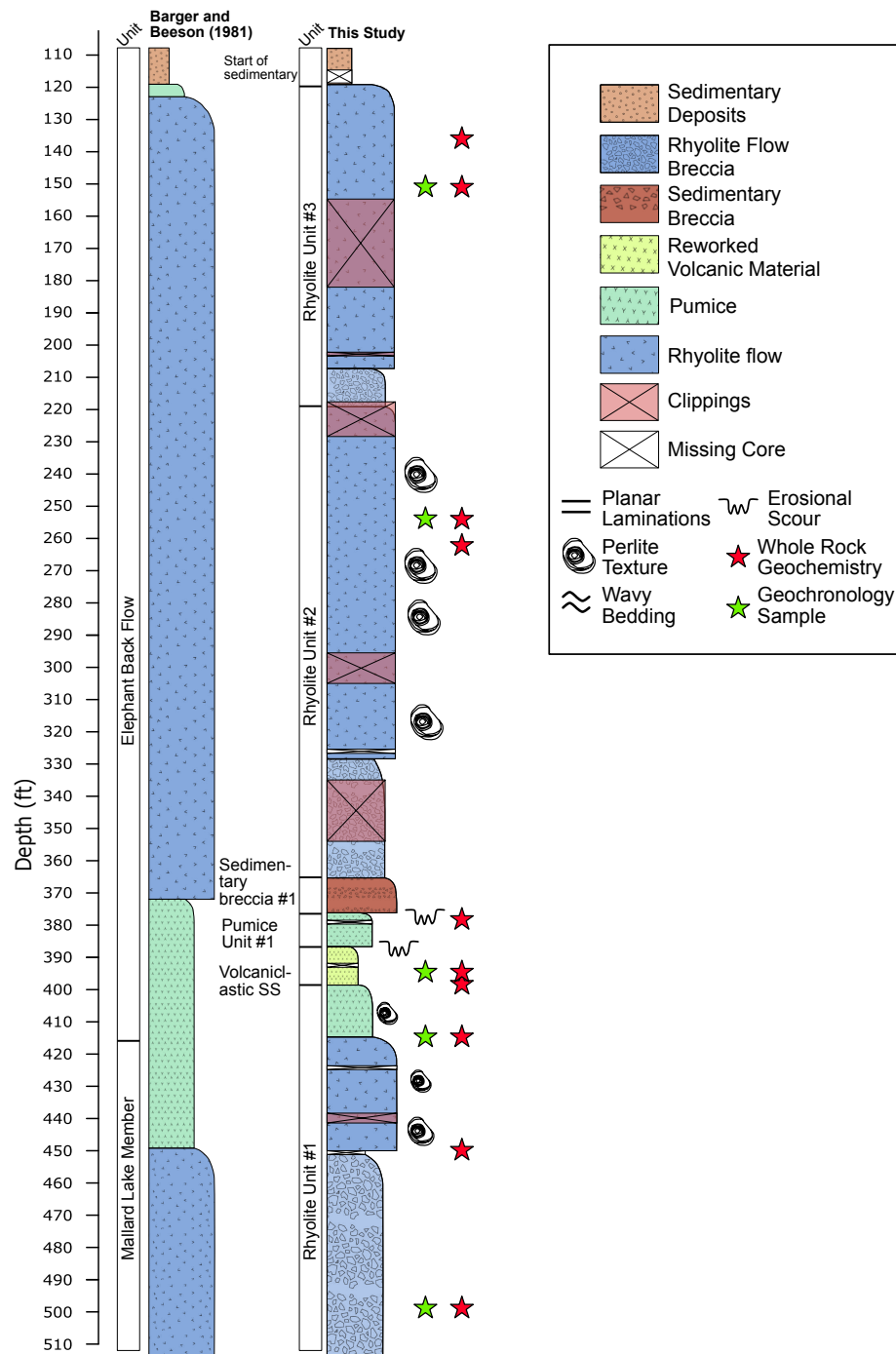


Figure 21: Comparison of the original stratigraphic log of the Y-2 drill core from Bargar and Beeson (1981) (left) with the revised stratigraphic column developed in this study (right) of the lower 400 feet of core. The revised column incorporates additional lithologic units identified through detailed core logging, petrography, whole rock geochemistry, and geochronologic analysis. Unit descriptions are provided in Section 3.1. Sample locations for geochronology (green stars) and whole rock geochemistry (red stars) are shown. Depths are reported in feet

below ground surface. A detailed stratigraphic column of the sedimentary interval is presented in Figure 20

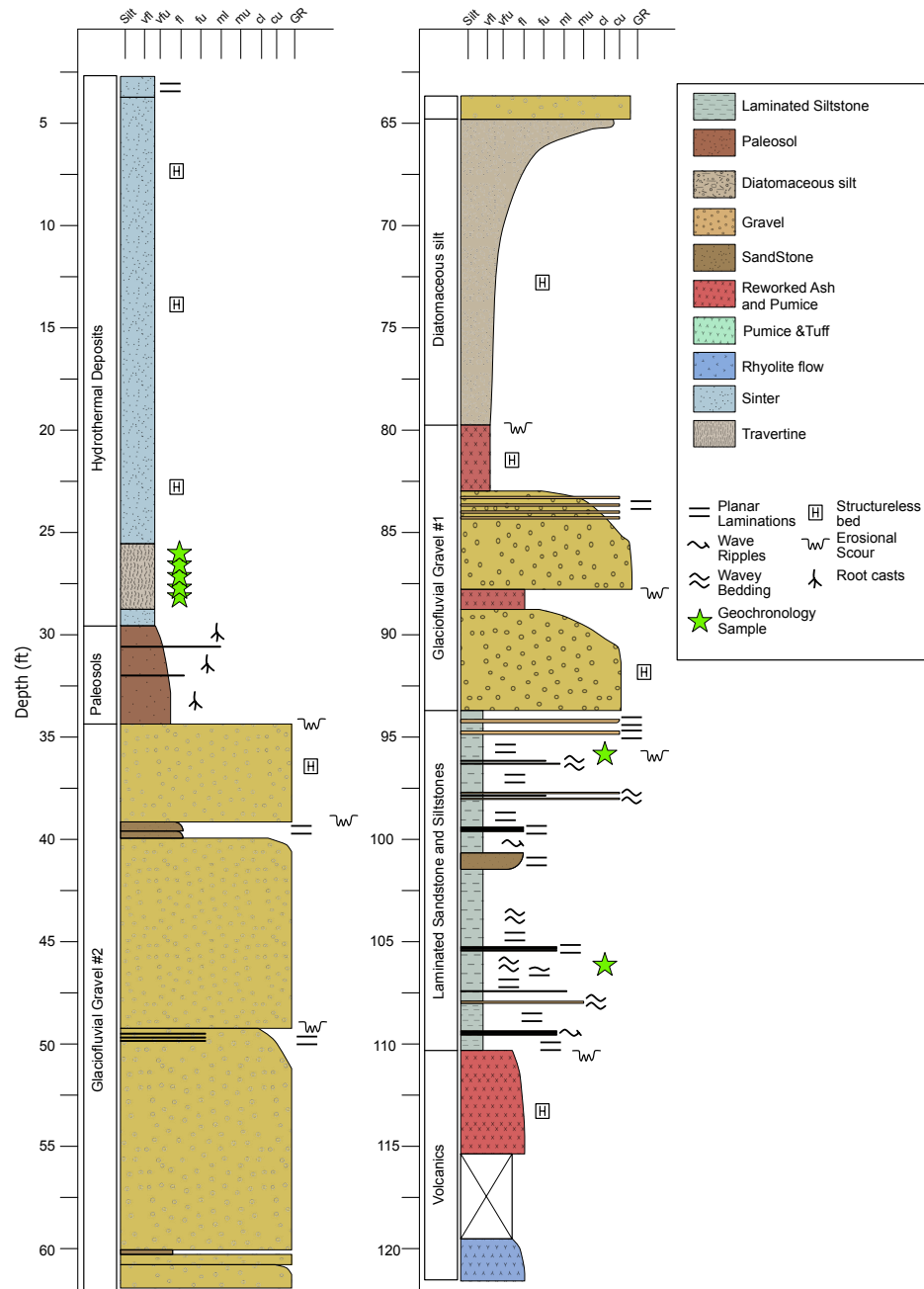


Figure 22: Expanded stratigraphic column of the sedimentary interval shown in Figure 19. The detailed column highlights lithologic variability, sedimentary structures, grain-size changes, and

key stratigraphic contacts that are not resolvable at the scale of the complete Y-2 stratigraphic column.

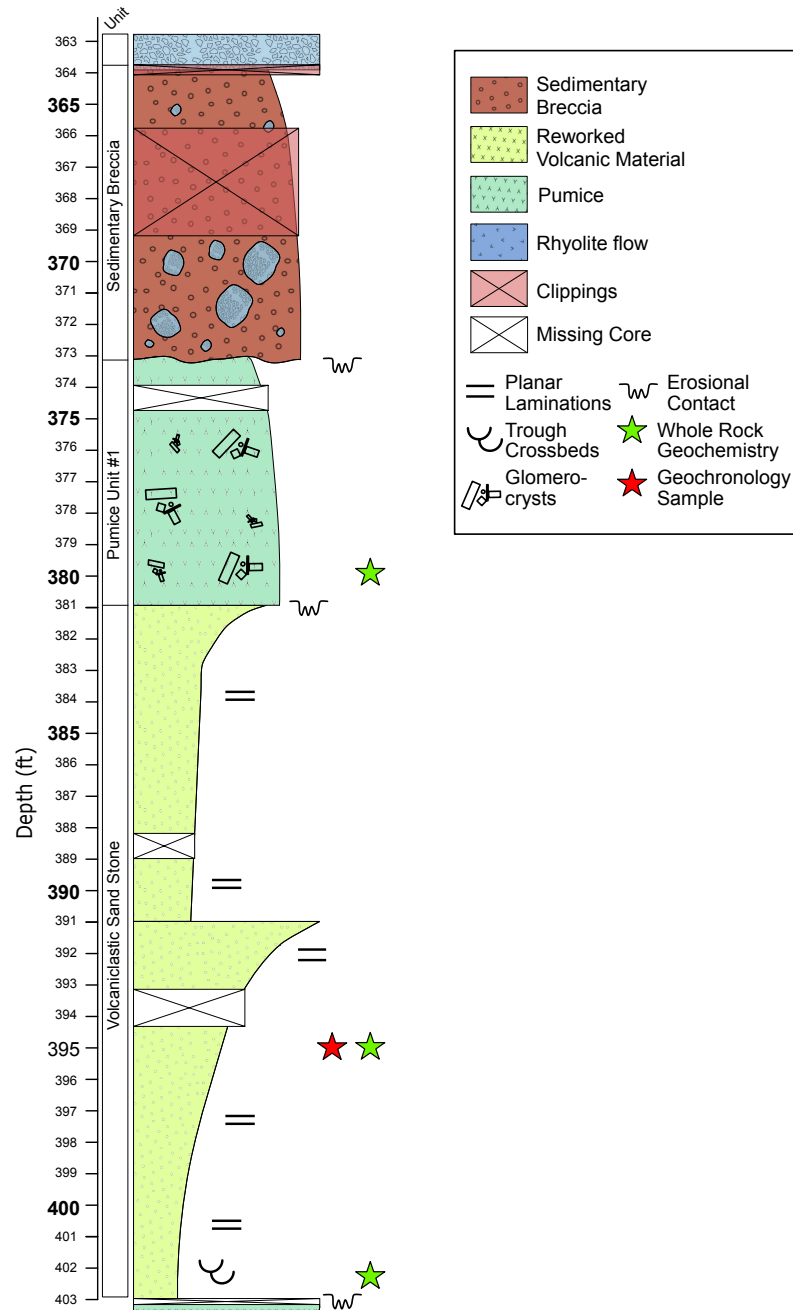


Figure 23: Expanded stratigraphic column of the volcanoclastic interval between 403 and 364 ft depth in the Y-2 drill core. The detailed column highlights lithologic variability, sedimentary structures, and stratigraphic relationships within an interval containing reworked volcanoclastic sandstones, Pumice Unit #1, and a sedimentary breccia. This interval is shown separately to

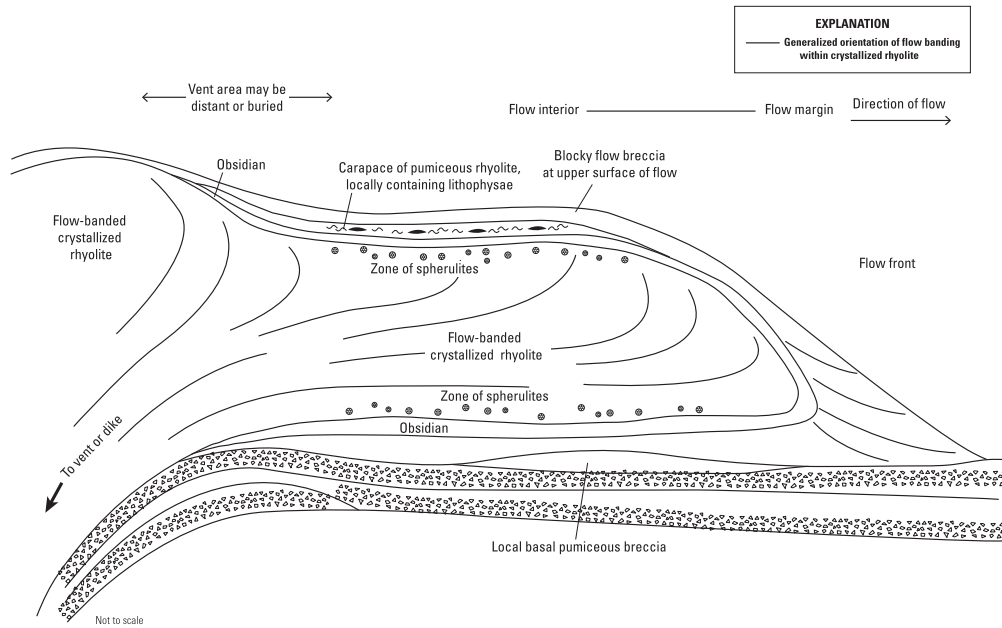
*emphasize features and contacts that are not resolvable at the scale of the complete Y-2 stratigraphic column.*

## 4. DISCUSSION

### 4.1 Volcanic Stratigraphy in the Y-2 Core

The Y-2 core preserves a stratigraphic succession of rhyolite flows and breccias, primary and secondary volcanoclastic deposits, and sedimentary rocks. Core logging, petrography, SEM imaging, geochronology, and geochemical observations enable us to define rhyolitic units, and identify depositional contacts within the Y-2 core.

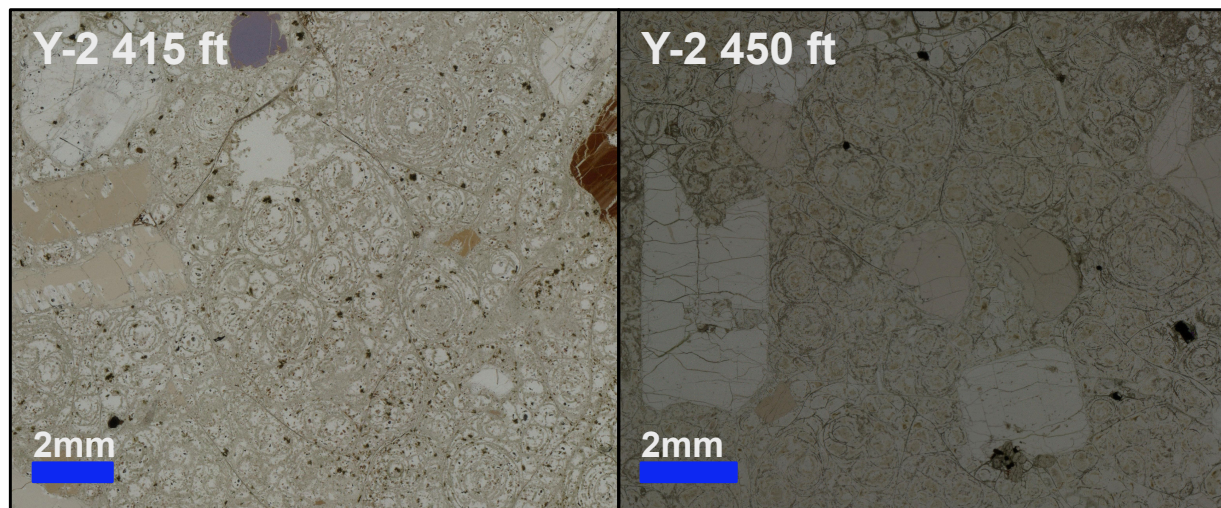
Rhyolite flow cores are typically dense and impermeable, whereas the top and bottom portions of flows are highly permeable breccias or pumiceous carapaces (Figure 24) (Doe et al., 1982; Hildreth et al., 1991; Christiansen, 2001; Bindeman et al., 2001; Christiansen et al., 2007; Girard and Stix, 2009, 2010; Watts et al., 2012; Till et al., 2019). Because flow cores act as barriers to hydrothermal fluid flow, alteration concentrates in the highly permeable brecciated contacts between flows (Finn and Morgan, 2002; Finn et al., 2022). In Y-2, intervals of poor core recovery commonly coincide with interpreted lithologic contacts and highly altered zones, consistent with preferential destruction of volcanic glass that does not recover a continuous core. Consequently, some stratigraphic contacts within the Y-2 core are not directly observed and instead are inferred.



*Figure 24: Schematic cross section of a rhyolite lava flow modified from Sweetkind and Bova (2015) showing characteristic internal flow architecture, including an autobrecciated flow base, coherent stony interior, flow banding, and spherulitic devitrification textures. These features are used throughout this study to interpret volcanic facies and identify individual rhyolite units within the Y-2 drill core.*

The lowermost rhyolitic interval (Rhyolite Unit #1) is interpreted as a single coherent rhyolite flow from 515.5 ft to 403 ft. This differs from Barger and Beeson (1981) who interpreted this flow as the Mallard Lake flow until a contact at 417 feet with “tuff and tuffaceous sediment.” However, new core observations found no erosional surface or sharp contact that would separate the lower stony rhyolite from an overlying pumice or primary explosive volcanic unit. Instead, the interval previously logged as tuffaceous material is interpreted as a highly altered, frothy upper portion of the same rhyolite flow (McPhie Jocelyn et al., 1993). This interpretation is supported by thin sections at 415 ft and 450 ft where the perlitic texture is still apparent in the groundmass, much like the groundmass texture that is present in rhyolite samples lower in the same flow (Figure 25).

The two dated samples from Rhyolite Unit #1 yielded ages around ~220 ka which differs from the originally logged CPM member (Mallard Lake Member that erupted  $\sim 159.2 \pm 2.0$  ka; (Stelten et al., 2023). This age does not correlate with any known ages of flows in the UBM or CPM. Thus, Rhyolite Unit #1 may represent a previously unrecognized rhyolite flow not found at the surface.



*Figure 25: Perlitic textures in the groundmass, similar mineralogy, the absence of an interpreted contact, and the fragmented nature of the recovered core support interpretation of both intervals as a single flow unit (Rhyolite Unit #1).*

Volcaniclastic sandstone #1 starts near 403 ft at an unrecovered section of core interpreted as a sharp contact between the coherent vesicular Rhyolite #1 flow top into a stratified clastic deposit above. This interval is characterized by parallel and planar bedding, truncated beds, and two distinct upward-coarsening depositional pulses separated by a preserved sharp contact near 391 ft (Figure 5). Poor sorting throughout the interval, combined with mixed grain angularity, suggests the deposit is derived from the reworking of multiple units rather than representing a primary pyroclastic deposit as originally interpreted by Barger and Beeson (1981). SEM imaging shows rounded quartz and sanidine grains intermixed with angular to sub angular



grains, indicating multiple source materials that have undergone different degrees of weathering in the same deposit.

Zircon U-Th ages from this interval ( $213.5 \pm 27.89$  ka) are consistent with the  $\sim 220$  ka population identified in the underlying rhyolitic unit, suggesting the material in this deposit is temporally related to the same eruptive system. Although outcrop-scale observations are unavailable to fully constrain depositional processes, the combined sedimentologic, petrographic, SEM, EPMA, and geochronologic observations support interpretation of this interval as a reworked volcaniclastic deposit associated with the underlying rhyolitic unit rather than an unrelated younger sedimentary sequence.

The overlying coherent pumiceous unit (Pumice unit #1; 388.1 – 373 ft) is lithologically distinct from both the underlying volcaniclastic interval and other rhyolitic units in the core. This unit contains abundant polymineralic glomerocrysts that consist of plagioclase and Fe-Ti oxides with lower An contents and isolated sieved plagioclase phenocrysts with higher An contents. The higher-An, sieved phenocrysts are interpreted to have crystallized under less evolved or higher temperature conditions and were subsequently destabilized, whereas the lower-An glomerocrystic population likely reflects a more evolved plagioclase assemblage. Together, these textural and compositional differences indicate multiple plagioclase populations were amalgamated into the erupted magma, resulting in the disequilibrium textures. Although this unit was not dated, temporally this unit is most likely related to the UBM rhyolite flows because of the abundance of plagioclase (Christiansen, 2001; Girard and Stix, 2009).

Rhyolite unit #2 & #3 yielded weighted mean zircon ages of  $170.8 \pm 8.56$  ka and  $134.8 \pm 11.78$  ka, respectively. Sanidine  $^{40}\text{Ar}/^{39}\text{Ar}$  analyses from Rhyolite Unit #3 overlap with zircon U-Th age uncertainties;  $^{40}\text{Ar}/^{39}\text{Ar}$  analyses for Rhyolite Unit #3 are ongoing. However, existing

geochronology supports the interpretation that this interval belongs to the Central Plateau Member. These two rhyolites are interpreted as separate flows from their resolvable U-Th age difference, changes in vesiculation and perlitic textures, and another interval of non-recovered core where a contact would be located between the changes in lithology.

Based on currently available geochronologic constraints, Rhyolite Unit #2 correlates temporally to CPM rhyolites such as the Elephant Back flow ( $161.7 \pm 2.7$  ka), the Mallard Lake flow ( $160.2 \pm 1.1$  ka), the Aster Creek flow ( $162.0 \pm 2.2$  ka), the Nez Perce Creek flow ( $160.8 \pm 1.1$  ka), the Spruce Creek flow (not dated but assumed to be  $\sim 160.6 \pm 2.9$ ), the West Thumb flow ( $160.7 \pm 0.9$  ka), the Dry Creek Flow ( $159.9 \pm 1.7$  ka), or the Mary Lake flow ( $160.9 \pm 1.7$  ka) (Stelten et al., 2023). However, only the Elephant Back flow and the Mallard Lake flow outcrop around the drill site; they are therefore the most likely candidates for Rhyolite Unit #2. CPM rhyolites erupted many flows in pulses of activity over short periods of time and are homogenous in whole rock geochemical compositions between flows, therefore it is difficult to distinguish flows based only on geochemistry and geochronology (Stelten et al., 2023). Current petrologic, geochemical, and geochronologic datasets remain insufficient to confidently distinguish between the two mentioned flows.

Temporally, both CPM flows in the Y-2 core overlap with the Bull Lake glacial period (140-150 ka; Licciardi and Pierce, 2018) on the YPVF. However, there is no direct textural evidence within the Y-2 core that suggests ice-contact eruptions (i.e., no hyaloclastite or palagonite). In many cases, evidence for glaciovulcanism originates from field relationships and structures such as tuyas, transitions from subaqueous to subaerial facies during an eruption, or reversed stratigraphy in lava flow chronology (Edwards et al., 2015; Cole et al., 2020). Field

context is lacking to assist with interpreting the Y-2 core, so it is difficult to confirm or deny the presence of glacial ice on the surface of the YPVF solely from Y-2.

#### **4.2 Limitations of Whole Rock and Geochronologic Interpretations**

Interpretation of the Y-2 core is complicated by pervasive hydrothermal alteration and the limits of subsurface sampling. Many intervals contain altered volcanic glass, secondary mineralization, and evidence for physical reworking, all of which may modify primary whole rock geochemical signatures. To evaluate the relative degree of hydrothermal alteration throughout the core, loss on ignition (LOI) and chemical index of alteration (CIA) are used (Nesbitt and Young, 1983). LOI is the release of water and volatiles when a whole rock powder of the sample is heated, and CIA is a geochemical proxy that measures the degree of chemical weathering by comparing depletion of fluid mobile alkali and alkaline metals to relatively immobile alumina. These values are plotted vs. depth and samples with high LOI and CIA have experienced a higher degree of alteration (Fig. 24). Elevated LOI and CIA values are consistent with pervasive hydration and secondary silica precipitation (Rollinson, 1993, Nesbitt and Young 1982). These alteration effects likely contribute to preferential breakdown of volcanic glass while also modifying portions of the whole rock geochemical signal.

Trace-element spider diagrams normalized to unaltered post-LCT Yellowstone rhyolites (Doe et al., 1982; Hildreth et al., 1991; Christiansen, 2001; Bindeman et al., 2001; Christiansen et al., 2007; Girard and Stix, 2009, 2010; Watts et al., 2012; Till et al., 2019) and prevalent mantle (PREMA) (McDonough and Sun, 1995) indicate that several trace elements experienced

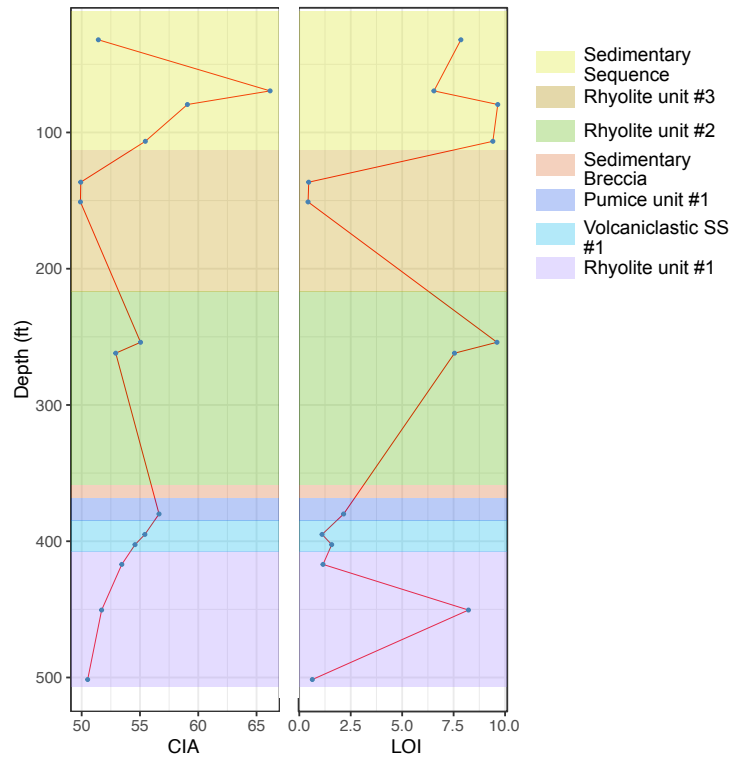


Figure 26: Chemical Index of Alteration (CIA) and Loss on Ignition (LOI) plotted versus depth for samples from the Y-2 drill core. Elevated values indicate increased degrees of hydration, weathering, and hydrothermal alteration. These parameters are used to identify altered intervals and assess the reliability of whole rock geochemical compositions.

mobilization during hydrothermal alteration. These elements include Ba, Cs, Sr, U, K, Si, and Rb. Immobile trace elements include Zr, Hf, Nb, Th, and Y and are not affected by hydrothermal alteration; these trace-elements are used in this study for identification of primary compositions and linking unknown rhyolites with known eruptive events. Samples displaying the greatest geochemical disturbance and alteration signatures are interpreted cautiously and not emphasized in compositional comparisons.

Despite these limitations, integration of multiple datasets including stratigraphy, petrography, feldspar chemistry, whole rock geochemistry, and geochronology provides a framework for interpreting the volcanic and sedimentary history preserved in the Y-2 core. While

each dataset contains uncertainties, their collective agreement places meaningful constraints on the origin and stratigraphic relationships of the units identified in this study.

### **4.3 Geochronologic Constraints on Emplacement of Rhyolite Unit #1**

#### *4.3.1 Inconsistent $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Th ages*

Integrated zircon U-Th and sanidine  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology provide important temporal constraints on the Y-2 core despite evidence for inheritance and mixed crystal populations. Yellowstone rhyolite zircon ages are interpreted as crystallization ages that span from growth within long lived crustal magmatic mush zones to crystallization immediately prior to eruption. Because zircon rims were targeted during analyses, the resulting ages are interpreted as reasonable approximations of eruption age. Nevertheless, individual zircon populations may contain a mixture of antecrystic and near-eruptive crystals, which must be considered when interpreting geochronologic results.  $^{40}\text{Ar}/^{39}\text{Ar}$  ages, on the other hand, are interpreted as eruption ages because the closure temperature of argon in sanidine is relatively low ( $\sim 250\text{--}300^\circ\text{C}$ ).

Three samples from Rhyolite Unit #1 (501.5 and 415 ft) and Volcaniclastic Sandstone #1 (395 ft) from the Y-2 core yield weighted mean ages that fall between established Upper Basin Member (UBM) and Central Plateau Member (CPM) periods of volcanism (Figure 27). Reproducibility of these ages from multiple depths suggests coherent magmatic histories within portions of the core.

Sanidine  $^{40}\text{Ar}/^{39}\text{Ar}$  analyses yielded exclusively Lava Creek Tuff-aged grains from sample depths 501.5 ft ( $633.5 \pm 0.7$  ka  $1\sigma$ ; range from max  $641.2 \pm 4.9$  ka to min  $628.5 \pm 2.6$  ka,  $n=9$ ) and 415 ft ( $639.6 \pm 1.7$  ka  $1\sigma$ ; range from max  $645.6 \pm 3.9$  ka to min  $631.7 \pm 4.9$  ka,  $n=18$ ),

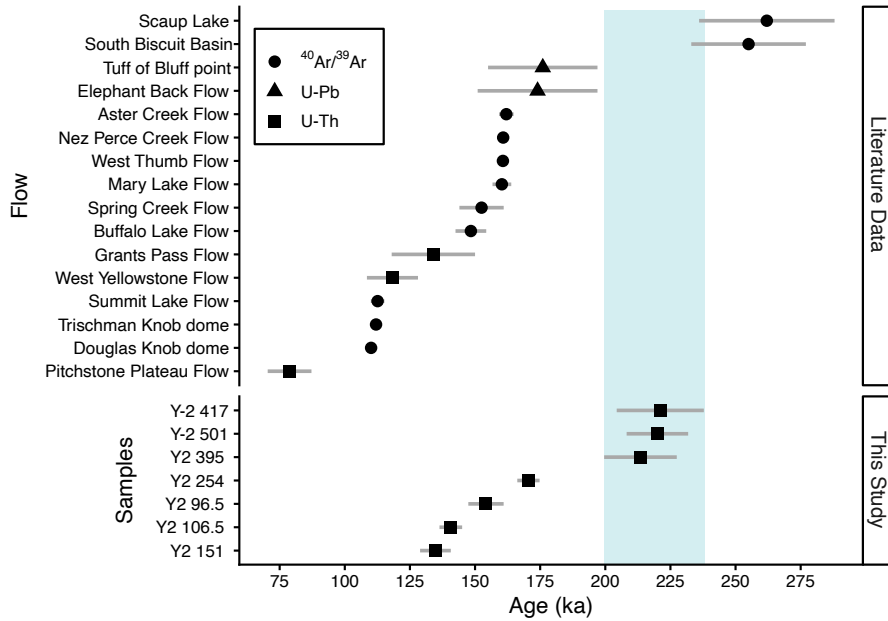


Figure 27: Comparison of zircon U-Th weighted mean ages from the Y-2 drill core with published age ranges for Upper Basin Member (UBM) and Central Plateau Member (CPM) rhyolites. Error bars represent  $2\sigma$  uncertainties. The blue shaded region highlights the age range of Rhyolite Unit #1, which falls between established periods of UBM and CPM volcanism.

despite being interpreted as younger than the LCT based on U-Th ages of ~220 ka. Notably, no sanidine grains yielded ages younger than the LCT. This is inconsistent with the younger weighted mean zircon ages identified from the same sampled intervals. SEM imagery reveal that these sanidine grains are heavily fractured, which is consistent with initial emplacement of these grains in a high-energy, explosive eruption (like the LCT) rather than an effusive extrusion of rhyolite (like the rhyolite flow they were separated from) (Figure 4 and 25). This mismatch can be reconciled if the sanidine grains originated in older, likely poorly or unconsolidated, LCT deposits that were disaggregated and entrained into Rhyolite Unit #1 when it erupted.

The eruption of the Lava Creek Tuff dropped the present-day caldera floor down several kilometers relative to surrounding areas and deposited thick sheets of LCT both within the caldera and extending outside the rim. The caldera floor, therefore, during post-LCT volcanism

would have been extensively covered with pre-existing Lava Creek Tuff (Christiansen, 2001), providing a likely source for recycled sanidine grains and subsequent lava flows established conduits through this material and flowed across the surface. It is also likely that eruption of the LCT left behind a crystal-rich rhyolitic mush underlying the caldera; this material would have crystallized fully or been rejuvenated by injection of new magma in post-LCT time. Although entrainment of LCT sanidine grains could have occurred in the subsurface as Rhyolite Unit #1 magmas traversed through this crystallized mush, or at the surface as the lava flowed over the terrain, two lines of evidence suggest entrainment occurred at the surface. One is the fractured morphology of the grains, which must have been broken violently in an eruption like the LCT event. The other is that the closure temperature of argon in sanidine ( $T_C = \sim 250 - 300\text{ }^{\circ}\text{C}$ ) (Reiners et al., 2018) is low enough that if grains were carried in higher temperature subsurface magmas for significant amounts of time, the LCT age sanidines would have been reset to agree with the younger eruption age by diffusion of radiogenic argon from the crystal lattice.

It is also possible that the erroneously old LCT ages in these sanidine grains is a result of trapped excess argon. To test whether the older LCT aged sanidine grains from 501.5 ft and 415 ft represent true age signals or reflect trapped/excess argon, reverse isochrons are shown in Figure 28. Initial argon compositions from these regressions plot near atmospheric values of 295.5, suggesting that excess argon is unlikely to explain the observed ages (Lee et al., 2006; Dickin, 2018). It is also highly unlikely if excess argon was the cause of older ages that it would uniformly affect all grains to the same extent to result in the same age, and even less probable that the age would coincidentally be a geologically significant age. Sanidine grains in Rhyolite Unit #1 with LCT ages are  $633.5\text{ ka} \pm 0.7\text{ ka}$  ( $n=18$ ) for 501.5 ft and  $639.7 \pm 1.4\text{ ka}$  ( $n=9$ ) for 415 ft, suggesting that statistically speaking, excess argon is an improbable cause of older ages. If the

inconsistent sanidine ages resulted from argon loss, younger apparent ages would be expected rather than the older LCT-aged populations observed here (Dickin, 2018). Altogether, these results support interpretation of the sanidine grains as genuinely older inherited crystals rather than artifacts produced by argon systematics.

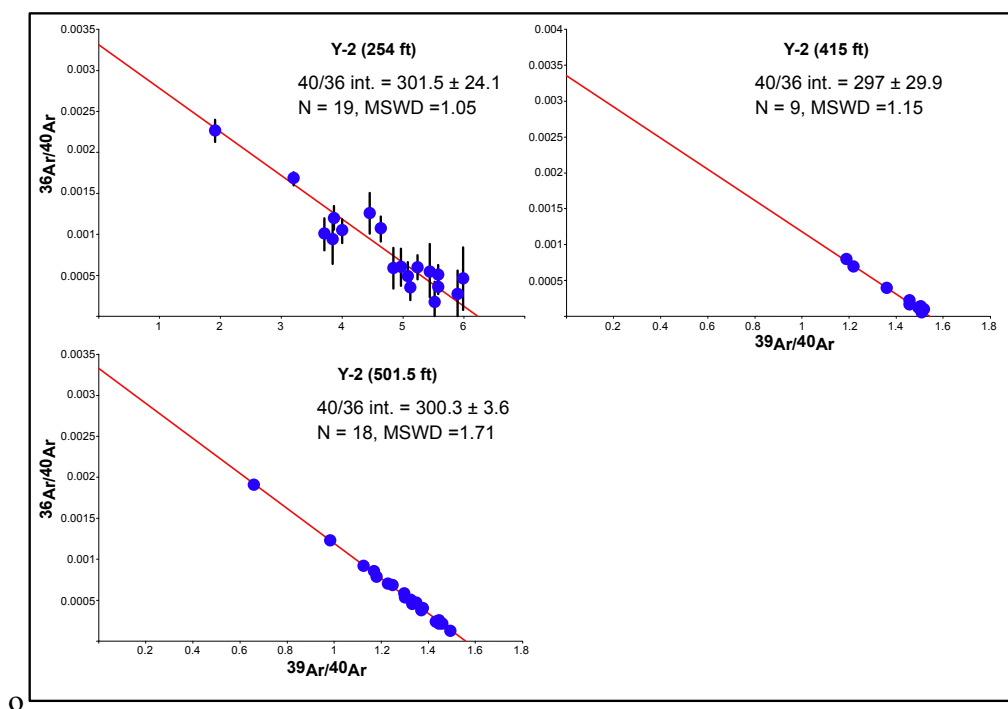


Figure 28: Reverse isochron plots for sanidine  $^{40}\text{Ar}/^{39}\text{Ar}$  analyses from the Y-2 drill core. Regression intercepts represent the initial  $^{40}\text{Ar}/^{36}\text{Ar}$  composition of the analyzed samples. All intercept values overlap the atmospheric  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio of 295.5 within analytical uncertainty, suggesting that excess argon was not a significant influence on the resulting age determinations.

Electron microprobe results help distinguish different eruptive episodes characterized by different states of magmatic evolution, Ba concentrations, and Orthoclase (Or) content. Or content and Ba concentrations from sanidine grains in samples 501.5 ft and 415 ft overlap closely with published Lava Creek Tuff sanidine compositions from Till et al. (2016) and do not overlap with compositions reported from other Upper Basin Member rhyolites (Middle Biscuit Basin, South Biscuit Basin, and Scaup Lake flows) (Figure 29). Combined with the older



$^{40}\text{Ar}/^{39}\text{Ar}$  ages, reverse isochron results, and SEM observations of fractured shard-like morphologies, these data further support the interpretation that sanidines were recycled LCT-derived grains rather than eruption-age grains that crystallized from the rhyolite magma that contained them.

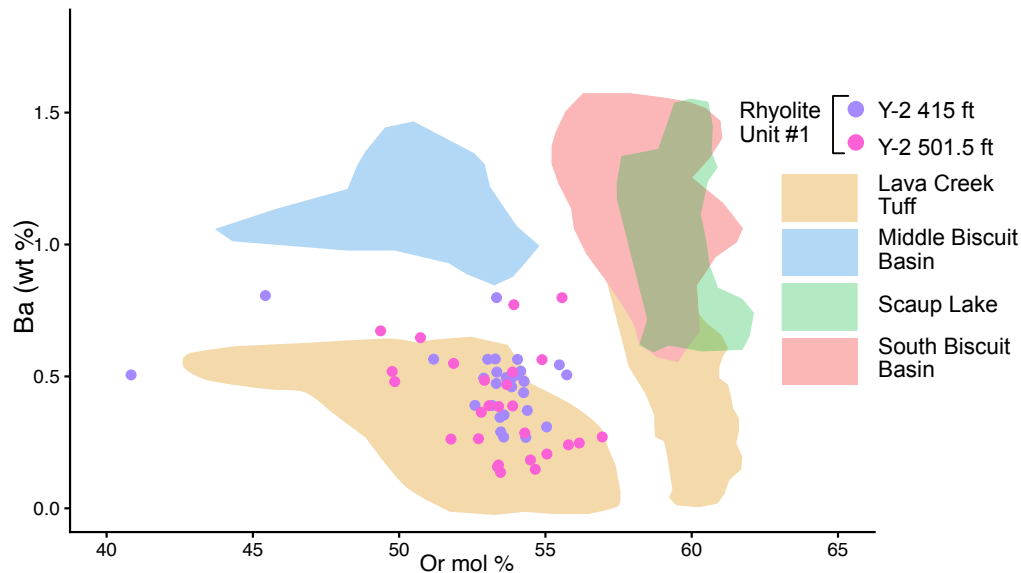


Figure 29: Ba concentration (wt%) versus orthoclase content (Or mol%) for sanidine core compositions from Rhyolite Unit #1 in the Y-2 drill core. Shaded fields indicate published Yellowstone sanidine compositions from Till et al. (2019). Comparable sanidine data are unavailable for several Rhyolite Units, including the Biscuit Basin Flow. The Y-2 data are shown for comparison with established Yellowstone mineral-chemical fields.

#### 4.3.2 Evidence for a Distinct Post-LCT Unit

Multiple lines of evidence suggest that Rhyolite Unit #1 of the Y-2 core represents a previously unknown post-LCT rhyolite eruptive unit. Zircon U-Th weighted mean ages place the eruption of Rhyolite Unit #1 during a time thought to be quiescent between known UBM and CPM eruptive periods (Figure 27). Whole rock trace element geochemistry was examined to determine whether a compositional relationship exists between Rhyolite Unit #1 and a known eruption of either UBM or CPM rhyolites (Figure 30). Immobile trace element plots of Rhyolite

Unit #1 consistently occupy a composition that does not plot cleanly in any of the established compositional fields of UBM, whereas Rhyolite Units #3 and #4 consistently plot within CPM compositional fields. This pattern is reproduced with multiple immobile elements, suggesting the offset is not solely based on hydrothermal alteration, but rather is reflective of the original chemistry. Ideally, glass compositions would provide a more direct comparison to melt chemistry; however, primary glass is not preserved in most Y-2 samples due to pervasive hydrothermal alteration. As a result, whole rock compositions and ratios between relatively immobile elements are used as a framework for comparing rhyolitic units (Shaw, 2006). Although whole rock data cannot uniquely isolate melt evolution from crystal cargo or alteration effects, these relationships support the interpretation that the intermediate interval records a distinct magmatic history relative to both UBM and CPM rhyolites.

Although the geochemistry of Rhyolite Unit #1 does not correlate cleanly with established mapped rhyolite units, petrographic characteristics from Pumice Unit #1 suggest stronger affinity with Upper Basin Member (UBM) rhyolites than Central Plateau Member (CPM) rhyolites. Girard and Stix (2009) have described the presence of mineral aggregates consisting of plagioclase, pyroxenes, and Fe-Ti oxides as a feature of UBM rhyolites. Similar glomerocrystic textures are observed in the Pumice Unit #1, including aggregates dominated by

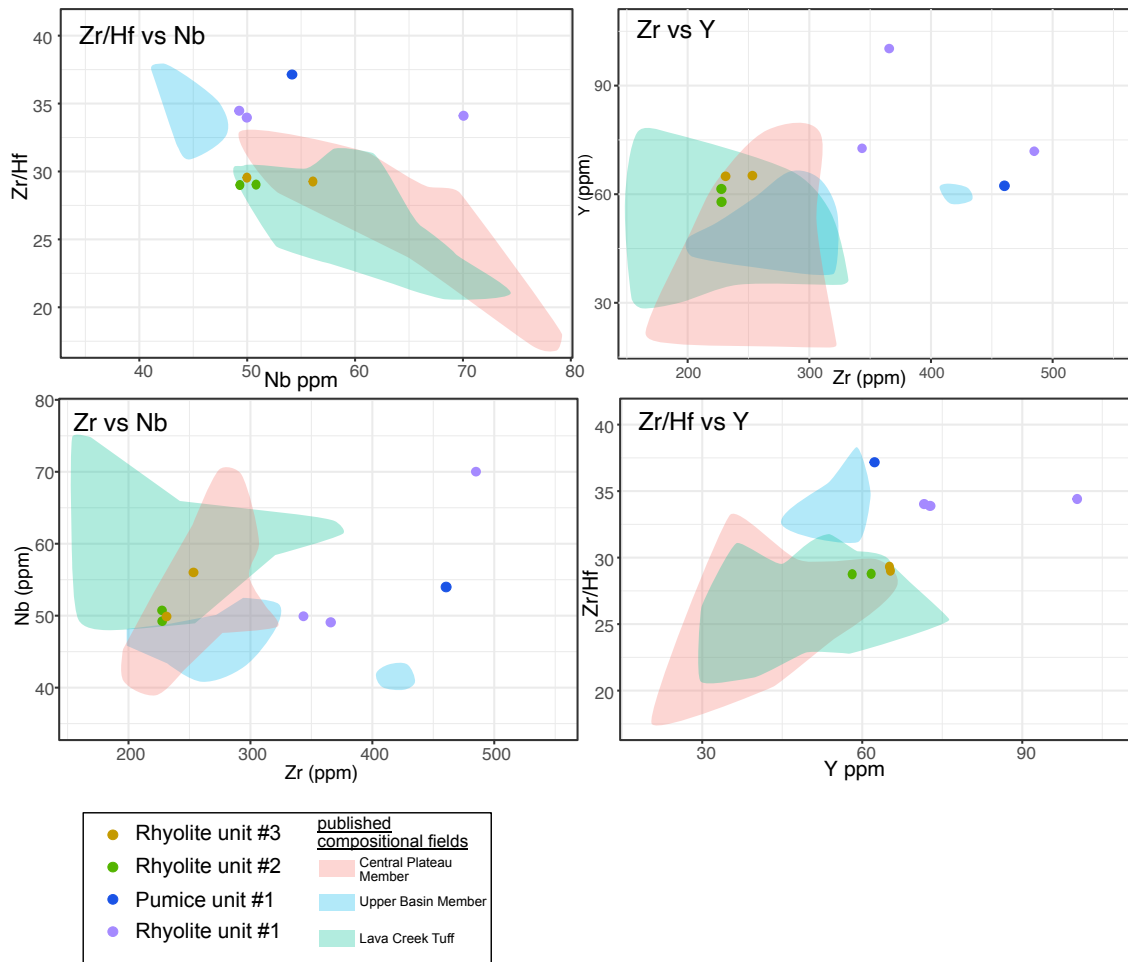


Figure 30: Whole rock trace element compositions of rhyolitic units from the Y-2 drill core compared with published compositional fields for Upper Basin Member (UBM) and Central Plateau Member (CPM) rhyolites. Rhyolite Unit #1 and Pumice Unit #1 consistently plot outside established Yellowstone compositional fields, whereas Rhyolite Units #2 and #3 plot within the CPM field. The contrasting behavior of these units is reproduced across multiple trace element diagrams.

plagioclase and Fe-Ti oxides (Figure 6). The abundance of plagioclase is also diagnostic of UBM flows. As Pumice Unit #1 occurs stratigraphically above Rhyolite Unit #1, this relationship provides another line of evidence that underlying Rhyolite Unit #1 also belongs to UBM period volcanism.

Despite these observations, the altered nature of the interval limits the ability to develop a robust petrogenetic model of how the Yellowstone magmatic system was evolving during this time or confidently fingerprint individual eruptive flows, especially considering the homogeneity in rhyolite compositions during eruptive periods. The integrated dataset does support the interpretation that the Y-2 core preserves a temporally and compositionally distinct interval of post-LCT volcanism not found at the surface or on existing geologic maps.

#### **4.4 Sedimentary Deposition and Paleodrainage Evolution**

##### *4.4.1 Evidence of a Proglacial Lake Associated with Bull Lake Glaciation*

The unit “Laminated Sandstones and Siltstones” (110.5–94 ft) exhibit fine laminations, wavy bedding, planar laminations, and repeated alternations between coarser ash-rich beds and finer-grained sediments, consistent with volcanic ash deposition in a low-energy lacustrine environment. This environment is ideal for preservation of primary volcanic ash, and there are possibly dozens of ash beds from a pulsating eruption. The ash beds contain angular cusped glass shards interpreted as primary or near-primary ash deposits that experienced minimal transport prior to deposition. Furthermore, the laminations of ash are stratified in fining-upward sequences consistent with ash settling into a standing body of water (Freundt et al., 2022). Among these sequences are rounded phenocrysts deposited along with the primary ashes, a feature commonly observed in primary ash-fall deposits into standing water (Freundt et al., 2022).

Two samples from the unit “Laminated Sandstones and Siltstones” (106.5 and 96.5 ft) yielded weighted mean ages of  $140.7 \pm 8.71$  ka and  $154.2 \pm 13.46$  ka, respectively. Although these populations likely contain both detrital and primary zircons which slightly shift the

weighted mean age older, they indicate deposition occurred during or immediately following Bull Lake glaciation. These ages place deposition roughly concurrent with eruption of Group 2 CPM rhyolites, the Spring Creek Flow ( $152.5 \pm 3.5$  ka) and Buffalo Lake Flow ( $148.2 \pm 2.5$  ka), and after Group 1 CPM rhyolites ( $\sim 160$  ka) (Stelten et al., 2023).

The presence of a large lake in Lower Geyser Basin has been invoked in the past as a mechanism to trigger hydrothermal explosions (Muffler et al., 1971). Muffler et al. (1971) hypothesized that the retreat of glacial ice resulted in proglacial lakes occupying the LGB (Figure 31). Although the Pinedale glaciation overprinted all but the most distal deposits of the Bull Lake glaciation, ice during both is thought to have originated on high alpine peaks surrounding the YPVF to the east (Absaroka Range), north (Beartooth Uplift), and northeast (Gallatin Range), eventually accreting enough ice on the center of the plateau that it became a self-sustaining ice sheet (Licciardi and Pierce, 2018). Our interpreted proglacial lake would be from the recession of the Bull Lake glaciers, bounded in the south by CPM groups 1 and 2 and bounded to the east by the caldera wall.

#### *4.4.2 Evidence of Bull Lake and Pinedale Glaciation Events*

After drainage of the lake positioned over the Y-2 drill site, the sedimentary sequence transitioned into a glacial outwash setting dominated mostly by massive fining upward conglomerates interpreted as stacked fluvial bar deposits interbedded with reworked ash beds that contain clasts of pumice and perlite fluvial gravel #1. fluvial Gravel #1 did not yield any dateable zircons or sanidine, however, this interval is interpreted to be associated with recession

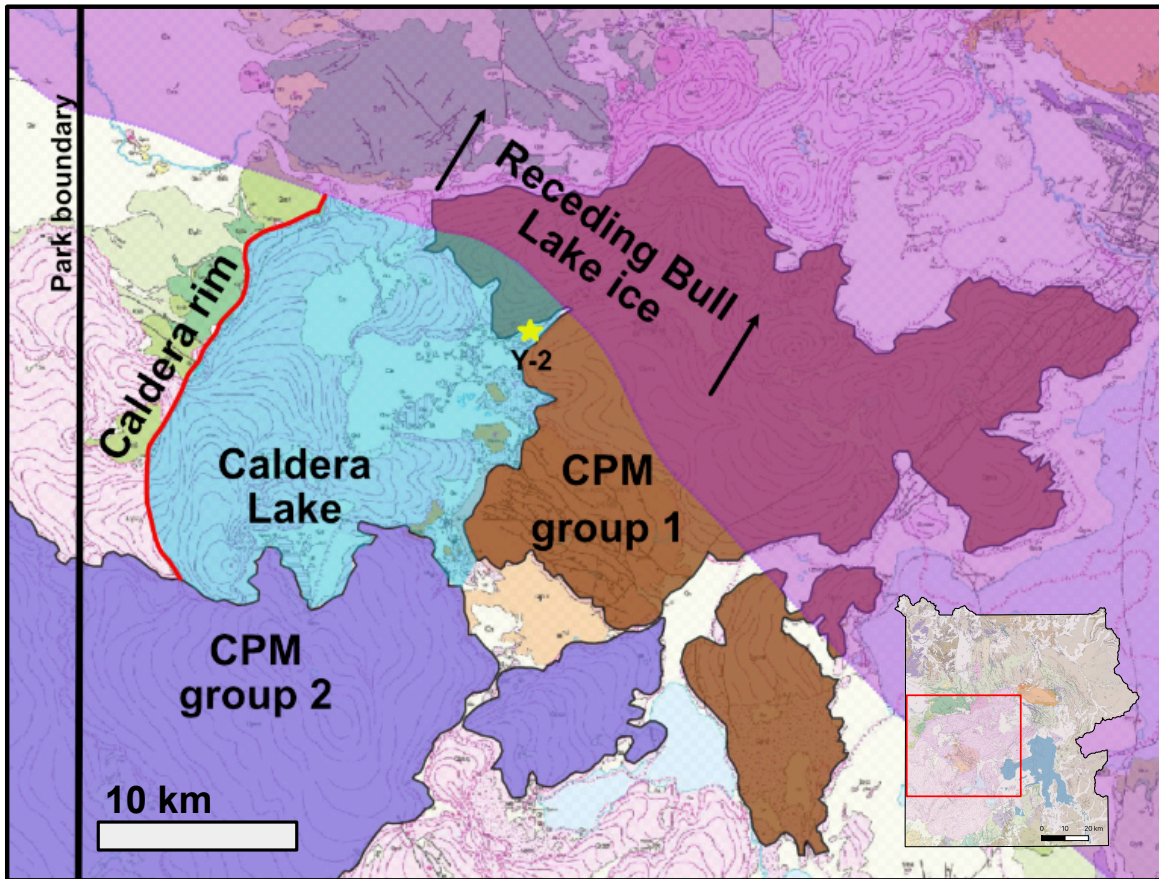


Figure 31: Paleoreconstruction of Lower Geyser Basin during deposition of the ash beds preserved within the “Laminated Sandstones and Siltstones”. The reconstruction illustrates a proposed proglacial lake bounded to the south by CPM Group 1 ( $160.3 \pm 1.0$  ka) and Group 2 ( $149.8 \pm 4.0$  ka) rhyolite flows, to the east by the caldera wall, and to the north by a schematic extent of residual Bull Lake glacial ice. Base map modified from Christensen 2001. The underlying geologic map is retained for geographic reference only and does not represent the interpreted paleotopography reconstructed in this study

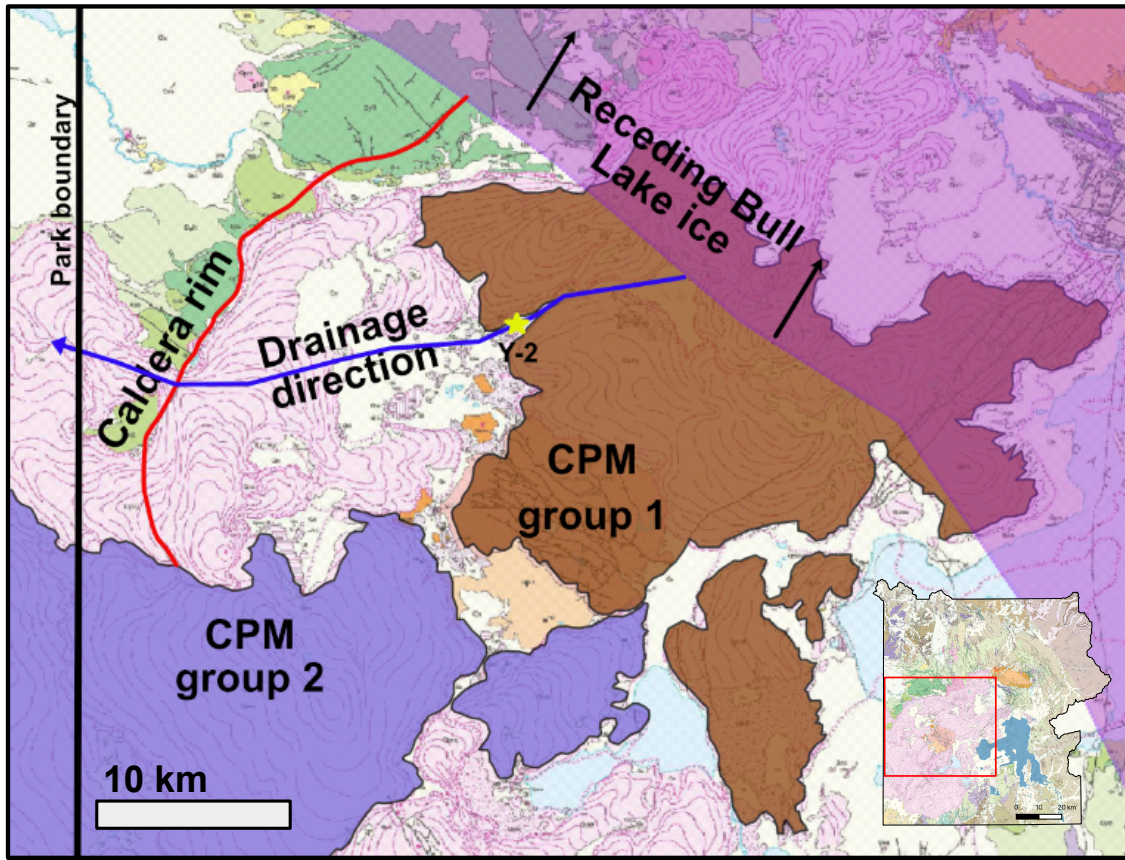
of the Bull Lake glacier due to its direct contact with the lacustrine deposit. The stacked bar deposits are sometimes massive, whereas others have apparent cross bedding and planar beds interbedded with each other, consistent with traction-dominated transport within a fluvial system. The beds distinguished in the core vary in thickness from four to eight feet, providing an estimate of maximum-flow depths of the ancestral river. This is deeper than the current Firehole River that starts in Upper Geyser Basin and drains Upper, Midway, Biscuit, Black Sand, and Lower Geyser Basins before joining the Madison River. The modern Firehole River has an

average depth of approximately one to five feet. An ancestral Y-2 proglacial river of significant size and depth is logical considering the outwash emanating from a retreating Bull Lake ice cap (Figure 32).

Above Glaciofluvial Gravel #1 is a fine-grained white silt that is interpreted as diatomaceous silt, which is a common unit found in geyser basins including the LGB and associated with hydrothermal features (Muffler et al., 1982). Diatomaceous silt requires ponded, standing water, likely marshes, providing evidence that the hydrothermal system at Y-2 has been a long-lived feature at this location through drastic land surface changes. The overlying diatomaceous silt also represents the evolution of the environment following glaciation, starting with a proglacial lake, and then an outwash fluvial system, and finally a thermal pond at the Y-2 drill site. It should be noted that the central plateau of Yellowstone has modest relief. It is a caldera with a series of domes and plateau-like rhyolite flows. This region does not accumulate as much winter snowpack as the high mountains that surround the plateau, and it drains to each side from the center, resulting in small drainage catchments for each direction of drainage.

A second fluvial gravel overlying the diatomaceous silt deposit is characterized by coarser grain sizes and, on average, thicker bars (up to 15 feet). These deposits indicate a renewed period of high-energy deposition. There is evidence for scour at the base of gravel beds, and it is unknown how much is missing from the record due to erosion or how much time the ~15 ft thick diatomaceous silt represents. It is possible that Glaciofluvial Gravel #2 records a younger episode of glacial outwash related to the recession of the Pinedale glaciation.





*Figure 32: Paleoreconstruction of Lower Geyser Basin during recession of Bull Lake glaciation. Residual glacial ice is shown retreating toward the northeast, while the blue line represents a hypothetical glacial outwash drainage pathway through the basin. This drainage route may have followed low-lying topography similar to that inferred from flow-direction indicators (oogives) preserved on nearby rhyolite flows. Base map modified from Christiansen (2001). The underlying geologic map is retained for geographic reference only and does not represent the interpreted paleotopography reconstructed in this study.*

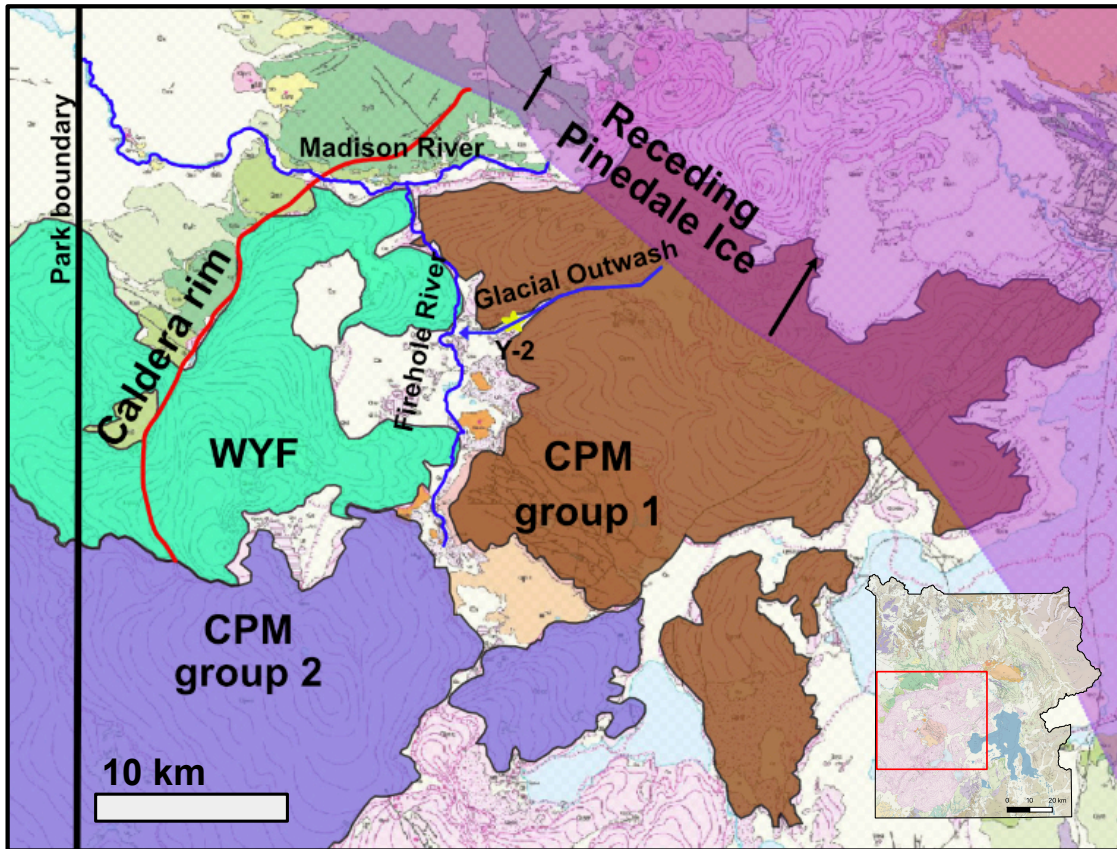
Interpretation of the glaciofluvial deposits is complicated by the emplacement of the West Yellowstone Flow (WYF), which occurred around 109.9 ka which is present in the LGB but not present in the Y-2 core. Zircon U-Th ages of the Laminated Siltstones and Sandstones below the Gravel #1 yield an age older than the WYF and it is interpreted to have deposited during the recession of Bull Lake glaciers ~140 ka. We interpret Gravel #2 as deposited during recession of Pinedale glaciers much later in time (~13 ka). Thus, we suggest Glaciofluvial Gravel #1 was deposited before the emplacement of the WYF, and the emplacement of the WYF likely altered



drainage pathways before deposition of Gravel #2. Emplacement of the WYF may have altered drainage pathways and contributed to diversion of ancestral river systems from westward flowing drainages to northward drainages to the modern Madison River (Figure 33).

Before the WYF erupted, ancestral rivers across LGB would likely have flowed directly to the west, carving a path of steepest descent that was later followed by the WYF, which would follow low-lying topography in the same way the preceding river would. The WYF vent is located on figure 33 and map scale flow directions indicated it flowed northward through low lying topography out of the caldera. That is, the WYF flow direction likely followed a paleocanyon drainage on the western side of LGB, where a low-lying area presumably existed between the pre-existing Mount Jackson rhyolite flows (1.3 – 0.7 Ma). Later, at the time of Gravel #2, the WYF may have been emplaced, blocking the previous drainage and diverting this river northward to its present pathway into the Madison River.

The presence of paleosols with developed root casts and insect burrows at 34-30 ft show subsequent stabilization of the landscape and subaerial exposure. Thus, fluvial deposition ceased or shifted away from the Y-2 drill core site, which could again be due to full glacial retreat removing a major source of water to feed the river.



*Figure 33: Paleoreconstruction of Lower Geyser Basin during recession of Pinedale glaciation. Glacial outwash drainage is shown flowing through the basin as ice retreated from the Yellowstone Plateau. By this time, the West Yellowstone Flow (WYF) had been emplaced and likely acted as a topographic barrier, diverting drainage northward toward its modern course where the Firehole River joins the Madison River at Madison Junction. Base map modified from Christiansen (2001). The underlying geologic map is retained for geographic reference only and does not represent the interpreted paleotopography reconstructed in this study.*

#### 4.4.3 Modern Hydrothermal System

The uppermost portion of the core consists of hydrothermal deposits composed primarily of siliceous sinter interbedded with minor travertine and ferromanganese hydrothermal deposits. These deposits record the continued presence of a hydrothermal system within Lower Geyser Basin. U-Th ages obtained from these deposits are variable. Ages range from  $22.7 \pm 7.1$  ka to  $8.3 \pm 11.2$  ka, with large uncertainties (Figure 34). However, all but two sample depths dated in this interval yield ages  $< 10$  ka ( $n = 5$ ) and one older sample has uncertainties that overlap with

this time frame. Although high uncertainty makes applying these ages to constrain hydrothermal deposition difficult, this, along with relative stratigraphic position of the hydrothermal deposits suggests hydrothermal activity was occurring at this location during the late Pleistocene to present day, after the recession of Pinedale glaciers (~13 ka).

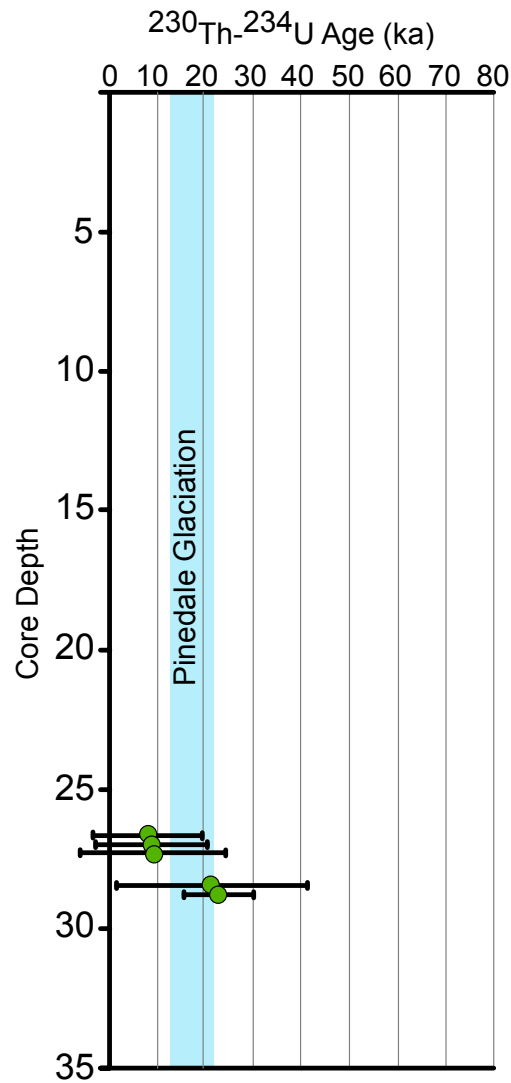


Figure 34: *U-series ( $^{234}\text{U}$ - $^{230}\text{Th}$ ) ages of travertine and calcite samples plotted versus depth in the Y-2 drill core. Error bars represent analytical uncertainties, which are large relative to the duration of Pinedale glaciation (blue shaded field; 23–13 ka).*

#### 4.5 Alternate Hypothesis

The unit of paleosols identified near the top of the Y-2 and directly overlying both glacial outwash deposits provide an important constraint on the paleoenvironmental reconstruction but remain one of the more uncertain aspects of the stratigraphy due to a lack of age control on this section. Poor core recovery in the unconsolidated paleosol units prevents the observation of well-developed soil horizons that would be necessary to determine how long the paleosols developed. Paleosol development has been studied around Yellowstone Plateau that found that well developed paleosols with extensive development of a thin gray A horizon (5-20 cm), a thick sandy silt B horizon (50 to 75 cm), require tens of thousands of years to form, and therefore are associated with post-Bull Lake interglacial time, rather than the short time available post-Pinedale where paleosols are far less developed and difficult to recognize with a A horizon 5-15 cm thick and a “color B” horizon 15 to 30 cm thick (Pierce et al., 1976). If the paleosols are more extensively developed, they could potentially correlate with the Sangamon interglacial (130-75 ka, (Eyles and Williams, 1992)) that occurred immediately after MIS6 (Bull Lake), rather than a relatively short period of landscape stability after the Pinedale glaciation as discussed in above sections.

If the paleosols are indeed Sangamon in age, both underlying glaciofluvial deposits would be associated with Bull Lake glaciation requiring reinterpretation of the gravel units previously attributed to both Bull Lake and Pinedale glaciations. Under this interpretation, Lower Geyser Basin would not preserve evidence of Pinedale outwash within the Y-2 core. This may reflect differences in paleodrainage resulting from evolving topography or localized non-deposition related to the Y-2 drill site's position within a small canyon. However, the incomplete recovery precludes determination of whether the paleosol is sufficiently developed to require a

significantly longer period of landscape stability that would be observed with a warm period like the Sangamon. Age constraints within the sedimentary section is limited, only by ash beds in the lacustrine unit ( $154.2 \pm 13.46$  ka and  $140.7 \pm 8.71$ ), and travertine deposits in the upper most hydrothermal unit portion of the core  $22.7 \pm 7.1$  ka which bracket the glacial gravels. This limits the ability to answer which glaciation each gravel is associated with. Thus, stratigraphic relationships were used to interpret the origin of each gravel unit.

Future studies could attempt to date the depositional timing of the fluvial gravels using a technique such as optically stimulates luminescence (OSL), which has been applied to feldspars reset by hydrothermal explosion events in LGB (Cordero et al., 2026). However, the immense amount of hydrothermal alteration that has occurred within the Y-2 core easily could reset the OSL signal from heat exposure. Conversely, if the paleosol was Pinedale in age, some of the roots preserved in this unit may be within the age range of radiocarbon. Radiocarbon dating in Yellowstone has proven to be difficult from influx of  $\text{CO}_2$  from the volcanic system which is non atmospheric and makes radiocarbon dates unreliable at times (Churchill et al., 2020). Due to the lack of a continuous paleosol stratigraphic section and adequate age constraints, it is impossible to determine which interpretation of the sedimentary section is correct with available data.

## 5. CONCLUSIONS

The Y-2 drill core preserves a more complex record of post-Lava Creek Tuff volcanism and sedimentation within the Lower Geyser Basin than is represented by modern surface exposures alone. Integration of core logging observations, petrography, SEM imaging, whole rock geochemistry, electron microprobe analysis of feldspar, and geochronology supports the presence of multiple volcanic, volcanoclastic, sedimentary, and hydrothermal intervals recording a prolonged and dynamic post-caldera history within the Yellowstone Volcanic Plateau Field subsurface.

Interpretation of the Y-2 core is complicated by extensive hydrothermal alteration, volcanic material reworking, and inherited crystal populations. Pristine magmatic compositions are not preserved throughout much of the core due to hydrothermal alteration that has variably modified major and trace element concentrations and removed volcanic glass. However, signatures preserved in relatively immobile trace elements, combined with petrography and U-Th zircon ages suggest the presence of a previously unknown volcanic unit identified within the core. Significantly, this unit erupted during a time previously thought to be a quiescent period between eruption of UBM and CPM rhyolites, requiring revision of eruption recurrence interval and understanding of the evolution of the Yellowstone magmatic system through time.

Zircon U-Th geochronology supports the identification of two different Central Plateau Member volcanic units in the Y-2 core. In the lowermost unit Rhyolite Unit #1, sanidine  $^{40}\text{Ar}/^{39}\text{Ar}$  analyses yielded predominantly Lava Creek Tuff-aged grains from intervals interpreted to be stratigraphically younger than the LCT from U-Th zircon weighted mean ages. Reverse

isochron analyses together with SEM textures and feldspar chemistry show the interpretation of these sanidines as recycled inherited crystals derived from solidified surficial Lava Creek Tuff rather than artifacts produced by excess argon. These results demonstrate the difficulty of interpreting volcanic chronologies within altered and reworked Yellowstone deposits, in which inherited crystal populations may persist through younger eruptive and sedimentary processes.

Volcaniclastic and sedimentary intervals within the Y-2 core record repeated episodes of volcanic reworking, sediment transport, and localized deposition within the caldera following the eruption of the Lava Creek Tuff. Mixed grain populations, variable geochemistry, and sedimentary structures collectively suggest a dynamic post-caldera environment influenced by both volcanism and evolving depositional systems. The sedimentary intervals preserved within the core likely represent part of a poorly preserved temporal window within the Lower Geyser Basin prior to extensive modification by Pinedale glaciation and younger hydrothermal activity.

Overall, the Y-2 core demonstrates that important portions of Yellowstone's post LCT volcanic and sedimentary history remain preserved primarily within the subsurface record. While no individual dataset uniquely constrains eruptive or depositional history, integration of multiple independent datasets provides a framework for reconstructing portions of Yellowstone evolution that are incompletely represented by surface mapping alone.

Ongoing work associated with this study includes additional incremental-heating of  $^{40}\text{Ar}/^{39}\text{Ar}$  analyses of sanidine that may further refine temporal relationships between Rhyolite Unit #3 and Rhyolite Unit #2. This investigation focuses on one drill core in the YPVF; there are 13 other cores available for further research that could be investigated in more detail using modern techniques. Expansion of similar integrated analyses, as presented in this work, to the

other Yellowstone drill cores may allow volcanic and sedimentary intervals to be correlated between boreholes and further improve reconstruction of post-caldera stratigraphy within the YPVF. Additional shallow geophysical investigations may also help constrain the lateral extent of subsurface volcanic units and identify structural offsets affecting preserved stratigraphy beneath the modern hydrothermal system.



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## 7. APPENDIX

Table 5 ICP-MS trace-element concentrations for selected samples from the Y-2 drill core.

| Depth (ft) | 32    | 69.5   | 79.5   | 106.5  | 136.5  | 151    | 254    | 262    | 380    | 395    | 402.5  | 415    | 450.5  | 501.5  |
|------------|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Element    |       |        |        |        |        |        |        |        |        |        |        |        |        |        |
| La ppm     | 50.46 | 115.39 | 102.34 | 87.86  | 82.09  | 85.92  | 86.66  | 85.83  | 82.95  | 67.33  | 95.61  | 125.42 | 135.36 | 86.66  |
| Ce ppm     | 96.03 | 215.62 | 197.56 | 161.95 | 150.21 | 151.72 | 161.47 | 159.35 | 160.90 | 117.33 | 170.89 | 232.88 | 270.28 | 161.47 |
| Pr ppm     | 10.76 | 24.08  | 22.12  | 18.10  | 16.92  | 18.03  | 17.60  | 17.87  | 17.80  | 12.38  | 18.69  | 25.99  | 31.45  | 17.60  |
| Nd ppm     | 37.86 | 84.86  | 79.05  | 63.44  | 59.10  | 64.36  | 62.62  | 62.78  | 64.77  | 41.41  | 64.97  | 91.64  | 117.41 | 62.62  |
| Sm ppm     | 7.31  | 16.50  | 15.51  | 12.12  | 11.13  | 12.40  | 11.29  | 11.90  | 12.83  | 7.36   | 12.33  | 16.45  | 22.75  | 11.29  |
| Eu ppm     | 0.46  | 0.97   | 1.09   | 0.81   | 0.74   | 0.73   | 1.57   | 0.81   | 2.15   | 2.15   | 0.91   | 2.30   | 1.97   | 1.57   |
| Gd ppm     | 6.65  | 15.20  | 14.61  | 11.18  | 10.09  | 11.34  | 11.15  | 11.01  | 11.60  | 6.35   | 11.39  | 14.45  | 18.96  | 11.15  |
| Tb ppm     | 1.14  | 2.56   | 2.63   | 1.93   | 1.69   | 1.93   | 1.99   | 1.87   | 1.96   | 1.05   | 1.97   | 2.32   | 2.96   | 1.99   |
| Dy ppm     | 6.89  | 15.07  | 16.28  | 11.69  | 10.15  | 11.17  | 12.94  | 11.10  | 11.44  | 6.31   | 11.83  | 13.27  | 15.91  | 12.94  |
| Ho ppm     | 1.44  | 3.09   | 3.38   | 2.40   | 2.05   | 2.19   | 3.00   | 2.32   | 2.30   | 1.31   | 2.38   | 2.65   | 2.94   | 3.00   |
| Er ppm     | 3.98  | 8.92   | 9.95   | 6.90   | 5.66   | 5.98   | 8.99   | 6.44   | 6.53   | 3.70   | 6.66   | 7.33   | 7.54   | 8.99   |
| Tm ppm     | 0.60  | 1.35   | 1.59   | 1.08   | 0.85   | 0.90   | 1.40   | 1.00   | 1.00   | 0.56   | 1.01   | 1.11   | 1.14   | 1.40   |
| Yb ppm     | 3.81  | 8.13   | 9.90   | 6.59   | 5.35   | 5.49   | 8.91   | 6.13   | 6.31   | 3.62   | 6.25   | 7.02   | 6.88   | 8.91   |
| Lu ppm     | 0.56  | 1.21   | 1.43   | 0.98   | 0.79   | 0.80   | 1.47   | 0.90   | 0.96   | 0.55   | 0.94   | 1.05   | 1.00   | 1.47   |
| Ba ppm     | 186   | 394    | 612    | 986    | 322    | 316    | 801    | 244    | 754    | 1487   | 399    | 1131   | 922    | 801    |
| Th ppm     | 15.24 | 29.70  | 33.01  | 27.46  | 25.66  | 26.48  | 24.15  | 25.88  | 25.12  | 17.94  | 28.61  | 32.40  | 24.78  | 24.15  |
| Nb ppm     | 31.02 | 58.45  | 65.26  | 51.83  | 49.32  | 50.82  | 49.20  | 49.97  | 54.07  | 34.87  | 54.61  | 70.11  | 50.02  | 49.20  |
| Y ppm      | 42.73 | 84.55  | 92.11  | 74.21  | 58.12  | 61.67  | 100.37 | 65.10  | 62.18  | 36.91  | 66.91  | 71.73  | 72.54  | 100.37 |
| Hf ppm     | 3.95  | 9.25   | 10.82  | 8.19   | 8.02   | 8.01   | 10.60  | 7.98   | 12.29  | 10.05  | 10.29  | 14.24  | 10.13  | 10.60  |
| Ta ppm     | 1.62  | 4.01   | 4.46   | 3.78   | 3.52   | 3.55   | 3.03   | 3.56   | 3.52   | 2.12   | 3.70   | 4.16   | 3.07   | 3.03   |
| U ppm      | 8.57  | 8.97   | 8.61   | 4.81   | 5.87   | 5.83   | 4.40   | 6.27   | 5.57   | 2.61   | 3.18   | 4.95   | 4.40   | 4.40   |
| Pb ppm     | 19.29 | 38.59  | 38.99  | 36.22  | 27.19  | 28.11  | 29.78  | 30.15  | 25.50  | 30.56  | 32.57  | 28.73  | 25.51  | 29.78  |
| Rb ppm     | 86.1  | 80.6   | 142.3  | 181.4  | 192.0  | 193.1  | 129.7  | 217.4  | 125.7  | 111.3  | 167.1  | 158.6  | 115.7  | 129.7  |
| Cs ppm     | 86.16 | 42.74  | 109.16 | 217.30 | 6.11   | 4.47   | 2.30   | 20.90  | 12.48  | 4.55   | 2.85   | 2.89   | 49.74  | 2.30   |
| Sr ppm     | 30    | 26     | 53     | 90     | 14     | 14     | 32     | 13     | 149    | 65     | 25     | 46     | 42     | 32     |
| Sc ppm     | 1.7   | 2.6    | 2.7    | 2.5    | 1.9    | 1.9    | 1.9    | 2.0    | 8.3    | 1.6    | 1.7    | 2.0    | 2.1    | 1.9    |
| Zr ppm     | 121   | 266    | 318    | 228    | 227    | 227    | 365    | 231    | 460    | 373    | 323    | 484    | 343    | 365    |

Table 6: XRF major- and minor-element concentrations normalized to 100 wt% for selected samples from the Y-2 drill core.

| Depth (ft)                     | 32     | 69.5   | 79.5   | 106.5  | 136.5  | 151    | 254    | 262    | 380    | 395    | 402.5  | 415    | 450.5  | 501.5  |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Element wt %                   |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| SiO <sup>2</sup>               | 88.37  | 77.48  | 73.46  | 71.47  | 78.25  | 77.97  | 75.36  | 78.54  | 73.91  | 76.89  | 80.40  | 69.02  | 76.52  | 77.15  |
| TiO <sup>2</sup>               | 0.13   | 0.23   | 0.25   | 0.20   | 0.15   | 0.16   | 0.20   | 0.17   | 0.53   | 0.18   | 0.17   | 0.24   | 0.20   | 0.19   |
| Al <sup>2</sup> O <sup>3</sup> | 6.45   | 14.80  | 16.71  | 13.61  | 11.49  | 11.78  | 14.34  | 12.29  | 14.21  | 13.19  | 10.55  | 17.15  | 13.26  | 11.73  |
| FeO*                           | 0.88   | 1.85   | 1.49   | 2.05   | 1.30   | 1.06   | 1.68   | 1.53   | 3.52   | 1.54   | 1.78   | 2.58   | 1.63   | 2.21   |
| MnO                            | 0.03   | 0.08   | 0.09   | 4.92   | 0.02   | 0.01   | 0.06   | 0.05   | 0.09   | 0.02   | 0.04   | 0.05   | 0.05   | 0.03   |
| MgO                            | 0.07   | 0.09   | 0.08   | 0.14   | 0.02   | 0.02   | 0.08   | 0.04   | 0.37   | 0.04   | 0.08   | 0.10   | 0.03   | 0.02   |
| CaO                            | 1.69   | 0.94   | 1.89   | 1.79   | 0.37   | 0.34   | 1.16   | 1.21   | 1.46   | 0.49   | 0.27   | 0.40   | 1.75   | 0.42   |
| Na <sup>2</sup> O              | 0.80   | 1.72   | 2.91   | 2.49   | 3.14   | 3.27   | 3.38   | 3.69   | 3.37   | 2.59   | 1.90   | 5.15   | 3.73   | 3.19   |
| K <sup>2</sup> O               | 1.58   | 2.80   | 3.10   | 3.32   | 5.25   | 5.39   | 3.74   | 2.46   | 2.46   | 5.05   | 4.77   | 5.30   | 2.83   | 5.07   |
| P <sup>2</sup> O <sup>5</sup>  | 0.01   | 0.02   | 0.01   | 0.01   | 0.01   | 0.01   | 0.01   | 0.01   | 0.06   | 0.01   | 0.03   | 0.01   | 0.01   | 0.01   |
| Sum                            | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

Table 7: Unnormalized XRF major- and minor-element concentrations for selected samples from the Y-2 drill core.

| Depth (ft)                     | 32    | 69.5  | 79.5  | 106.5 | 136.5 | 151   | 254   | 262   | 380   | 395   | 402.5 | 415   | 450.5 | 501.5 |
|--------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Element wt %                   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| SiO <sup>2</sup>               | 80.96 | 71.93 | 66.08 | 64.41 | 77.77 | 77.62 | 67.80 | 72.61 | 72.12 | 75.56 | 78.85 | 67.98 | 69.83 | 76.24 |
| TiO <sup>2</sup>               | 0.120 | 0.210 | 0.228 | 0.178 | 0.153 | 0.156 | 0.177 | 0.157 | 0.520 | 0.174 | 0.165 | 0.238 | 0.181 | 0.184 |
| Al <sup>2</sup> O <sup>3</sup> | 5.91  | 13.74 | 15.03 | 12.27 | 11.42 | 11.73 | 12.90 | 11.37 | 13.86 | 12.96 | 10.35 | 16.89 | 12.10 | 11.59 |
| FeO*                           | 0.80  | 1.72  | 1.34  | 1.84  | 1.29  | 1.05  | 1.51  | 1.42  | 3.44  | 1.51  | 1.75  | 2.54  | 1.48  | 2.18  |
| MnO                            | 0.029 | 0.076 | 0.080 | 4.437 | 0.017 | 0.008 | 0.050 | 0.051 | 0.087 | 0.022 | 0.037 | 0.054 | 0.045 | 0.027 |
| MgO                            | 0.07  | 0.08  | 0.08  | 0.12  | 0.02  | 0.02  | 0.07  | 0.04  | 0.36  | 0.04  | 0.08  | 0.10  | 0.02  | 0.02  |
| CaO                            | 1.54  | 0.87  | 1.70  | 1.61  | 0.37  | 0.34  | 1.04  | 1.12  | 1.43  | 0.48  | 0.27  | 0.39  | 1.60  | 0.41  |
| Na <sup>2</sup> O              | 0.73  | 1.60  | 2.62  | 2.24  | 3.12  | 3.25  | 3.04  | 3.41  | 3.29  | 2.54  | 1.86  | 5.07  | 3.40  | 3.15  |
| K <sup>2</sup> O               | 1.45  | 2.60  | 2.78  | 2.99  | 5.21  | 5.37  | 3.36  | 2.27  | 2.40  | 4.96  | 4.68  | 5.22  | 2.58  | 5.01  |
| P <sup>2</sup> O <sup>5</sup>  | 0.008 | 0.017 | 0.011 | 0.010 | 0.006 | 0.007 | 0.007 | 0.006 | 0.062 | 0.012 | 0.034 | 0.009 | 0.008 | 0.008 |
| Sum                            | 91.62 | 92.84 | 89.95 | 90.12 | 99.38 | 99.56 | 89.96 | 92.46 | 97.58 | 98.27 | 98.07 | 98.50 | 91.25 | 98.82 |
| LOI %                          | 7.85  | 6.54  | 9.65  | 9.41  | 0.46  | 0.43  | 9.61  | 7.55  | 2.16  | 1.11  | 1.58  | 1.15  | 8.22  | 0.63  |

Table 8: Accuracy estimated from comparison of 100 CRM analyses to GeoReM consensus values over five years. \*\* Precision estimated from the relative standard deviation of 50 AGV-1 analyses over five years. \*\*\* Precision estimated from the average relative percent difference between 500 repeat-pair analyses over five years.

| ICP-MS                         | Limit of detection       | *Accuracy RPD (%) | **Precision RSD (%) | ***Precision RPD (%) |
|--------------------------------|--------------------------|-------------------|---------------------|----------------------|
| La ppm                         | 0.00693                  | 3.05              | 0.59                | 1.12                 |
| Ce ppm                         | 0.02067                  | 2.41              | 0.57                | 1.16                 |
| Pr ppm                         | 0.00261                  | 2.56              | 0.77                | 1.29                 |
| Nd ppm                         | 0.01485                  | 1.89              | 0.95                | 1.25                 |
| Sm ppm                         | 0.00926                  | 5.73              | 1.46                | 1.87                 |
| Eu ppm                         | 0.00255                  | 6.35              | 1.28                | 1.73                 |
| Gd ppm                         | 0.00410                  | 3.45              | 1.1                 | 1.33                 |
| Tb ppm                         | 0.00158                  | 7.15              | 1.75                | 1.58                 |
| Dy ppm                         | 0.00298                  | 7.42              | 1.15                | 1.43                 |
| Ho ppm                         | 0.00132                  | 9.02              | 1.06                | 1.47                 |
| Er ppm                         | 0.00246                  | 4.87              | 1.24                | 1.64                 |
| Tm ppm                         | 0.00090                  | 2.55              | 1.68                | 1.52                 |
| Yb ppm                         | 0.00299                  | 1.88              | 1.12                | 1.42                 |
| Lu ppm                         | 0.00130                  | 2.7               | 1.93                | 2.09                 |
| Ba ppm                         | 0.35147                  | 1.66              | 1.08                | 1.37                 |
| Th ppm                         | 0.00475                  | 2.77              | 1.1                 | 2.22                 |
| Nb ppm                         | 0.00353                  | 7.01              | 0.84                | 1.77                 |
| Y ppm                          | 0.01381                  | 2.5               | 0.74                | 1.43                 |
| Hf ppm                         | 0.00164                  | 2.29              | 0.98                | 1.58                 |
| Ta ppm                         | 0.00057                  | 2.66              | 1.47                | 2.15                 |
| U ppm                          | 0.00083                  | 2.28              | 1.12                | 2.03                 |
| Pb ppm                         | 0.03522                  | 2.79              | 0.85                | 2.09                 |
| Rb ppm                         | 0.03440                  | 2.37              | 0.83                | 1.97                 |
| Cs ppm                         | 0.00440                  | 2.75              | 1.83                | 2.38                 |
| Sr ppm                         | 0.33335                  | 1.99              | 0.67                | 1.88                 |
| Sc ppm                         | 0.03726                  | 3.07              | 1.71                | 4.06                 |
| Zr ppm                         | 0.05440                  | 2.76              | 1.08                | 1.49                 |
| XRF                            | Replicate R <sup>2</sup> |                   |                     |                      |
| SiO <sup>2</sup>               | 0.26                     | 0.99975           |                     |                      |
| TiO <sup>2</sup>               | 0.012                    | 0.99996           |                     |                      |
| Al <sup>2</sup> O <sup>3</sup> | 0.097                    | 0.99995           |                     |                      |
| FeO*                           | 0.14                     | 0.99977           |                     |                      |
| MnO                            | 0.002                    | 0.99983           |                     |                      |
| MgO                            | 0.073                    | 0.99999           |                     |                      |
| CaO                            | 0.061                    | 0.99995           |                     |                      |
| Na <sup>2</sup> O              | 0.029                    | 0.99992           |                     |                      |
| K <sup>2</sup> O               | 0.010                    | 0.99999           |                     |                      |
| P <sup>2</sup> O <sup>5</sup>  | 0.003                    | 0.99997           |                     |                      |