

LAYER BY LAYER:
REMAPPING, PETROLOGY, AND GEOCHRONOLOGY
OF THE MADISON JUNCTION AREA, YELLOWSTONE NATIONAL PARK

by
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DEDICATION

To Kari Jolink, Mildred Irwin, and Millard Irwin. I take you with me everywhere.

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There are so many people to thank for this project. I could not do this alone, and I am forever grateful to everyone who has helped me through this research. First, I would like to thank the foundations who funded this project: NSF Foundation, Brinson Foundation, Sloan Scholars Program, Tobacco Root Geological Society, Montana Geological Society, and the Geological Society of America. Thank you to my amazing advisor, Dr. Madison Myers. I would not be here without you, and I am so grateful for your continued support through graduate school. Thank you to my committee members, Drs. Colin Wilson and Mark Stelten, for their incredibly helpful support and knowledge. Thank you to the MOnSTER lab, with a special thanks to my Yellowstone Mom, Stacy Henderson. Thank you to all the friends that I've made in and out of school, all of whom have constantly supported me through this experience in and out of school. Thank you to my undergraduate field assistants for their help in the field and the lab, I could not do this without them: Lexi Luft, Liam Arnold, Faith Nolander, and Lynne Gormley. A special thank you to the Yellowstone Volcano Observatory and Yellowstone National Park for letting me run around the park for two summers. All fieldwork was conducted under permit numbers YELL-2024-SCI-0031 and YELL-2025-SCI-5248. To Mom, Dad, Calli, and Alyssa, and the rest of my family, thank you for answering my countless phone calls and supporting me through graduate school. And to Miss Mae Mae, I love you sweet girl. Thank you for everything.

AMERICAN INDIAN HERITAGE

Olivia Wheeler is an enrolled member of the Sault Ste. Marie Tribe of Chippewa Indians in Sault Ste. Marie, Michigan. She was raised in Marshall, Michigan. Her mother's family is connected to their tribal heritage, living in and around the reservation. Olivia's dedication to researching geology stems from her childhood experiences, where she was constantly immersed in the outdoors. Her love for nature sparked a deep connection between herself and her ancestors. She received a Bachelor of Science degree in Environmental Geosciences with a concentration in Geophysics and a minor in Digital Humanities. She took advantage of the numerous self-motivated projects in her minor to explore topics on digital and government relationships with Native American tribes, especially her own. The research illustrated in this paper focuses on honoring tribal sovereignty while bringing scientific rigor to the topic of active volcanoes. Olivia is grateful for being Native American and strives to bridge the gap between Western and Indigenous knowledge in her future work.

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ABSTRACT

Recent reevaluation of the Lava Creek Tuff (LCT; 0.631 Ma) has begun to challenge the two-member subdivision of the LCT, with evidence across the Yellowstone Plateau Volcanic Field for greater diversity and the presence of numerous, discrete packages, rather than two members. During this reassessment, a vitrophyre unit in the Madison Junction area, previously classified as part of the LCT, has now been dated as part of the Mount Jackson Rhyolite series (MJR; 0.78 Ma). As this unit does not fall within known MJR units, this finding raises questions about the stratigraphy, frequency, and volume of MJR eruptions, challenging previous assumptions about the relationship between these units. Remapping, petrologic descriptions, $^{40}\text{Ar}/^{39}\text{Ar}$ dating, whole-rock geochemistry, and electron probe microanalysis on sanidine of each LCT package and MJR unit in the Madison Junction area document five LCT packages and three MJR units. The five LCT packages are divided based on field observations, with variations in lithic types and crystallinity counts. Within these five packages, whole-rock trace-element concentrations and Ba in sanidine suggest that two to three magma bodies fueled the LCT in the Madison Junction area. The three MJR units are divided based on ages, petrologic descriptions, and barium concentrations in sanidine, where the Mount Haynes (0.70 Ma) and Gibbon River vitrophyre (0.78 Ma) have similar, lower barium concentrations than the Harlequin Lake flow (0.83 Ma); further, this vitrophyre is found to contain glass shards, suggesting an explosive component to the MJR, never before documented. Additionally, a local stratigraphic section was found with a lower crystal-rich lava flow capped by a basal vitrophyre grading into the overlying LCT. This is the first finding of a clear stratigraphic section from a pre-LCT lava flow to the onset of the LCT eruption. Nearby, another isolated lava outcrop, dated 0.64 Ma has barium concentrations that lie within the low Ba LCT population, suggesting these lower, older lavas may represent the onset of LCT volcanism. This research expands our understanding of the LCT and the MJR eruptions, finding several new components to both the LCT and the MJR eruptive suites.

INTRODUCTION

Silicic eruptions associated with caldera-formation are among the world's most hazardous volcanic events (Newhall and Dzurisin, 1988; Cole et al., 2005; Wilson, 2008; Gregg et al., 2012; Barraza, 2024). These eruptions generate massive pyroclastic flows made of a poorly-sorted mixture of crystals, pumice, and rock fragments, the deposits of which are called ignimbrites, together with voluminous widespread fall deposits. Caldera-forming eruptions are defined as producing over 450 km³ of magma (Miller and Wark, 2008). During such massive eruptions, the magma chamber is emptied, causing the overlying crust to collapse and form a caldera (Lipman, 1976; Druitt and Sparks, 1984; Gudmundsson, 1988; Lipman et al., 1997; Cole et al., 2005).

The Yellowstone Plateau Volcanic Field (YVF) has seen three major caldera-forming events, all of which are pre- and post-dated by frequent, effusive basalt to rhyolite flows (Christiansen, 2001). Ongoing fieldwork throughout the YVF (Wilson et al., 2018; Henderson et al., 2023; Salazar, 2023; Myers et al., 2026) has actively challenged our understanding of the caldera-forming systems at Yellowstone. For instance, the most recent caldera-forming eruption, the Lava Creek Tuff (LCT; 0.631 Ma), was originally divided into two members, A and B, based on varying welding intensities and the presence of amphibole in member A (Christiansen, 2001). However, updated observations based on extensive field mapping have uncovered near-source ignimbrite diversity that does not fit the classic A/B description (Wilson et al., 2018; Salazar, 2023; Myers et al., 2026). In these studies, the reassessment of mapped LCT A verses B outcrops was unable to verify that amphibole can be used to distinguish only member A, but rather is sometimes found in both mapped units, although relatively scarce throughout (Henderson et al.,

in prep). Additionally, barium concentrations in LCT sandstone vary spatially and stratigraphically, alluding to more eruptive packages than originally mapped (Wilson et al., 2018; Salazar, 2023; Myers et al., 2026; Henderson et al., in prep). During this reassessment, a vitrophyre unit in the Madison Junction area mapped as LCT member A was discovered. Its petrologic description does not match documented LCT (Christiansen, 2001) or MJR (Troch et al., 2017) units. Clarifying what units are present in the Madison Junction area, and the number and characteristics of LCT packages is essential to fully understanding the timing and volume of past eruptive activity at Yellowstone (Christiansen et al., 2007; Bachmann, 2010; Allan et al., 2012; Myers et al., 2016; Swallow et al., 2019; Henderson et al., in prep; Myers et al., 2026).

The area's proximity to the Yellowstone Caldera boundary allows south-facing cliffs to expose both the LCT and the pre-caldera MJR series, including the newly discovered vitrophyre unit (Figure 1). Focusing on these south-facing cliffs allows for in-depth understandings of LCT packages and their relationship to the MJR. This study incorporates detailed field mapping (i.e. documenting crystallinity, lithic (rock fragments), pumice and fiamme (flattened pumice) types and counts), petrologic descriptions (i.e. thin sections), geochemical analyses (i.e. whole-rock major, minor, and trace elements, electron probe microanalysis), and $^{40}\text{Ar}/^{39}\text{Ar}$ dating to better understand the rocks of the Madison Junction area, to address the following questions:

- 1) What is the full extent of the vitrophyre unit, and does remapping the Madison Junction area at a finer detail uncover other new units?
- 2) What can petrologic descriptions, geochemistry, and radiometric dating tell us about the relationships between the pre-caldera MJR lava flow units and LCT caldera-forming ignimbrites?

- 3) How many packages of the LCT are represented and how do they relate to their earlier designation within the two-member LCT framework?

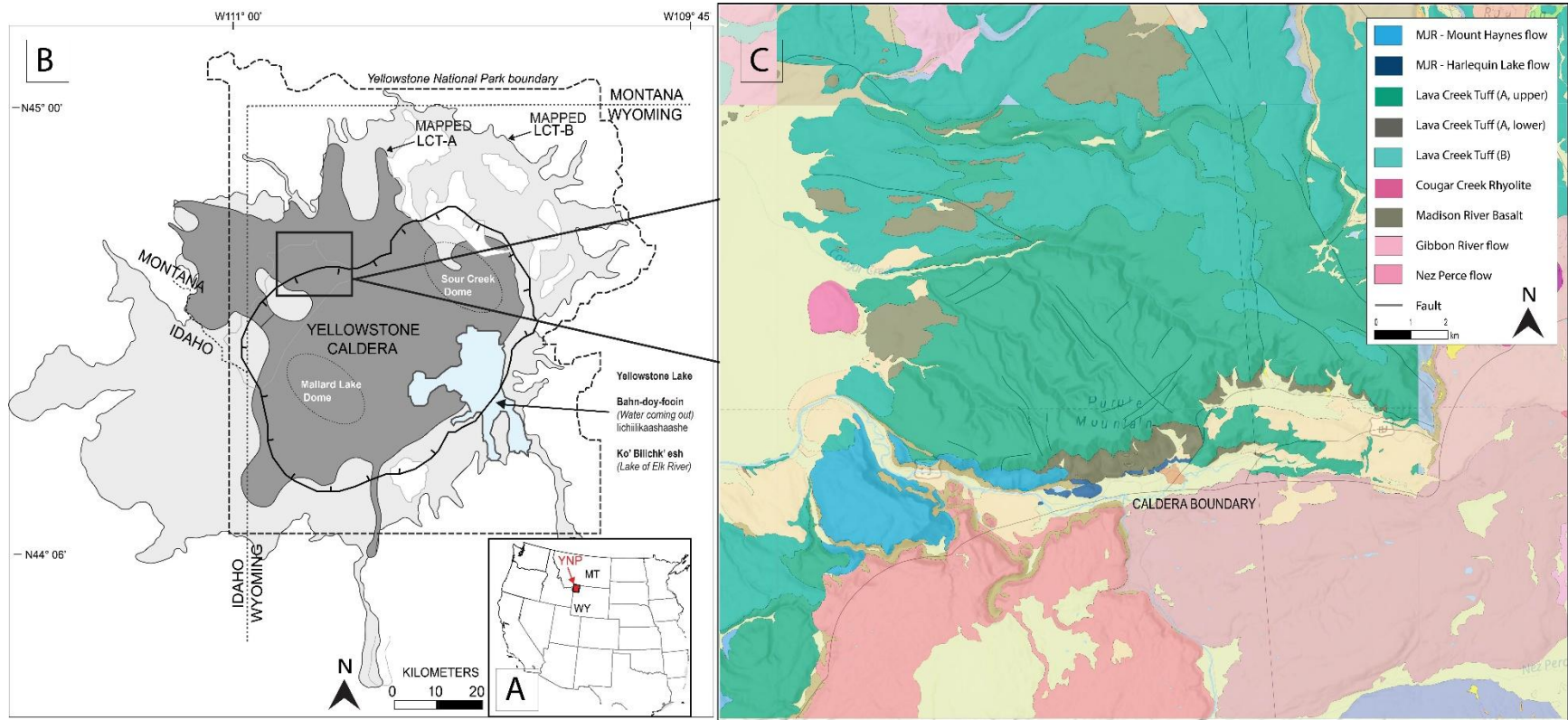


Figure 1. (a) Schematic map of the western United States, with a red box and label showing the location of the Yellowstone National Park. (b) Map of Yellowstone National Park with mapped boundaries showing the general locations of the Lava Creek Tuff A and B. Black areas are a part of the Mount Jackson-Island Park Rhyolites, with blue spots representing the Mount Haynes flow and purple spot as the Harlequin Lake flow of the Mount Jackson Rhyolite series. The pink spot represents the post-LCT Gibbon River lava flow. (c) A geologic map of the Madison Junction Quadrangle. Modified from Christiansen 2001.

Geologic Background

Yellowstone National Park spans roughly 9,000 km², situated in the northwest corner of Wyoming and contains the youngest expression of a volcanic chain shaped by the Yellowstone Hotspot (Pierce and Morgan, 1992; Smith et al., 1994; Christiansen et al., 2002). This chain extends along the Snake River Plain, and is formed by the apparent northeastward migration of predominately rhyolitic and basaltic volcanism (bimodal; Christiansen and McKee, 1978), with only traces of intermediate volcanism (Szymanowski et al., 2015), over 17 million years as the North American Plate moved over a mantle hotspot (Armstrong et al., 1975; Waite et al., 2006).

Over its history, the YVF has experienced three major explosive eruptions, each producing extensive caldera-related ignimbrites: the 2.1-million-year-old Huckleberry Ridge Tuff (HRT; ~2500 km³; Lanphere et al., 2002; Rivera et al., 2014; Singer et al., 2014), the 1.3-million-year-old Mesa Falls Tuff (MFT; ~230 km³; Gansecki et al., 1998; Lanphere et al., 2002; Rivera et al., 2016; Ellis et al., 2017), and the 631,000-year-old Lava Creek Tuff (Figure 1; LCT; ~1000 km³; Malde, 1991; Christiansen, 2001; Matthews et al., 2015; Jicha et al., 2016). Effusive bimodal volcanism occurred before and after caldera-forming eruptions (Geist and Richards, 1993; Hooper et al., 2007; Wolff et al., 2008; Stelten et al., 2015; Messa et al., 2025).

Predating the HRT was the eruption of the Junction Butte Basalt (2.15-2.01 Ma) and the rhyolite of Snake River Butte (2.15 Ma; Wotzlaw et al., 2015). At 2.1 Ma, the ~95x65 km Huckleberry Ridge Caldera collapsed, erupting three HRT ignimbrite members with multiple fall deposits (Christiansen, 2001; Swallow et al., 2019). Following the HRT event, caldera recovery continued with basaltic and silicic effusive activity, including the Basalts and Sediments of the Narrows (1.57 Ma) and the Big Bend Ridge Rhyolites (1.98-1.3 Ma). Though petrologically

similar, the Big Bend Ridge Rhyolites are divided into two post-HRT and two pre-MFT rhyolites based on K-Ar and modern $^{40}\text{Ar}/^{39}\text{Ar}$ dates.

After this period of basaltic and silicic eruptions, the explosive eruption of the MFT at 1.3 Ma, the smallest of the YVF's three major caldera-forming events, occurred through the Island Park area, Idaho. Post-MFT volcanism included the Island Park Rhyolite domes, which is said to erupt from 1.29 to 1.21 Ma (Troch et al., 2017) and the pre-LCT Mount Jackson Rhyolite lava flow series (1.28-0.708 Ma; Troch et al., 2017). The Warm River Basalt also erupted during this time (0.752 Ma; Obradovich, 1992; Messa et al., 2025).

The third caldera-forming event in the YVF is the LCT. Christiansen and Blank (1972) laid the framework for the LCT eruption, proposed as two members, A and B, divided by a thin, medium-grained, well-sorted crystal ash bed. However, recent fieldwork (Wilson et al., 2018; Salazar, 2023; Henderson et al., 2023; Myers et al., 2026) has challenged the two-member model to describe the full LCT eruption. For example, Christiansen (2001) noted the use of amphibole as a petrographic distinction of LCT member A from LCT member B, but the small amount of amphibole found in any of the LCT deposits has questioned this distinction (Henderson et al., in prep). During this reassessment (Henderson et al., in prep), a vitrophyre unit in the Madison Junction area, previously classified as part of the LCT and preserving ample amphibole, was dated and returned an age as part of the Mount Jackson Rhyolite series (MJR; 0.78 Ma). The implications of this mis-mapping, and the fact that this new vitrophyre represents a new unit of the MJR series, warranted remapping the Madison Junction area.

The eruption of the LCT was followed by the Plateau Rhyolites (0.58-0.25 Ma; Till et al., 2019; Christiansen et al., 2007; Watts et al., 2012), the Central Plateau Member (0.16-0.07 Ma;

Stelten et al., 2023), the Roaring Mountain Member (0.53-0.08 Ma; Pritchard et al., 2013), the Obsidian Creek Member (0.33-0.135 Ma; Pritchard et al., 2013) and five post-LCT basalts.

The following includes preliminary descriptions of the units currently mapped in the Madison Junction area:

Lava Creek Tuff Member A (Lower) Christiansen (2001) divided member A into lower and upper parts, with lower part only found in the lower two-thirds of Purple Mountain, Tuff Cliff, and Secret Valley, all of which are near Madison Junction (Figures 1, 2). Lower-member A is a poorly welded ignimbrite and contains a low phenocryst content of ~3-5%. Individual phenocrysts range in size from 0.1 to 0.3 cm, dominated by quartz and sanidine. This member contains large, dark gray fiamme (flattened pumice; ~2-6.5 cm) that can sometimes preserve quartz and sanidines. Lower-member A contains dark-colored subangular recycled rhyolitic lithic inclusions, which can sometimes reach up to 30 cm in size. Lower-member A varies from pink to purple and gray to pale yellow in outcrop, with gray the most common color.

Lava Creek Tuff Member A (Upper) Upper-member A is a densely-welded ignimbrite characterized by a higher phenocryst content (20-35%) than lower member A. Individual phenocrysts range in size from 0.3 to 0.5 cm. Upper member A is mapped more broadly than lower member A, found in most of the Madison Junction area. It is often found devitrified and usually light gray when fresh, but weathers to a crumbly brown, often forming steep bluffs with rounded joint columns. This member contains larger fiamme than lower member A (up to 30 cm), which can also preserve quartz and sanidine. However, it contains fewer lithics than lower member A.

Lava Creek Tuff Member B Christiansen (2001) describes member B of the Lava Creek Tuff as widely exposed outflow sheets around the Yellowstone Caldera. Member B ranges in welding intensity with its stratigraphy, being generally less welded than upper member A and more welded than lower member A. Compared to member A, it has fewer (~10%) and smaller (0.2 to 1 cm) phenocrysts. Member B is generally more resistant to erosion, often displaying well-defined columnar jointing and a bluish to purplish-gray hue, distinguishing it from the brown-weathering member A. Upper-member A and member B are mapped in contact in the northwest part of this study field area.

Mount Jackson Rhyolite series The Mount Jackson Rhyolite (MJR) series is a widely distributed series of seven effusive pre-LCT lava flows (Figure 1): the Moose Creek Butte (1.28 Ma), Wapiti Lake (1.21 Ma), Harlequin Lake (0.83 Ma), Lewis Canyon/Flat Mountain (0.83-0.826 Ma), and Mount Haynes/Big Bear Lake Rhyolite (0.702 Ma) flows (Troch et al., 2017). The MJR units represented in the Madison Junction area include the Harlequin Lake and Mount Haynes flows. Both flows are porphyritic with a microcrystalline groundmass. Phenocrysts of sanidine (0.2–2 mm) and quartz (0.2–3 mm) are common, occasionally forming glomerocrysts or exhibiting exsolution textures (Troch et al., 2017). Mafic phases like pyroxene are included in these flows, but both lack amphibole (Troch et al., 2017).

The Harlequin Lake flow lies north of Madison Junction, surrounding Harlequin Lake, and is partially buried by the LCT lower-member A (Figure 1). Troch et al. (2017) states that the Harlequin Lake flow is less crystal-rich (~13-15%) than the Mount Haynes flow (15-19%); however, its phenocrysts are usually larger (0.4-0.8 mm) in size and the lava flow typically appears pale yellow to blue in hand sample with minimal flow banding. In contrast, the Mount

Haynes flow is more extensively exposed, forming prominent cliffs at Mount Jackson (Figure 1). Hand samples of this unit range from light to dark blue, with prominent flow banding, and it contains smaller phenocrysts (0.2-0.5 mm) than the Harlequin Lake flow (Troch et al., 2017).

Roaring Mountain Member and Post-LCT Basalts The Roaring Mountain Member (RMM) is a part of the Plateau Rhyolites, a large set of post-LCT rhyolite lava flows (Christiansen, 2001). The RMM is extracaldera flows, which distinguishes it from other flows of the Plateau Rhyolites that infill the caldera (Christiansen and Blank, 1972). The RMM consists of five flows: the Riverside Rhyolite (0.526 Ma; Christiansen, 2001; Nastanski, 2005), the Cougar Creek Rhyolite (0.368 Ma; Christiansen, 2001; Nastanski, 2005), the Obsidian Cliff (0.326-0.059 Ma; Nastanski, 2005; Wooton, 2010), the Gibbon River (0.108 Ma; Dallegge, 2008), and the Crystal Spring flows (0.059 Ma; Wooton, 2010). Though the Riverside, Cougar Creek, and Gibbon River flows erupted as singular bodies from a large-scale silicic magma system beneath the Norris-Mammoth Corridor, mafic enclaves in the Crystal Spring Rhyolites suggest magma mixing and concurrent eruptions with the Obsidian Cliff flow (Wooton, 2010).

The RMM units represented in this field area are the Cougar Creek Rhyolite (CCR) dome and the Gibbon River flow (Figure 1). The CCR is mapped as a dome of rhyolite in the Mount Jackson 7.5-minute Quadrangle. The Gibbon River flow is a lava flow that erupted along the Yellowstone Caldera boundary. It was first described as a Central Plateau Member unit, but after further petrologic investigation, Christiansen (2001) linked the Gibbon River flow to the RMM. Both the CCR and Gibbon River flow are glassy and phenocryst-poor (Christiansen, 2001). Wooton (2010) discovered complexities within the Gibbon River flow, with variable petrologic and geochemical characteristics.

Currently, six post-LCT basalts have been found along the margins of the caldera boundary: the Swan Lake Flat (0.590-0.119 Ma; Bennett, 2006), the Falls River (0.64-0.11 Ma, *probable age*; Christiansen, 2001), the Mariposa Lake/Geode Creek (0.64-0.13 Ma, *probable age*; Christiansen, 2001), the Madison River Basalt (0.40-0.13 Ma, *probable age*; Christiansen, 2001), the Gerrit Basalt (0.57-0.35 Ma; Messa et al., 2015), and the Osprey Basalts (0.220 Ma; Obradovich, 1992). These basalt units are separated due to their wide spatial arrangement around the caldera, with the Basalt of Mariposa Lake/Geode Creek separated due to its siliceous composition with xenocrysts of quartz and sodic plagioclase (Christiansen, 2001). Some of the extent and ages of these basalts are not widely known, which are denoted by “*probable age*” from Christiansen (2001). These ages were determined widely based on their correlation to other post-MFT/pre-LCT basalts (Christiansen, 2001).

The post-LCT basalt represented in this field area is the Madison River Basalt (MRB), which is mapped in the Madison Junction area as a vesicular tholeiitic basalt with olivine, clinopyroxene, plagioclase and oxides that is confined by old valley topographies (Christiansen, 2001). A major vent location of the MRB is just east of the CCR dome (Christiansen, 2001; Figure 1).

METHODS AND METHODOLOGY

Sample Collection and Remapping

Remapping of the Madison Junction and Mount Jackson 1:24,000 Quadrangles built off the geologic map of Christiansen (2001), retracing contacts and updating previous mapping accuracy. ArcGIS Pro hillshades from the United States Geological Survey (USGS) were used to find cliff exposures and infer faulting relationships in the area. Outcrop and sample descriptions focused on detailed mineralogical and physical attributes. Crystals (≥ 2 mm) and components like lithics (≥ 2 mm) and fiamme/pumice (≥ 5 mm) were counted on each sample and/or outcrop visited and normalized to 10 cm by 10 cm, or 100 cm², to ensure consistency when comparing across the field area. Rock samples ($n = 60$) were collected at sites that contain an uncertain or mismatched rock description to its mapped unit, where a suitable outcrop for sampling was minimally altered from post-emplacement processes. Variations within the LCT were also sampled. Field descriptions of every individual waypoint can be found in the ArcGIS geodatabase in Appendix A.

Samples were brought to Montana State University, and all information was entered into a geodatabase using GPS points, outcrop and hand sample photos, and component counts of every waypoint visited (Figure 2). This database supports the remapping process required to update the geologic map. Of the 60 samples collected, 42 samples were chosen as representative LCT, MJR, and unknown units for petrological descriptions. These samples were cut into billets using oil and water rock saws at Montana State University and sent to Wagner Petrographic in Utah for thin section creation. Point counts of major and minor mineral phases of major LCT, MJR, and units that do not match their mapped description were performed using an optical

microscope. A minimum of 1,000 points on each thin section were counted to robustly quantify mineralogy variation (Van der Plas and Tobi, 1965) within and between the LCT and MJR units, to be used in our evolving understanding of the LCT's eruptive variability and add to our limited knowledge of the MJR petrology.

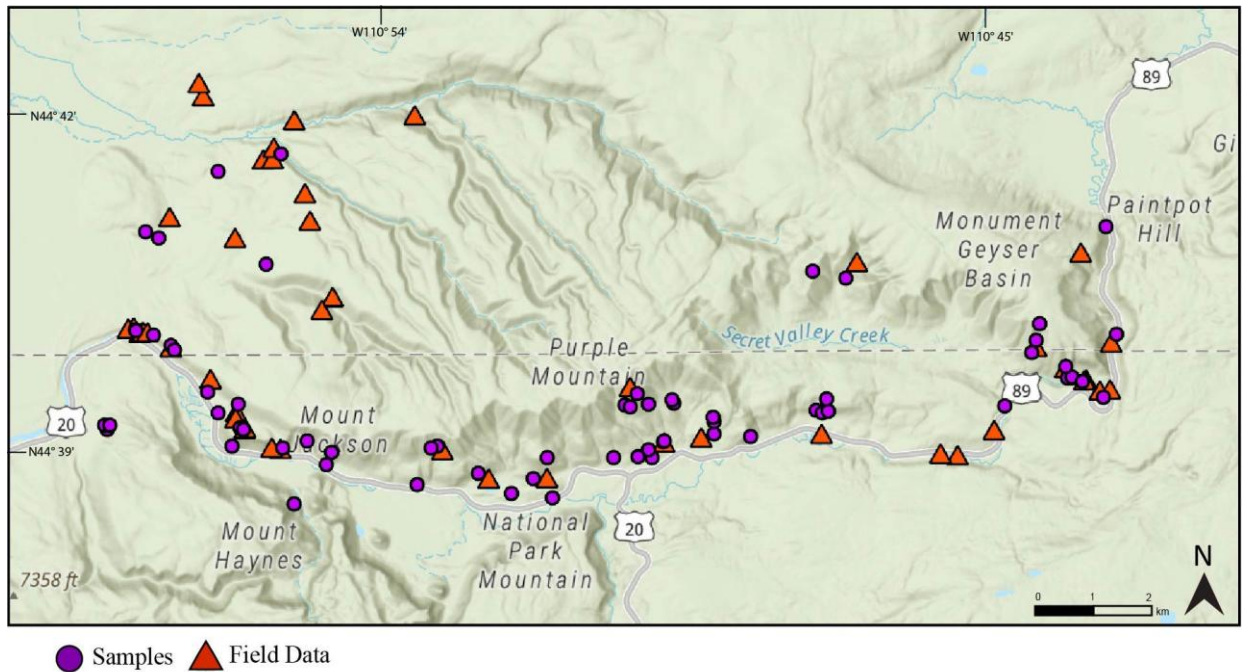


Figure 2. Shaded relief map of the Madison Junction, Yellowstone area with each GPS point (Appendix A). Purple dots represent waypoints that have a sample taken and red triangles represent field data where a sample was not taken.

$^{40}\text{Ar}/^{39}\text{Ar}$ Dating

To confirm the identity of rocks collected in the Madison Junction region, material was sent for $^{40}\text{Ar}/^{39}\text{Ar}$ dating at the USGS Menlo Park, CA facility. The crystals in the LCT and other YVF rhyolites consist primarily of quartz and sanidine (Christiansen 2001), sanidine being a feldspar with high potassium and typically high radiogenic ^{40}Ar for a given age (Stelten et al.,

2015). As $^{40}\text{Ar}/^{39}\text{Ar}$ is the preferred choice for accurately dating K-bearing minerals (Schaen et al, 2021), sanidine was separated for determining ages of unknown units. First, the samples were crushed in a chipmunk crusher at Montana State University. Care was taken to crush samples with limited lithics present, to maximize the amount of sanidine that reflects the true, younger age. Then, they were sieved into < 0.5 mm, $0.5\text{-}1$ mm, and > 1 mm size fractions, with the $0.5\text{-}1$ mm size fractions used as the primary size for individual sanidine picking. For each sample, 100 sanidine crystals were picked, being careful to avoid those with visible melt inclusions, which can host excess Ar.

Ages were determined in the central thimble of the USGS TRIGA reactor in Denver, CO (Dalrymple et al. 1981), at a power level of 1 MW. The decay constant follows methods from Steiger and Jager (1977), and a Bodie Hills sanidine monitor was used ($9.7946\text{ Ma} \pm 0.0031\text{ Ma}$; Fleck et al., 2019). By choosing the stable radiogenic ^{40}Ar isotope after it decays from ^{40}K , the isotope can be plotted against itself as another stable radiogenic isotope chosen as a proxy for ^{39}K , ^{39}Ar (Kelley, 2002). Each eruption age was calculated from the weighted mean of eruption ages and is reported with a 1σ confidence level (Schaen et al., 2021).

Whole-Rock Major and Trace Element Analyses

Whole-rock X-Ray fluorescence (XRF) and inductively coupled plasma-mass spectrometry (ICP-MS) analyses were conducted at the Peter Hooper GeoAnalytical Lab in Pullman, Washington, to determine whole-rock major, minor, and trace element signatures of units in the Madison Junction region. Twenty-six samples were chosen for whole-rock analysis. These samples were first crushed and milled at Montana State University. Around 50 grams from

each sample were then sent to Pullman for processing. In the lab, a tungsten-carbide ring mill ground the material into a fine powder, which was then mixed with spec pure di-lithium tetraborate (Johnson et al., 1999) and heated in a muffle furnace for fusion. The resulting beads were subsequently labeled, polished, and analyzed using XRF.

Electron Probe Microanalysis (EPMA)

Due to the devitrified nature of the LCT, I also utilized Electron Probe Microanalysis (EPMA) to obtain major element percentages and barium concentrations in sanidine, furthering exploration of geochemical variations in rocks in the Madison Junction area (Figure 1). Barium, a compatible element with a fixed partition coefficient, can be used as a proxy in the k-bearing sanidine feldspar for understanding the composition of the melt (Wolff et al., 2020). EPMA on sanidine grains were conducted at the USGS lab in Menlo Park, CA. Fourteen samples were analyzed: ten LCT, two MJR, and two samples that do not match their mapped description from Christiansen (2001). Samples were analyzed for Si, Ti, Al, Fe, Ca, Na, K, and Ba by wavelength-dispersive methods at 15 keV accelerating voltage. A spot size of 5-um was utilized on 30 crystals per sample, with analysis conducted at inferred crystal rims. Albite and bytownite standards were analyzed every three to four hours to account for drift.

RESULTS

Field and Petrological Descriptions

Within the Madison Junction area, I further break up the field area into 10 localities. Outcrops in each locality are described below to help organize observations and discrepancies in the region (Figure 3).

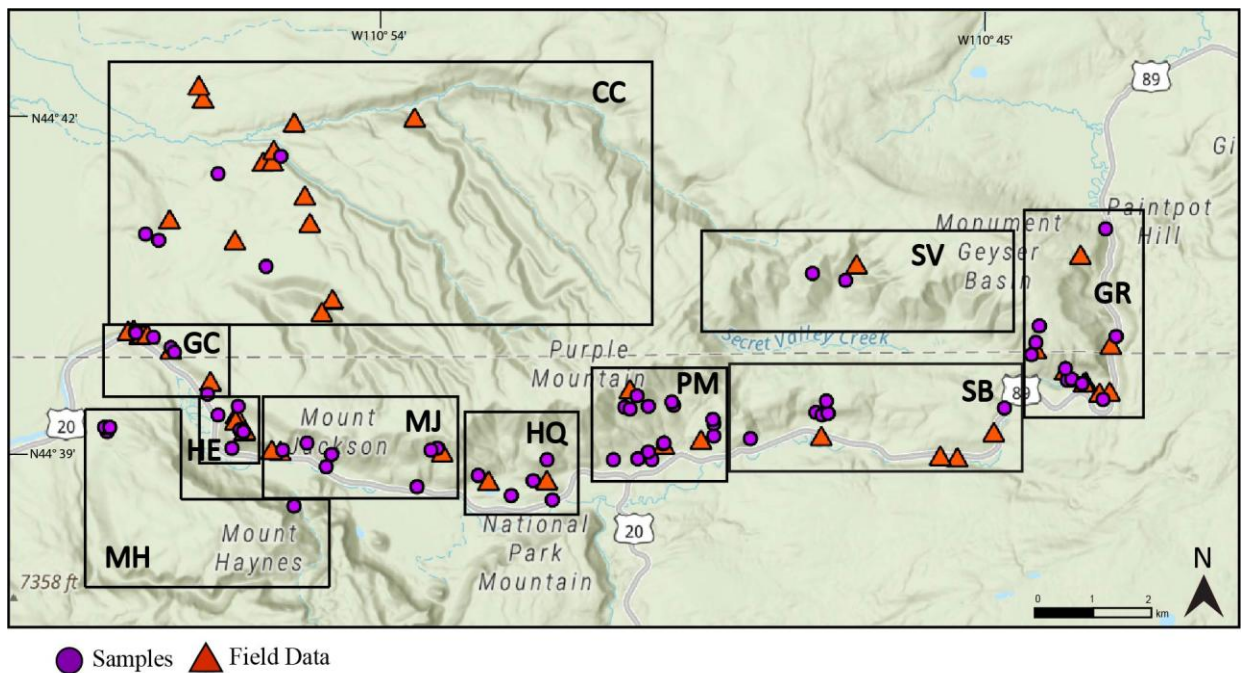


Figure 3. Shaded relief map of the Madison Junction area, Yellowstone with each GPS point (waypoint) denoted by purple dots (sample taken) and red triangles (field data collected, no sample). Boxed areas are localities that organize field and petrological descriptions: CC – Cougar Creek, GC – Gneiss Creek, HE – History Exhibit, MJ – Mount Jackson, MH – Mount Haynes, HQ – Harlequin Lake, PM – Purple Mountain, SB – Slump Block, SV – Secret Valley, GR – Gibbon River. Descriptions begin at CC – Cougar Creek and travel eastward, incorporating localities that are stratigraphically related.

Cougar Creek (CC) Cougar Creek trends east to west through Cougar Creek Valley, where it is joined by multiple tributaries that fill in the northwest-trending valleys of the Madison Junction area. These valleys provide access points into the cliffs behind the frontal exposed area

along the Madison River. The boxed area of CC (Figure 3) consists of mapped LCT upper member A, the dome of Cougar Creek Rhyolite (CCR; 0.368 Ma; Christiansen, 2001; Nastanski, 2005), and a vent-proximal flow of the Madison Junction Basalt (MRB; 0.40-0.13 Ma, *probable age*; Christiansen, 2001). Field assessment of this area focused on the attributes and mapped boundaries of the CCR and MRB; however, a few samples of the LCT were taken to compare with other LCT localities.

During field mapping, exposures observed the MRB flowing radially in all directions from the mapped vent site and lapping up against the mapped circular dome of the CCR, on the west side of the north-south Gneiss Creek trail. I also find evidence of the MRB north, east and upslope of the mapped vent. These findings require the MRB's mapped boundary to be extended about 230 m to the north, west, and east. The CCR is mapped correctly with southern and northern outcrops against the hillside. It is composed of 100% black glass with pink devitrified spherulites.

An abrupt contact between exposures of the MRB and the LCT was found north of the CCR and the MRB (44.697N, 110.955W). The LCT in this area is a pink, densely-welded ignimbrite with 69 crystals (0.2-0.5 cm) per 100 cm² consisting of quartz and sanidine with some plagioclase, and black elongated fiamme (0.2-0.4 cm). This ignimbrite does not vary southward for ~2,000 m.

Heading eastward and along multiple northwest-trending gullies in Cougar Creek valley, I encountered multiple comparable outcroppings of LCT ignimbrite, with an average of 50 crystals (0.2-0.4 cm) per 100 cm², consisting of quartz and sanidine with some plagioclase, and frequent, sometimes hollowed out, black fiamme (23 fiamme per 100 cm²). These outcrops

appear as gray to pink 6-inch horizontal subrounded blocks that weather into pea gravel down steep slopes. These crystal counts slightly decreased traveling eastward (~30 crystals (0.3-0.5 cm) per 100 cm²), but outcrop appearance, weathering, and fiamme counts remain consistent.

Gneiss Creek (GC) The western edge of the Madison Junction area along Gneiss Creek is currently mapped as a package of LCT member B likely atop the LCT upper-member A. The west-oriented trail lies along the talus banks of south-facing, horizontally slabbed cliffs. Traversing the base of the cliffs eastward exposes a dark-gray ignimbrite (100 crystals per 100 cm²; 0.4-0.7 cm) with sanidine, quartz, and thin section identified clinopyroxene (1.73%; Table 1) with thin, altered white fiamme along the outcrop face (12 fiamme per 100 cm²; 0.5-17 cm long). It has a glassy, spherulite matrix and the exposure gradually thickens eastward, from ~2 to ~7 m (Figure 4A). The east edge is buried in talus, but the west side is truncated by an overlying ignimbrite, which consists of 10 m-tall, rounded columnar bluffs with a lower crystal count (29 crystals per 100 cm²; 0.3-0.4 cm). These bluffs are orange to gray and exhibit small, hollowed-out fiamme (33 dark orange fiamme per 100 cm²; 2-6.5 cm long). This ignimbrite gets up to 20 m thick eastward and gradually becomes more crystal- (104 crystals per 100 cm²; 0.4-0.6 cm), fiamme- (92 fiamme per 100 cm²; 20-150 cm long), and glass-rich (Figure 4B).

A few small exposures of visually distinctive ignimbrites lie conformably above this second ignimbrite. One is a 1 m-thick densely-welded, chalky-pink, crystal-poor ignimbrite (8 crystals per 100 cm²; 0.1-0.2 cm) that is exposed underneath a tree and, ~250 m east, a 1x2 m outcrop of the LCT with fist-sized red, black, and gray clasts tucked between the second ignimbrite and the capped ignimbrite.

The GC cliffs are capped by a 2m-thick moderately-welded black-pumice-rich ignimbrite (Figure 4C). This capped pumice-rich ignimbrite loosely matches the ignimbrite found in the Cougar Creek section. Although most of this capped ignimbrite contains pumice, some of the pumice along the top of GC may have been weathered out, as small sections of the top include pink pumice-absent ignimbrite with identical crystallinities. About halfway across the cliffs is a rounded exposure of gray rheomorphic ignimbrite tucked into a gully (44.667N, 110.967W). This small (~1x2 m) exposure has northeast-trending, elongated vesicles and crystals, which can be explained by a stretching of the exposure (Figure 4D). GIS hillshade analysis shows that the gully follows the direction of the vesicles.

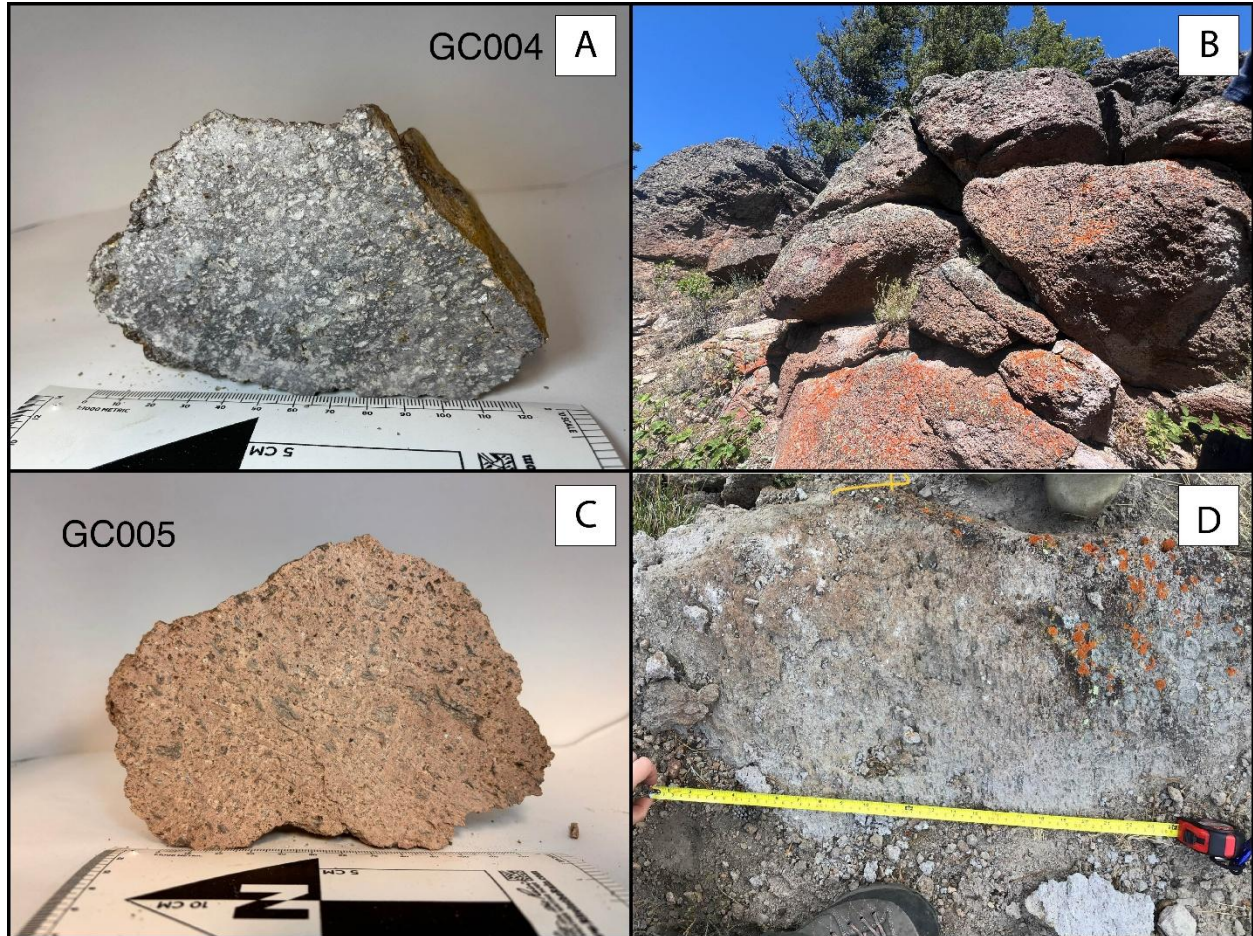


Figure 4. Outcrop and hand sample photos in the field of the major Gneiss Creek LCT exposures/hand samples, where A – lower crystal-rich ignimbrite, B – columnar bluffs with fiamme, C – overlying pumice-rich ignimbrite cap, and D – exposure with north-trending elongated vesicles.

History Exhibit (HE) The History Exhibit section was named for its proximity to the exhibition stop, which highlights the Indigenous and animal history of the park. This section is mapped as a thin alluvium patch overlaid by a steep exposure of the Mount Haynes flow of the MJR (0.73 Ma; Troch et al., 2017), which is truncated by the LCT to the north and east (Figure 1). In the field, the contact between the MJR and the LCT is accurate, broadly denoted by the vegetation, whereby trees cover the LCT, and grassy vegetation covers the MJR. Exposures are difficult to find, with only a few located on the insides of uprooted trees. Both the MJR and the

LCT near the contact are altered white, likely from post depositional alteration, making it difficult to discern their groundmass. However, one 15x3 m gully exposure stratigraphically lower than this contact and mapped as alluvium preserves an intact outcrop consisting of subrounded, pale blue boulders weathered to brown (54 crystals per 100 cm²; 0.2-0.3 cm; Table 1). This outcrop does not include any clastic components (e.g. pumice, fiamme, lithics) or clear flow banding and is not laterally extensive. In thin section it includes both devitrified glass and microcrystalline groundmass, making it difficult to discern as an ignimbrite or lava flow. However, the thin section includes intact crystals, which is more commonly observed in a lava flow. Because this outcrop is also inaccurately mapped as alluvium, material from it was sent for dating.

The Mount Haynes flow of the MJR is mapped south and stratigraphically above this outcrop and spans across the base of the HE section for ~1,040 m. These outcrops are well-developed columnar-jointed cliffs, where each column is ~0.3-1 m wide and contains abundant lithophysae with blue to white spherulites (46 crystals per 100 cm²; 0.2-0.3 cm). These cliffs do not exhibit flow banding but wrap around the west/southwest edge of the area until they are eventually truncated by the LCT.

Mount Jackson (MJ) The Mount Jackson section begins on the southeast side of the History Exhibit area and continues eastward until the Harlequin Lake section (Figure 3). At the western edge – truncating the columnar cliffs of the HE section – lays a thick group of rounded, steep, ~100 m tall ignimbrite bluffs mapped as the LCT upper member A that caps the entirety of the MJ section. Investigating the westmost point of these bluffs revealed a previously unmapped basal ~60 m-wide eruptive sequence (44.65N, 110.94W). The lowest unit (Figure 5) is ~6 m-

thick, black, crystal-rich rock, with large sanidine crystals (237 crystals per 100 cm²; 0.7-0.8 cm). This rock includes thick, local flow banding to the west, with white spherulites, and lacks any pumice material (Figure 5), suggesting a lava flow origin. A sharp contact above this basal lava flow is marked by a 20 cm-thick, matrix-supported gray ash layer (Figures 5, 6). This ash layer contains small (0.1 cm) felsic minerals too small for identification and includes similar-sized (1-8 cm), homogenous, crystal-rich black clasts that visually match the lower lava flow, with large sanidine crystals (0.5-0.8 cm). The similarity in crystallinity suggests that these clasts are derived from the lower lava flow. A 28 cm-thick, crumbly-brown, matrix-supported unit overlies the gray ash unit (Figures 5, 6). It includes brown, gray, and black clasts ranging from ~1 to 10 cm. The black clasts match the lower lava flow in appearance and crystallinity, whereas the brown and gray clasts do not match other units in the Madison Junction area. The lowest lava flow unit and the brown and gray clasts from the matrix-supported unit were sent in for dating and whole-rock geochemistry.

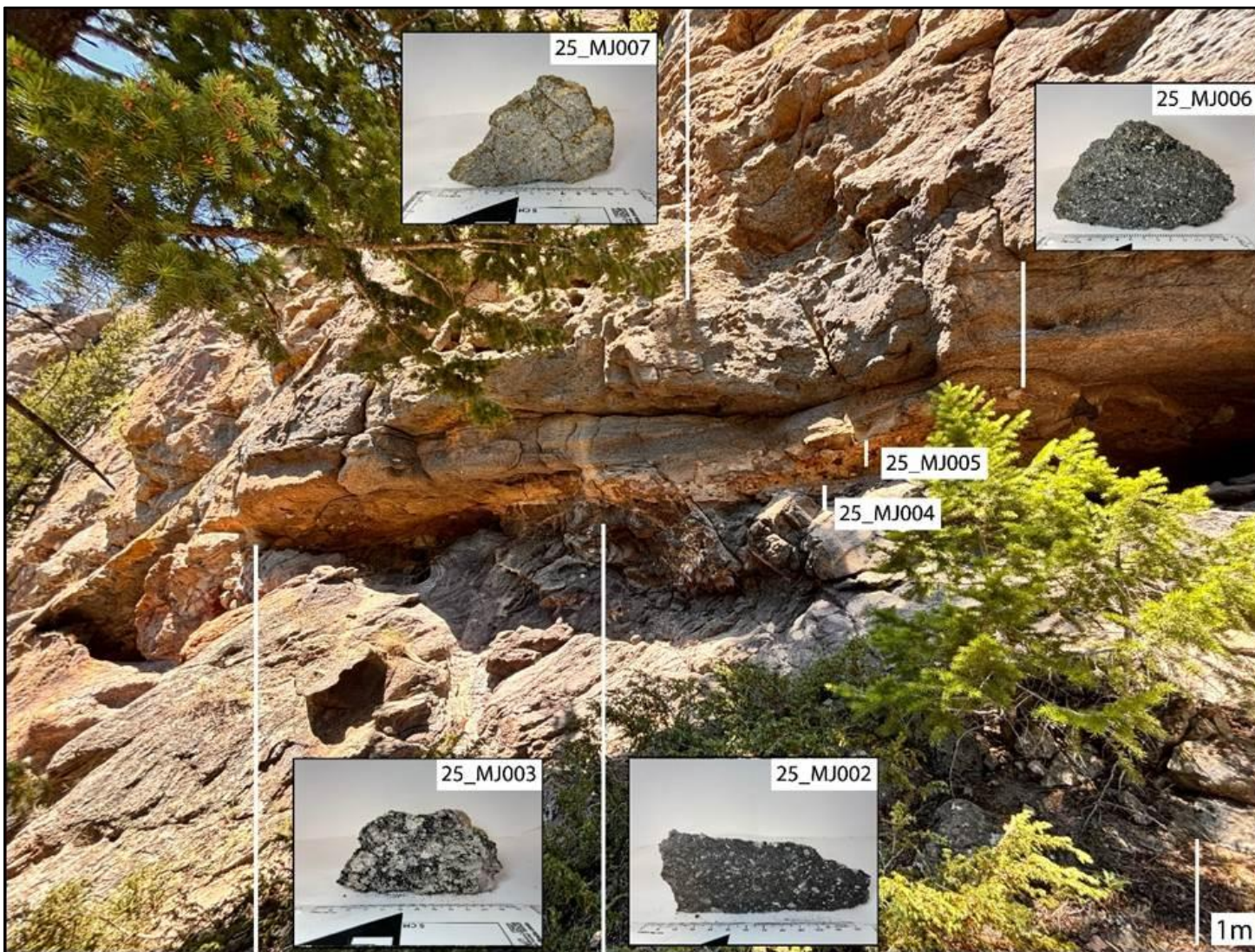


Figure 5. An outcrop photo of the stratigraphic section in the Mount Jackson section, containing six samples. White lines depict the thickness of each sample.

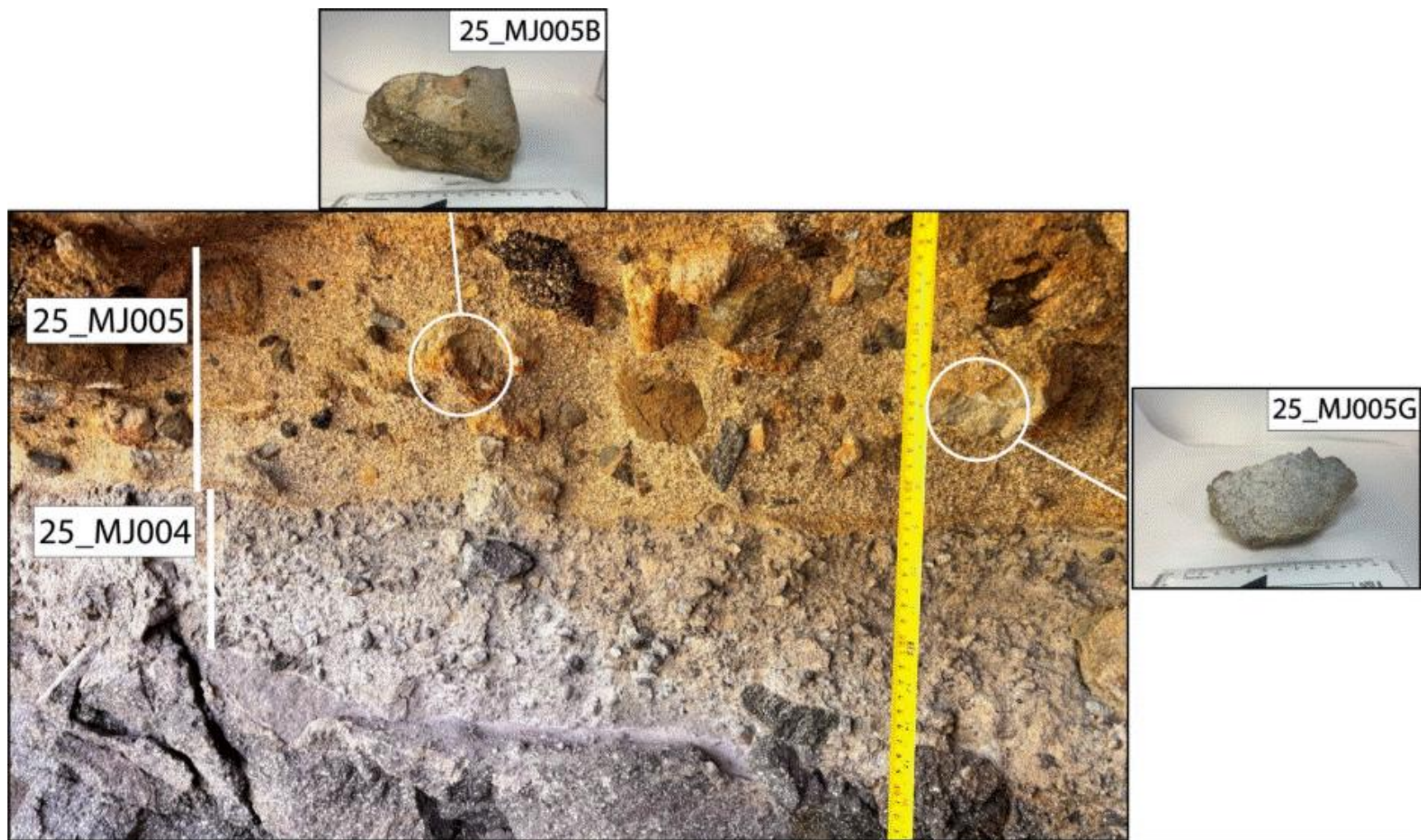


Figure 6. Zoomed in outcrop photo of Figure 4 showing clasts from the matrix of the two ash layers between the lower lava flow and the overlying ignimbrite. The upper layer also shows two photos of the brown and gray clasts not seen elsewhere.

Above the matrix-supported brown unit is a basal ignimbrite layer, evident by a black, glass-rich vitrophyre that gradually lightens and transitions into the overlying ignimbrite bluffs (Figure 5) that cap the entirety of the MJ section. The basal vitrophyre is ~2.5 m thick and includes black devitrified spherulites and large (2-13 cm) black clasts of the lowest unit (0.5-1 cm); the similarity of the crystallinity suggests these are the same lithics as the lower lava flow. The brown and gray clasts from the underlying unit are not included. As the basal vitrophyre gradually changes to an orange-brown ignimbrite up section, the lower lava flow clasts become absent, the groundmass gradually becomes devitrified, and crystallinity increases (92 crystals per 100 cm²; 0.3-0.5 cm). These densely-welded ignimbrite bluffs include white to orange fiamme across the entire cliffside (42 fiamme per 100 cm²). These bluffs continue eastward, curving northward and increasing elevation by ~170 m; the lower stratigraphic section just described is not observed elsewhere. Instead, the rising of these cliffs exposes multiple new underlying packages ~485 m east of the stratigraphic section. One such package is a 200x250 m white and orange, heavily altered sandy slope exposure that was unsuitable for point counts. The elevation and altered-white groundmass of this slope material closely match the altered-white tree-root material from the HE section. Conformably next to this sandy exposure is a massive set of columnar jointed rhyolite cliffs mapped as the Mount Haynes flow of the MJR (17 crystals per 100 cm²; <0.1-0.2 cm). Thick flow banding is visible in the outcrop and hand sample, with dark blue and white bands, which are absent in the columnar jointed mapped Mount Haynes flow that wrap around the HE section.

Exposures are limited east of the Mount Haynes columnar cliffs until the Harlequin Lake section; however, three exposures of mapped LCT upper member A, roughly 80 m apart and at the same elevation, are stratigraphically aligned above the columnar cliffs of the Mount Haynes flow. All three outcrops are roughly 40x20 m pink to gray bluffs with white fiamme (12-28 cm long). The westmost outcrop differs from the other two outcrops by preserving gray, rhyolitic lithics (1.5-2.5 cm), overlying a lower 0.5 m thick white ash layer with large black and gray clasts. Detailed examinations could not be completed on this ash layer because of the presence of a cougar den, but this outcrop would be worth future investigation. No basal contact below these three exposures could be found with the underlying Mount Haynes flow, but a monolithic float of glassy vitrophyre was found along the expected boundary.

Mount Haynes (MH) The Mount Haynes section lies on the south side of the Madison River, predominantly containing the Mount Haynes flow of the MJR with a small package of mapped LCT member B in the northwest corner. The crystal assemblage of the Mount Haynes flow here is mostly sanidine and quartz (56 crystals per 100 cm²; 0.2-0.4 cm) with thick blue and white flow banding, outcropping into 10 m-tall columnar joints and weathering into large (1-1.5 m) boulders, similar to what is seen in the History Exhibit section. The Mount Haynes flow in the Mount Haynes section is more crystal-rich (56 crystals per 100 cm²) than in the Mount Jackson section north of Madison River (17 crystals per 100 cm²). In the northwest of the Mount Haynes section, the small package of LCT is heavily devitrified and spherulitic, with quartz and sanidine dominating (40-50 crystals per 100 cm²; 0.2-0.5 cm). Unlike the mapped LCT member B of Gneiss Creek, this ignimbrite does not contain pumice or fiamme but has similar crystal counts.

Harlequin Lake (HQ) The Harlequin Lake section is mapped as the Mount Haynes flow, with the Harlequin Lake flow of the MJR stratigraphically east, both overlaid by the LCT lower-member A, all of which is capped by the LCT upper-member A. Finding contacts between each of these members proved to be difficult, but generally agreed with their mapped boundaries. The Mount Haynes flow in this section is a steep, dense, jagged, lithophysae-rich lava flow with thin blue and white flow banding. Lithophysae abundances decrease stratigraphically up the cliffs, but crystallinity and flow banding remains comparable. The Mount Haynes flow is crystal-poor (17 crystals per 100 cm²) with predominantly sanidine, quartz and some plagioclase (0.1-0.2 cm), but mostly contains a crystalline groundmass (95.3%; Table 1), all of which are similar to the Mount Haynes in the MJ section. East of the Mount Haynes flow but separated by Harlequin Lake and a massive talus slope, is the mapped Harlequin Lake flow of the MJR. This lava flow crops out as a dense, subrounded, lithophysae-rich, brown to pale blue, crystal-rich (110 crystals per 100 cm²) lava flow with large crystals (0.5-0.7 cm): predominantly sanidine, then quartz, with some plagioclase (Table 1).

About 200 m above the Harlequin Lake flow, the hills falsely summit into the mapped LCT lower-member A. These pink to gray ignimbrite cliffs span ~175 m and are over 30 m tall, containing crystal-poor, subrounded, moderately-welded horizontal plates with devitrified glass (13 crystals per 100 cm²; 0.1-0.2 cm). Pumice and fiamme are black, recrystallized, and abundant (4-10 cm long). Lithics are black and gray, likely recycled rhyolite (17 lithics per 100 cm²; ≤1 cm). Both lithic types are fully cooled, circular, and aphanitic, with some small quartz and sanidine phenocrysts identified in thin section. Reaching the capped mapped LCT upper-member A from this point was difficult due to the steepness of the area.

Purple Mountain (PM) The Purple Mountain section is where Christiansen (2001) described and defined in detail the lower- and upper-members of the LCT-A. Hiking up section, one begins in the Harlequin Lake flow of the MJR. The Harlequin Lake flow here is irregularly jointed, pale purple with brown-gray weathering and some localized flow banding (60 crystals per 100 cm²; 0.4-0.8 cm), slightly less crystal-rich than the Harlequin Lake flow in the Harlequin Lake section. West of the trailhead (~715 m) and within the mapped Harlequin Lake flow is a 3.5x1.5 m exposure of an extremely dense, crystal-rich lava with a dark gray groundmass (90 crystals per 100 cm²; 0.8-0.9 cm). Material from this exposure was sent in for dating due to its high crystallinity and uncertain petrologic affinity within the Harlequin Lake flow. The Harlequin Lake flow continues west and eastward, eventually being truncated on both sides by the LCT.

The first in-situ exposure of the LCT is ~100 m stratigraphically above the northernmost contact of the Harlequin Lake flow, with a talus slope observed between exposures. The LCT exposure is along a steep section of the Purple Mountain trail at a switchback, consisting of densely-welded, monolithic float and in-situ boulders of pink, crystal-poor ignimbrite (12 crystals per 100 cm²; 0.1-0.3 cm; Figure 7A; 44.657N, 110.848W). Its phenocryst assemblage is predominantly quartz and sanidine, with some plagioclase and clinopyroxene identified in hand sample and thin section (0.2%; Table 1). This ignimbrite includes dark gray recrystallized fiamme (32 fiamme per 100 cm²; 4-6.5 cm) and black recycled rhyolite lithics (12 lithics per 100 cm²; 0.2-0.5 cm); this unit is most similar to the overlying ignimbrite cliffs in the eastmost Mount Jackson and Harlequin Lake sections. From here the LCT shows a rapid (~20 m) upward stratigraphic transition from densely- to moderately-welded ignimbrite, with trail-exposed

outcrops of pumice-rich pink (“lower”) to purple (“upper”) ignimbrite (Figure 7B and 7C). The lower pink ignimbrite (Figure 7B) is chalky and bright pink with dark pink and gray pumice (40 pumice per 100 cm²; 0.5-3 cm) and black, gray, and red lithics (36 lithics per 100 cm²; 0.2-0.6 cm). The black lithics here match the lithics within the lower, first ignimbrite described in this section, whereas the gray lithics are identical to the lithics at the top of the Harlequin Lake section. The red lithics are inferred as hot recycled lava due to their glassy texture and red color. The lower pink ignimbrite (Figure 7B) is crystal-poor with predominantly quartz and sanidine (14 crystals per 100 cm²; 0.1-0.2 cm). The upper purple ignimbrite (Figure 7C) is porous and blue to purple with bright pink pumice (33 pumice per 100 cm²; 0.5-1 cm) and notably lacks lithics. It is also crystal-poor with limited quartz and sanidine (12 crystals per 100 cm²; 0.1-0.2 cm).

The upper purple ignimbrite continues for 45m before rapidly transitioning to a densely-welded yet crumbly fiamme-rich ignimbrite (20 fiamme per 100 cm²; >12-23 cm long; Figure 7D). This ignimbrite continues for more than 300 m, stratigraphically upward until the top of Purple Mountain. Originally mapped as the LCT upper-member A, this ignimbrite is quartz-rich with sanidine, some plagioclase, and minor clinopyroxene identified in hand sample and thin section (0.2%; Table 1). The lower part of this ignimbrite is less crumbly than the top but contains the same crystallinity (~40 crystals per 100 cm²; 0.2-0.5 cm). It is less crystal-rich than the upper ignimbrite at the westmost Mount Jackson section but matches it in fiamme counts.

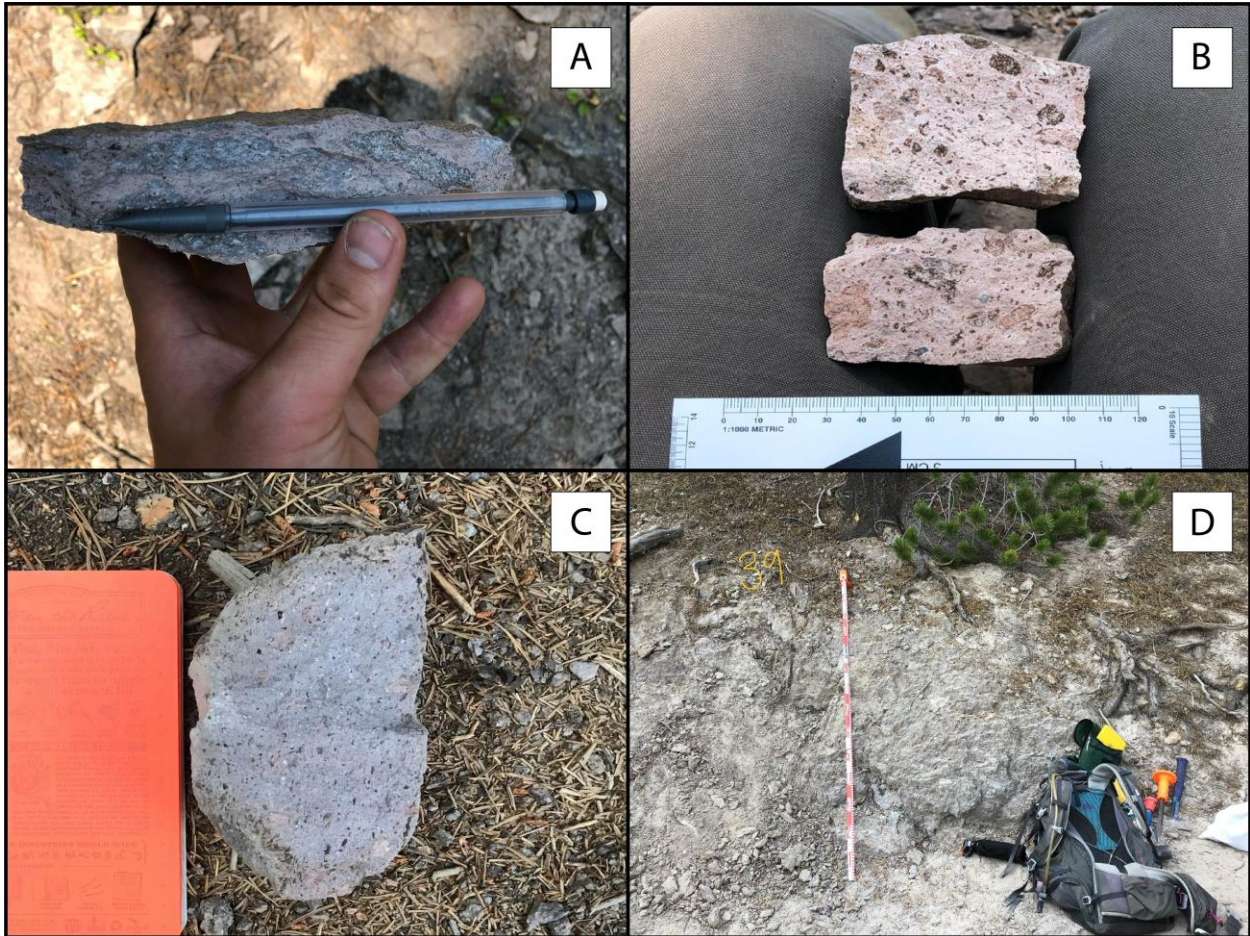


Figure 7. Outcrop and hand sample photos in the field of four major Purple Mountain LCT ignimbrites, listed from stratigraphic lowest to highest: A – crystal-poor, fiamme-rich with black lithics, B – pumice-rich with black, gray and red lithics, C – porous pumice-rich with no lithics, and D – fiamme-rich crumbly capped ignimbrite.

Slump Block (SB) Christiansen (2001) interpreted this area as a post-caldera collapse, marked by a wide valley and interpreted fault between the Secret Valley section to the north and the Purple Mountain section in the west. The mapped LCT lower-member A of Tuff Cliff outcrops as a single cliff with subrounded bluffs. Lower Tuff Cliff is a lithophysae-, pumice-, and lithic-rich locality, broadly distinct from the rest of the Slump Block section. It contains breadcrust bombs of gray, black, and mostly red lithics, closely matching the lower-middle-Purple Mountain ignimbrite. Red lithics are only found in these two areas in the Madison

Junction region. The lower Tuff Cliff ignimbrite is moderately-welded with large pumice and fiamme, but crumbly in outcrop and hand sample. Above this lower zone the LCT becomes more densely-welded, forming cliffs that match the weathering patterns of the Mount Jackson and Harlequin Lake upper LCT sections (Table 1).

To the east of Tuff Cliff, the mapped LCT lower-member A is crystal-poor (16 crystals per 100 cm²; 0.1-0.2 cm) with white and pink pumice (16 pumice per 100 cm²; 0.2-1.6 cm) and black recycled rhyolite lithics (8 lithics per 100 cm²; 0.1-0.4 cm), matching the lower Purple Mountain section. Multiple roadside exposures along the base of the Slump Block section were explored and found to vary in crystal content and componentry, ranging from the crystal-poor (16 crystals per 100 cm²; 0.1-0.4 cm), lithic-rich (10 black lithics per 100 cm²; 0.3 cm) and pumice-rich (40 per 100 cm²; 1-2 cm) ignimbrite to a crystal-rich (130 crystals per 100 cm²; 0.3-0.4 cm) ignimbrite. GIS hillshade implies that there could be up to four smaller, rectangular blocks slumped downward from the overlying region, explaining the close variability of these two types of ignimbrites (Figure 8).

Stratigraphically above these variable ignimbrites within separate faulted blocks (Figure 8), exposures begin as moderately crystal-rich ignimbrite containing 40 crystals (0.1-0.3 cm) per 100 cm² with altered white pumice (~10 pumice per 100 cm²; 2-5 cm). This is capped by a ~120 m-thick fiamme-rich (25 fiamme per 100 cm²; 12-108 cm long), densely-welded ignimbrite (80 crystals per 100 cm²; 0.5-0.6 cm). This upper fiamme-rich ignimbrite matches the ignimbrite seen at the upper Mount Jackson, Purple Mountain, and Harlequin Lake sections (Figure 10).

Secret Valley (SV) The Secret Valley section of the Madison Junction area is a marshland, with Secret Valley Creek flowing eastward. GIS hillshade analysis shows limited

exposures in the north cliffs of the valley, with hot spring deposits to the northeast, limiting access. At the base of a north-trending dry riverbed is a gray 2x1 m exposure of jagged, horizontally layered, densely-welded ignimbrite (44.679N, 110.807W). This ignimbrite has 85 crystals per 100 cm² (0.4-0.7 cm) with frequent gray lithics (4-8 cm). These gray lithics match those in the ignimbrite at the lowest Purple Mountain and upper Harlequin Lake sections. Moving upslope, the ignimbrite becomes more densely-welded, losing the gray lithics but gaining white-altered fiamme in a pale gray groundmass with consistent crystal counts of 50-60 per 100 cm², dominated by quartz and sanidine. Though these fiamme are usually found on a fresh surface as black, glassy lenses, white fiamme are likely explained by devitrification and/or alteration. Inside, the white-altered fiamme appears a darker orange core. Outcrops of this ignimbrite weather to boulders and cliffs >650 m-thick vertically, with fiamme increasing in length and size as you travel up section (from 1-3 cm long to 11-18 cm long at the top). The upper outcrops representative of the rocks of this region are similar to upper outcrops in the Mount Jackson, Harlequin Lake, Purple Mountain, and Slump Block sections (Figure 10).

Gibbon River (GR) The vitrophyre unit is exposed as both lichen-covered float and partially buried outcrop on a grassy bank slope along the Gibbon River (Figure 9A; 44.662N, 110.754W). It contains large (0.3-1 cm) sanidine phenocrysts with a high crystallinity (125 crystals per 100 cm²). Examining the vitrophyre unit in thin section reveals that its groundmass is made of angular, broken pieces of glass, suggesting an explosive rather than effusive origin.

Sixty meters east of this vitrophyre is a 6x2.5 m exposure of a red and black devitrified, crystal-poor, dense lava flow (Figure 9B) with shards of sanidine and some quartz (6 crystals per 100 cm²; 0.05-1 cm). This flow is not laterally extensive; for instance, evidence for this flow

could not be found on the opposite side of the Gibbon River. However, material from this flow was sent in for dating due to its proximity to the incorrectly mapped vitrophyre. To the east of the lava flow, the banks of the GB section are dominated by a south-facing 100 m-long set of densely-welded, devitrified, bulbous ignimbrite cliffs (60 crystals per 100 cm²) with elongated, altered white fiamme (4-20 cm long); these cliffs resemble the upper portion of Secret Valley cliffs, found just to the north. Material from a second singular dense lava flow to the east was also sent in for dating, due to its field similarities to the western lava flow.

Conformably overlying these outcrops, two stratigraphically linked but gully separated outcrops represent the upper ignimbrites in this region. The fault that divides the Slump Block section from the surrounding area cuts halfway through the west gully, with the downthrown block mapped as LCT lower-member A and the footwall mapped as LCT upper-member A. However, crossing over the mapped fault at this gully, no evidence for displacement was observed, nor other evidence of faulting (e.g., breccias, slickenlines, fluid alteration) observed. The east gully is mapped exclusively as LCT upper-member A. The first 350 m of both gullies are pink, densely-welded ignimbrites with dark gray fiamme (>5-7 cm long; recrystallized). The west lower ignimbrite consists of monolithic float with a modest crystal count (75 crystals per 100 cm²; 0.2-0.4 cm), whereas the east is a thick range of bluffs (Figure 9C) with fewer crystals (25 crystals per 100 cm²; 0.1-0.2 cm) containing black recycled rhyolitic lithics (142 lithics per 100 cm²) that are similar to those found at the lower Purple Mountain, Tuff Cliff, and Slump Block sections.

Whereas the east gully cliffs out, the west gully continues upward. The exposure gradually changes from slabbed monolithic float of pink densely-welded ignimbrite to rounded

boulders of monolithic devitrified, crumbly ignimbrite (~ 30 crystals per 100 cm^2 ; 0.3-0.5 cm) with white fiamme (~ 63 fiamme per 100 cm^2 ; 1-8 cm long). This continues for ~ 455 m vertically until the top of the gully, where 10 m-tall brown ignimbrite bluffs, with matching crystallinity and fiamme counts, cap the west gully. These bluffs wrap around the entire GB section (Figure 9D), overlying the pink ignimbrites from the east gully and continuing eastward to the Monument Geyser Basin. The rocks match the crystal and componentry counts of the upper LCT ignimbrites of the Mount Jackson, Harlequin Lake, Purple Mountain, Slump Block, and Secret Valley sections to the west (Figure 10).

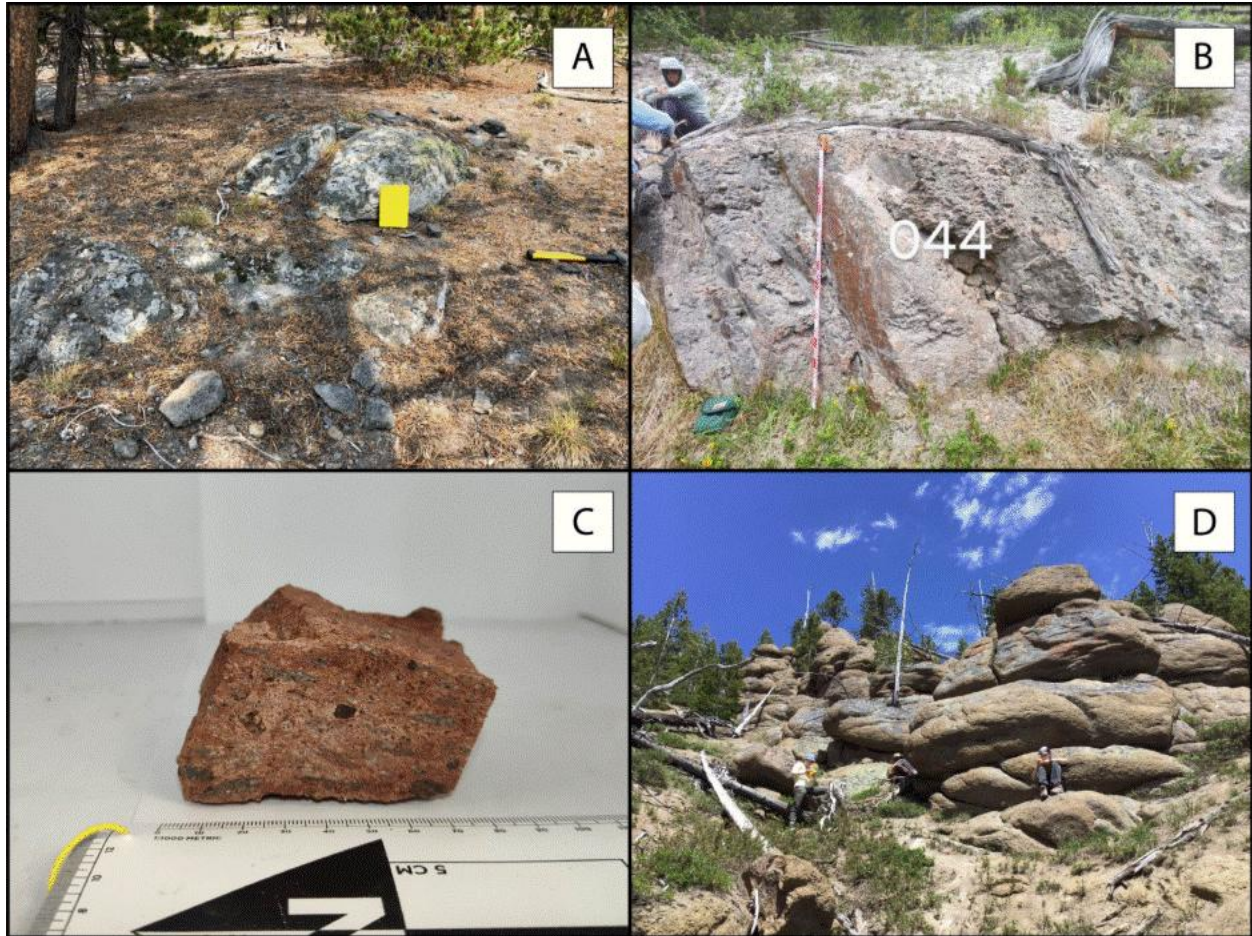


Figure 9. Outcrop and hand sample photos in the field of major Gibbon River outcrops, where A – New MJR vitrophyre unit, B – unmapped lava flow unit, C – east outcrop of LCT bluffs, and D – west outcrop of LCT bluffs stratigraphically overlying C.

Locality	Mapped unit	Qtz	Sani	Plag	Mafic	Pumice/ Fiamme	Opaque	Lithic	Matrix
Cougar Creek	LCT Upper A	9.4	6.4	2	0	0	1.5	0	80.7
Gneiss Creek (Fig. 8A)	LCT Member B	6.9	8.2	0.9	1.7	0	0.9	0	81.4
History Exhibit	Alluvium	7.2	6.4	0.4	0	0	0	0	86
Purple Mountain (Fig. 11D)	LCT Upper A	16.2	5.2	0.7	0.2	0	2.4	0	75.3
Purple Mountain (Fig. 11B)	LCT Lower A	4.3	4	1.6	0.2	0/4.8	0	0	85.1
Tuff Cliff*	LCT Upper A	7.4	1.7	0	0	13.4/0	0	0	77.5
Tuff Cliff*	LCT Lower A	15.8	4.3	0	0	0	0.6	0	79.3
Tuff Cliff*	LCT Lower A (recycled clast)	3.9	2.7	0.6	0	0	0.06	0	92.7
Gibbon River (Fig. 12C)	LCT Upper A	4.6	3.2	1.7	0	3.8/4.7	0.1	0.6	81.4
Harlequin Lake	MJR – Harlequin Lake flow	7.2	9.5	3.4	0	0	0.3	0	79.6
Mount Jackson	MJR – Mount Haynes flow	1.7	2	1	0	0	0	0	95.3
Gibbon River vitrophyre (Fig. 12A)*	LCT Upper A	8.6	3.8	0.3	0.1	0	0	0	87.2
Mount Jackson (Fig. 9)	MJR – Mount Haynes flow	3.2	5	0.4	2.2	0	0.2	0	89

Table 1. A summary table of mineral point counts, listed in percent, representing each distinctive ignimbrite and lava flow unit in the mapped area. For each sample, 1,000 point counts were completed using thin sections, with a total of 14 thin sections analyzed. Qtz = Quartz, Sani = Sanidine, Plag = Plagioclase. Groundmass can consist of vesicles, devitrified glass, or glass. *Point counts from Tuff Cliff and the “MJR – new vitrophyre” were taken by Henderson et al., in prep and measured in the same way.

While Henderson et al. (in prep) challenges the two-member LCT, work like this study and Myers et al. (2026), begin to rebuild the stratigraphy of the LCT using detailed fine-scale remapping. Field observations (i.e. crystal sizes, crystal and componentry counts) have been beneficial in separating packages of the LCT and dividing them from lava flows in the area (Table 1), and allowing the fiamme-rich capped LCT ignimbrite to be linked across the field area (Figure 10) with crystal-poor, lithic-rich lower ignimbrites in the Purple Mountain and Tuff Cliff sections. Further, these observations have strengthened descriptions for the Mount Haynes and Harlequin Lake flows of the MJR, even discovering several unmapped units of this series. Key takeaways from field observations include:

- 1) Gneiss Creek preserves several small outcrops and exposures that display significant horizontal and vertical variation indicating multiple depositional breaks between LCT emplacement (Figure 4), including a lower clinopyroxene-rich lower ignimbrite. Though Christiansen (2001) mapped Gneiss Creek as LCT member B, the upper bluffs of this section are weathered to brown, subrounded blocks, more like Christiansen (2001)'s description of the LCT member A.
- 2) A pumice-rich capping ignimbrite is observed consistently from Gneiss Creek to the westmost Cougar Creek, on the west side of the field area, spanning Christiansen's mapped LCT member B.
- 3) A gully outcrop in the History Exhibit section, that was previously mapped as alluvium, was found to be a lava flow with 54 crystals per 100 cm². If its age is within the LCT range, its existence would complicate our understanding of the LCT eruption. However, its age could also fall within the Mount Haynes flow of the MJR.

- 4) In the Mount Jackson section, an unmapped, glass-rich flow was found conformable at the base of a continuous stratigraphic section to an overlying LCT package. This is one of the only places in the field area where a clear contact can be seen between a lower lava and the LCT (Figure 5). Three clasts – including the lower lava flow – are well-formed and preserved in pyroclastic beds between the lava flow and the overlying LCT. They have all been sent for whole-rock geochemistry and dating.
- 5) Several sites (eastern Mount Jackson, Harlequin Lake, Purple Mountain, and Secret Valley) have a lower black and gray lithic-rich section of LCT in or just below the fiamme-rich upper package (Figure 10). These isolated sections are mapped in thinner packages than what Christiansen (2001) has described.
- 6) The Purple Mountain and Tuff Cliff localities include similar pumice-rich, crystal-poor lower ignimbrite packages with black, gray, and red lithics. Christiansen (2001) isolates Tuff Cliff and only mentions rhyolitic lithics.
- 7) The Gibbon River section contains a local vitrophyre unit dated within the MJR (0.78 Ma) that preserves glass shards suggesting it is the result of an explosive eruption. This region also contains two local, unmapped lava flows that were sent for dating.
- 8) A fiamme-rich capped unit is observed from Cougar Creek through all eastern locations in the larger map area. Due to similar crystallinity and componentry, observation 2 and 8 could be the same ignimbrite, but at different welding intensities. This capped unit has up to 80 crystals per 100 cm² in the Mount Jackson section and decreases eastward to as low as 20 crystals per 100 cm² in the Tuff Cliff section, then increases again to 60-80 crystals per 100 cm² in the Secret Valley and Gibbon River sections. It generally matches

Christiansen (2001)'s description of the LCT upper A but does not include any amphibole.

- 9) The Mount Haynes and Harlequin Lake flows of the MJR are broadly mapped correctly, where the Mount Haynes flow is crystal-poor to moderately crystal-rich (17-56 crystals per 100 cm²) and exhibits local flow banding, and the Harlequin Lake flow is crystal-rich (60-120 crystals per 100 cm²) with limited to no flow banding.

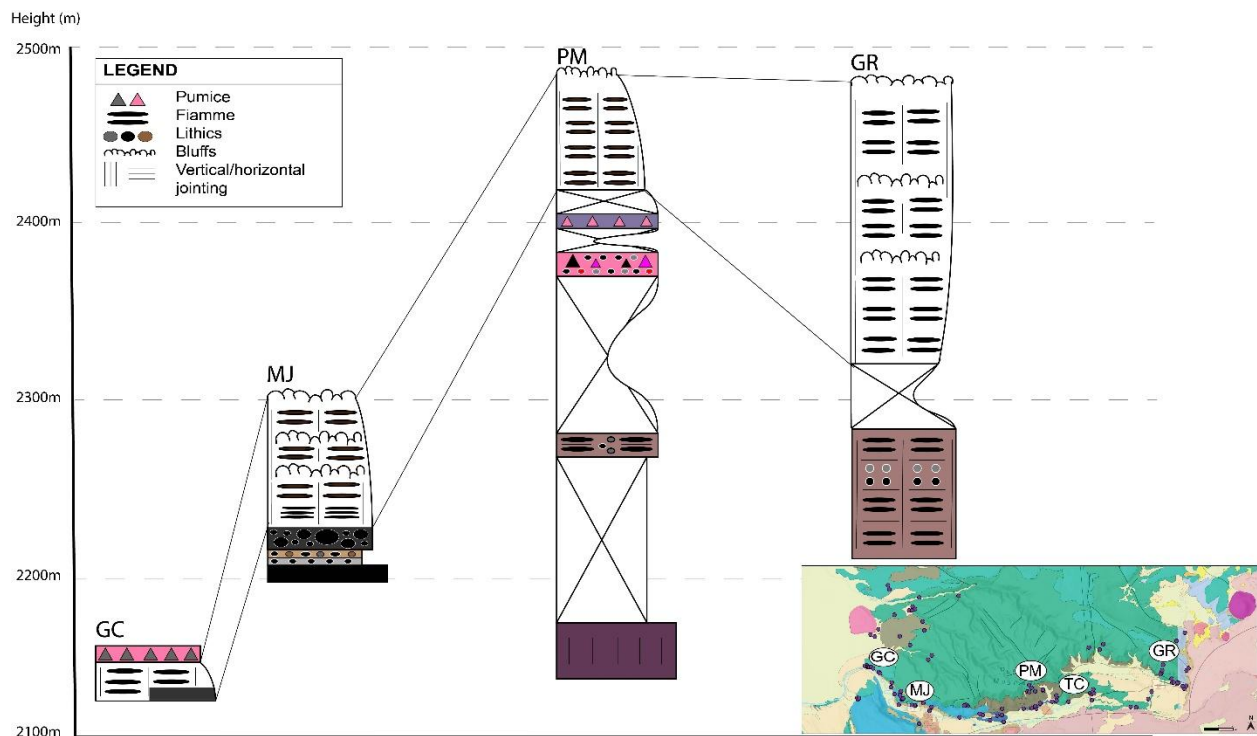


Figure 10. Simplified, composite stratigraphic columns of Gneiss Creek (GC), Mount Jackson (MJ), Purple Mountain (PM), and Gibbon River (GR) to show an observed fiamme-rich capped ignimbrite package and variable lower LCT and MJR units. Colors of each outcrop (purple, brown, white, black, and pink) reflect their outcrop colors. Sections with an X through them represent elevations with no outcropping. The x-axis is marked by relative resistivity of the units to erosion and weathering.

Together, field observations, crystallinity, and componentry analyses have identified five packages within the LCT, two new lava flows, and one new unit of the MJR. To further define

these units, geochronology ($^{40}\text{Ar}/^{39}\text{Ar}$ dating), whole-rock geochemistry, and EPMA on sanidines will further discriminate how many packages make up the LCT eruption in the Madison Junction area and allow for geochemical relationships between the MJR and new lava flows to be assessed.

$^{40}\text{Ar}/^{39}\text{Ar}$ Dating

Sixteen samples in the Madison Junction area were sent for $^{40}\text{Ar}/^{39}\text{Ar}$ dating (Figure 11). These samples were chosen because they represent outcrops that were either unmapped or whose field and petrologic descriptions did not correspond to the mapped unit. Further, samples from the Mount Haynes and Harlequin Lake flows of the MJR series (Troch et al., 2017) and the CCR (Christiansen, 2001; Nastanski, 2005) were dated to add to our limited knowledge of these units (Table 2).

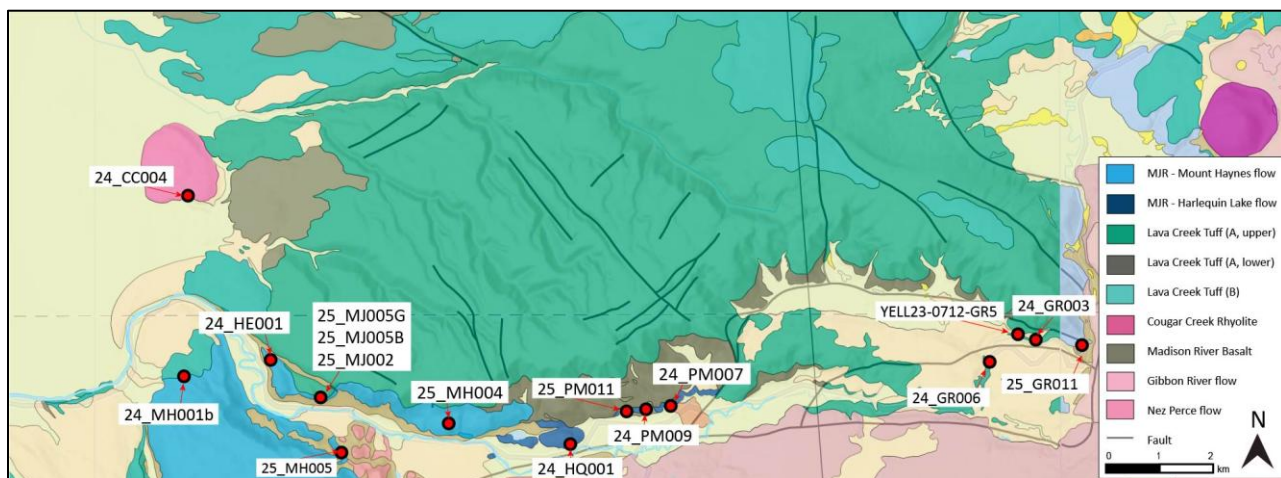


Figure 11. A map of the Madison Junction area showing the location and labels of samples used for $^{40}\text{Ar}/^{39}\text{Ar}$ dating. Modified from the map of Christiansen (2001).

Determined Unit	Mapped Unit	Sample	Age (Ma)	1 sig.	95% conf.	MSWD	n _{used} of n _{total}
Cougar Creek Rhyolite	Cougar Creek Rhyolite	24_CC004	0.3667	0.0034	0.0067	1.67	6 of 15
LCT	LCT	24_MH001b	0.62939	0.00065	0.00127	1.05	15 of 20
LCT	Alluvium	24_HE001	0.641	0.001	0.002	1.8	8 of 15
LCT	LCT	24_GR006	0.63025	0.00073	0.00143	0.97	14 of 20
Central Plateau – Gibbon	LCT	24_GR003	0.0856	0.0019	0.0037	0.21	7 of 19
River flow			0.1085	0.0022	0.0043	0.88	5 of 19
MJR – New vitrophyre	LCT	YELL23- GR5	0.7761	0.0018	0.0034	0.58	12 of 16
MJR – Harlequin Lake flow	MJR – Harlequin Lake flow	24_HQ001	0.8517	0.0021	0.0041	0.9	6 of 15
MJR – Harlequin Lake flow	MJR – Harlequin Lake flow	24_PM007	0.8502	0.0013	0.0025	1.34	7 of 15
MJR – Harlequin Lake flow	MJR – Harlequin Lake flow	24_PM009	0.8487	0.001	0.002	0.85	15 of 19
TBD*	MJR – Mount Haynes flow	25_MH004	--	--	--	--	--
TBD*	MJR – Mount Haynes flow	25_MH005	--	--	--	--	--
TBD*	LCT	25_MJ002	--	--	--	--	--
TBD*	LCT	25_MJ005G	--	--	--	--	--
TBD*	LCT	25_MJ005B	--	--	--	--	--
TBD*	LCT	25_GR011	--	--	--	--	--
TBD*	MJR – Harlequin Lake flow	25_PM011	--	--	--	--	--

Table 2. The weighted mean age of sixteen samples dated in the Madison Junction area in Mega-annum (Ma). *Samples were sent for dating on November 19th, 2025, and have not yet been received. These ages will be added to a published paper. The age of the MJR – new vitrophyre was taken from Henderson et al., in prep.

The Cougar Creek Rhyolite age is 0.3667 ± 0.0034 Ma (Table 2), which is well within error of the previous date (0.368 ± 0.002 Ma; Nastanski, 2005). Three samples from the Harlequin Lake flow of the MJR were dated due to their proximity along contacts with the LCT, to make sure that mapping boundaries were correct. All three samples yielded analytically indistinguishable ages between 0.85 and 0.851 Ma (Table 2) and return a weighted mean age of 0.850 ± 0.0007 Ma (MSWD = 1.01), ~ 0.02 Ma older than Troch et al. (2017)'s ages of this flow (0.83 ± 0.0031 Ma). Two mapped LCT samples were dated: one sample (24_MH001b) that lies on an LCT-MJR boundary and one sample along an alluvium and LCT boundary (24_GR006). Both samples have been confirmed as LCT age (0.631 Ma; Table 2).

Our first discrepancy is a lava flow in the Gibbon River section mapped as LCT upper member A (Christiansen, 2001) but which returned two dates: 0.1085 ± 0.0022 Ma and 0.0856 ± 0.0019 Ma (Table 2; Figure 12), both of which are within error of the age of the post-LCT Gibbon River flow (Wooton, 2010; Stelten et al., 2015). The second is the vitrophyre unit mapped as LCT upper member A (0.631 Ma) but dated to 0.7761 ± 0.0018 Ma (Henderson et al., in prep; Table 2; Figure 9A). This age confirms that the vitrophyre erupted between the Harlequin Lake and Mount Haynes flows of the MJR and is the first explosively erupted unit recognized in the MJR series. Third, a sample mapped as alluvium in the History Exhibit section, returned an age of 0.641 ± 0.001 Ma, roughly 10,000 years before the LCT eruption (Table 2). Based on isochron analysis, these three samples have trapped gas components that do not preserve evidence for excess ^{40}Ar , suggesting that these ages are not overestimated.

Two samples for the Mount Haynes flow of the MJR have been sent in, with one sample from the north cliffs of the Mount Jackson section (17 crystals per 100 cm^2) and one from the

south cliffs of the Mount Haynes section (56 crystals per 100 cm²). The variation in crystal counts and spatial separation are why they are submitted for dating. Other undetermined samples were sent in for dating: a mapped Harlequin Lake sample (25_PM011), which is dense and does not reflect the same petrologic descriptions as the MJR, and a mapped LCT sample (25_GR011), which is petrologically similar to the Gibbon River lava flow found stratigraphically nearby. Finally, the undated, unmapped crystal-rich (237 crystals per 100 cm²) lava flow from the Mount Jackson section, as well as two different clasts from the ash unit between the lava flow and the overlying LCT, have been sent for dating. These ages have not yet been received (Table 2).

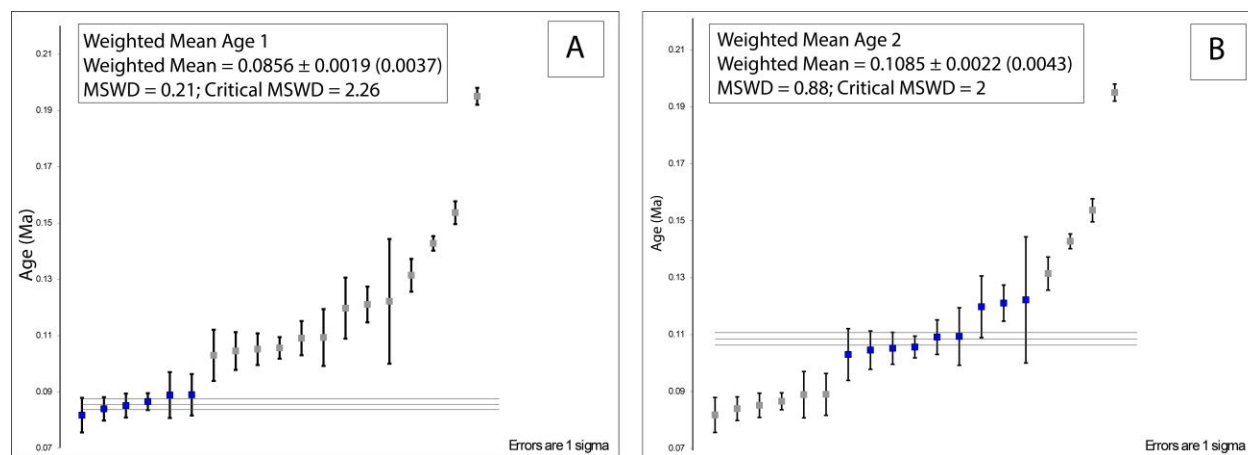


Figure 12. Weighted mean average of the two age populations of 24_GR003.

Major and Trace Element Analysis

Fifteen LCT, nine MJR, and five currently unknown samples were sent for whole-rock major, minor, and trace elements (Figures 13, 14; Appendix D). The five unknown samples, which are also the focus for dating, were: the new vitrophyre unit by the Gibbon River, the lava flow by the Gibbon River, the crystal-rich black lava flow from Mount Jackson, and a gray and brown clast from the unit between the crystal-rich black lava flow and the overlying LCT. The LCT, MJR, and all unknown samples from this study – alongside studies by Troch et al. (2017), Henderson et al. (in prep), and Salazar (2023) – highlight that whole-rock geochemical analysis reveals no significant major element variations between MJR and LCT, as they are all of high-silica rhyolitic composition (74.9- 77.6% SiO₂, calculated volatile-free).

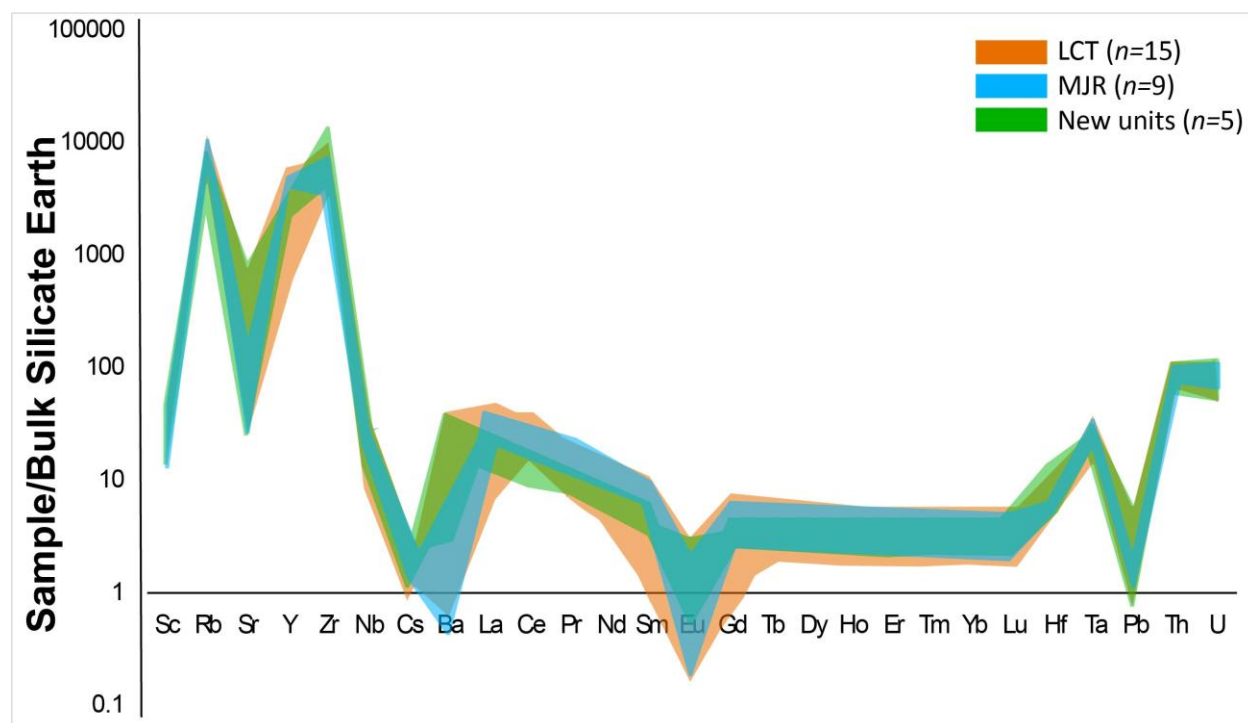


Figure 13. Trace element data were normalized to Bulk Silicate Earth from McDonough & Sun 1995. The LCT is orange (Henderson et al., in prep; this study) and the MJR is blue (Troch et al., 2017; this study), with uncertain units that do not match their mapped counterparts in green.

Further, minimal variability is observed in whole-rock trace element concentrations, with barium (Ba), strontium (Sr) and europium (Eu), all sensitive to feldspar fractionation, showing the greatest difference between the different groups (Figure 13). The MJR are the most depleted in Ba, Sr and Eu whereas most of the “new units” preserve higher concentrations. The LCT exhibits the greatest range in whole-rock Ba concentrations. For rhyolitic systems dominated by feldspar and quartz, trace elements that are influenced by feldspar crystallization (e.g. barium, strontium) may provide further clarity to understanding the chemical differences observed in the LCT, the MJR, and unmapped units (Swallow et al., 2019).

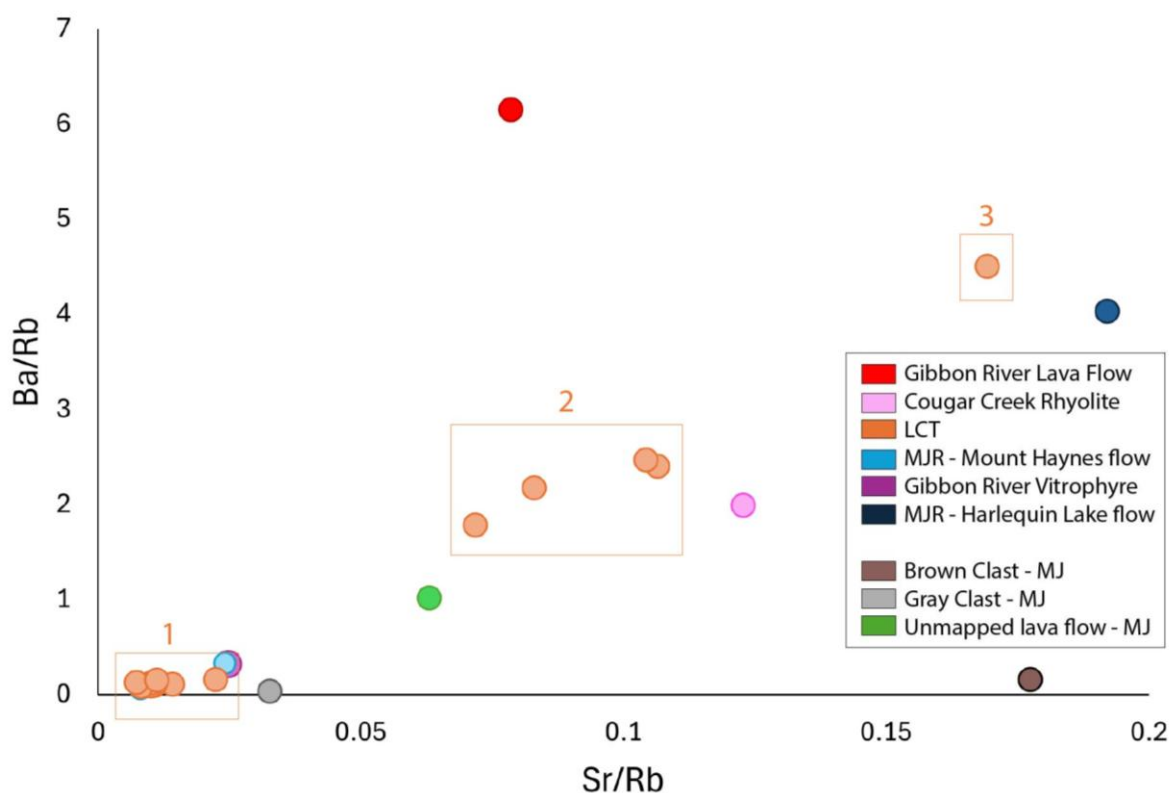


Figure 14. Whole-rock XRF Sr/Rb vs Ba/Rb plot of the LCT, MJR, CCR, and unmapped samples from this study. Brown Clast – MJ, Gray Clast – MJ, and Unmapped lava flow – MJ represent samples from the Mount Jackson (MJ) section. Three LCT populations are labeled 1-3.

In Ba-Sr/Rb whole-rock space, the LCT in the Madison Junction area has three distinct populations (Figure 14):

1. The first population shows the lowest ratios (0.0748-0.1514 Ba/Rb and 0.0074-0.0224 Sr/Rb). These eight samples are from exposures that lie in the lowest stratigraphy in the LCT sequence of Madison Junction, including lower Purple Mountain, Gibbon River, and Mount Haynes. These samples are crystal-poor, and often lithic- and pumice-rich.
2. The second population exhibits average ratios of 2.202 Ba/Rb and 0.0914 Sr/Rb. These four samples are from exposures that lie in the middle to upper LCT sequence, including the middle of Gneiss Creek (Figures 4B, 10) and Mount Haynes, and upper Cougar Creek.
3. The third population of LCT is a single sample from the stratigraphic top of Gneiss Creek, which exhibits elongated vesicle stretching. This sample has the highest ratio of 4.492 Ba/Rb and 0.1692 Sr/Rb.

These whole-rock XRF observations can help shed light on unknown units. The 0.64 Ma lava flow from the History Exhibit section reflects Ba-Sr/Rb within the first population of the LCT (0.1459 Ba/Rb and 0.0112 Sr/Rb). The brown clast from the Mount Jackson section does not appear to relate to either the LCT or the MJR and instead has a higher Ba-Sr/Rb ratio (0.1519 Ba/Rb and 0.1774 Sr/Rb), reflecting the least evolved rhyolite of all units in this study area (Figure 14). The gray clast (0.0259 Ba/Rb and 0.0328 Sr/Rb) from the Mount Jackson section and the conformably lower lava flow (1.010 Ba/Rb and 0.0631 Sr/Rb) include Ba-Sr/Rb ratios between two of the lower LCT populations. The Harlequin Lake flow of the MJR (4.024 Ba/Rb

and 0.1922 Sr/Rb) is less evolved in Sr/Rb than the third population of the LCT (4.492 Ba/Rb and 0.1692 Sr/Rb). The vitrophyre unit from the Gibbon River section and the Mount Haynes flow of the MJR overlap in geochemical space (~ 0.327 Ba/Rb and ~ 0.248 Sr/Rb) but are temporally separate. The Gibbon River lava flow shows a high Ba/Rb (0.3144) and low Sr/Rb (0.0248), potentially reflecting a lower proportion of sanidine crystallization relative to plagioclase. Although the Cougar Creek Rhyolite belongs in the same post-LCT member as the Gibbon River flow (Christiansen, 2001; Wooton, 2010), the Cougar Creek Rhyolite lies closer to the second population of the LCT at 1.986 Ba/Rb and 0.1229 Sr/Rb.

Electron Probe Microanalyses (EPMA)

Fourteen samples in the Madison Junction area were selected for Ba-in-sanidine analyses (Figure 15). Five mapped LCT upper-member A and four mapped LCT lower-member A samples were chosen, stratigraphically linked and representing horizontal variation. One mapped LCT member B sample was chosen to compare with the other LCT material, stratigraphically aligned with the LCT upper-A. One representative sample from the Mount Haynes and Harlequin Lake flows was selected, to compare against the unmapped lava flow of the lower Mount Jackson section. Finally, the newly dated MJR-age vitrophyre in the Gibbon River section was also selected.

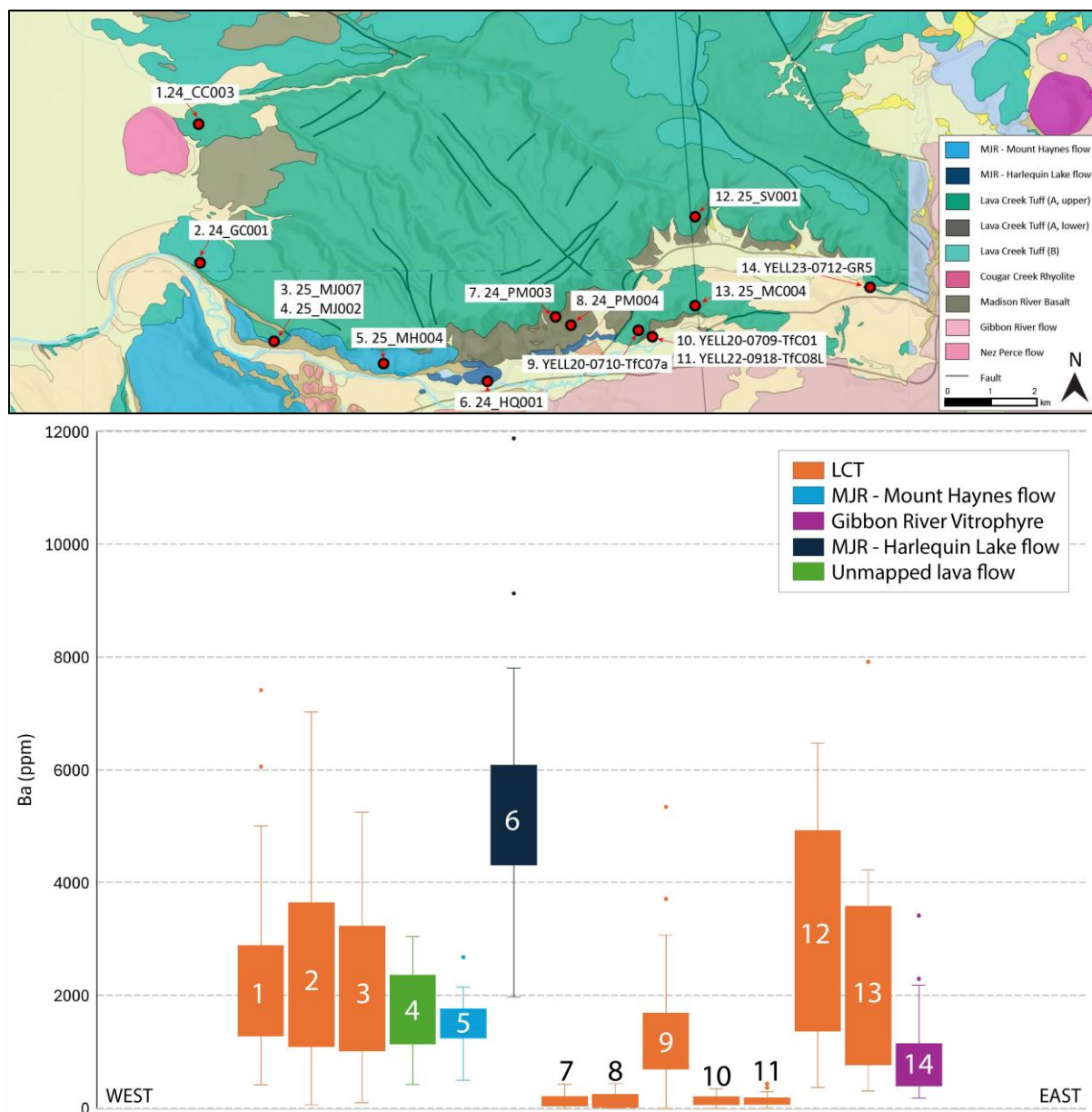


Figure 15. **Upper:** A map of the Madison Junction area showing the location of samples in which sanidine was measured by EPMA analyses. Samples from Tuff Cliff are from Henderson et al., in prep. Number eleven is a recycled clast from the mapped LCT lower-member A. Map is modified from Christiansen, 2001. **Lower:** Box and whisker plot of samples from the Madison Junction area, listed from left to right. Samples are numbered by section and colored by unit. The LCT are: 1 – Cougar Creek, 2 – Gneiss Creek, 3 – Mount Jackson, 7 – Lower Purple Mountain, 8 – Lower Purple Mountain, 9 – Upper Tuff Cliff (Henderson et al., in prep), 10 – Lower Tuff Cliff (Henderson et al., in prep), 11 – Lower Tuff Cliff (Henderson et al., in prep), 12 – Secret Valley, 13 – Slump Block. The MJR are: 5 – Mount Jackson, 6 – Harlequin Lake, 14 – Gibbon River vitrophyre. Unmapped, undated lava flow unit: 4 – Mount Jackson.

Ba concentrations in sanidine for LCT units in the Madison Junction area show two distinct populations, one with concentrations falling between the detection limit (DL; <350 ppm; Figure 15) and 432ppm, and the other ranging from DL up to 7,915 ppm (Figure 15; Table 3). The first LCT population includes four samples from the lower Purple Mountain and Tuff Cliff section, matching other work on Tuff Cliff (Henderson et al., in prep). The second LCT population includes six samples from the stratigraphically uppermost LCT, including mapped LCT member B, spanning from Cougar Creek to the upper Slump Block (BDL to 7,915 ppm Ba; Table 3).

The Mount Haynes flow of the MJR has a small range of Ba-in-sanidine that lies within the second LCT population (494 to 2,677 ppm; Table 3). The Harlequin Lake flow includes the highest Ba-in-sanidine concentrations of all samples in the Madison Junction area (1,970 to 11,881 ppm; Table 3). The unmapped crystal-rich lava flow in the Mount Jackson section (Figure 5) also lies within the second LCT population (415-3,044 ppm; Table 3), closest to the Mount Haynes flow. Finally, the new vitrophyre unit in the Gibbon River section exhibits Ba concentrations DL to 3,415 ppm (Table 3), overlapping both populations of the LCT.

Sample	Locality/Section	Min. Ba (ppm)	Max. Ba (ppm)	Average (ppm)
1	Cougar Creek	410	7416	2386
2	Gneiss Creek	DL	7024	2517
3	Mount Jackson	DL	5248	2293
4	Mount Jackson	415	3044	1665
5	Mount Haynes	494	2677	1520
6	Harlequin Lake	1970	11881	5357
7	Purple Mountain	DL	432	DL
8	Purple Mountain	DL	419	DL
9	Tuff Cliff	DL	5340	1212
10	Tuff Cliff	DL	DL	DL
11	Tuff Cliff	DL	DL	DL
12	Secret Valley	364	6472	2890
13	Slump Block	DL	7915	2233
14	Gibbon River	DL	3415	912

Table 1. Lowermost and upper values for measured barium concentrations (Ba; ppm) in sanidines rims from bulk rock samples taken throughout the field area (Figure 14; n = 14). Data for samples 9-11 are taken from Henderson et al., in prep. Number 11 is a recycled clast from the mapped LCT lower-member A. DL = “Detection Limit” which for this study is 350 ppm, determined by a Kernel Density Plot from Appendix E, Figure 18.

DISCUSSION

Required Map Updates

Most of the mapped contacts from Christiansen's (2001) geologic map of the Madison Junction area remain unchanged, with revisions as follows: the MRB contact in the Cougar Creek section was moved west, north, and east by 230 m, the upper LCT bluffs in the Mount Jackson section connecting to alluvium ~40 m west of the lower lava flow stratigraphy, and the fault dividing the Slump Block from the Gibbon River section has been brought down into the valley. In addition, stars on Figure 16 are labeled on units that are unmappable due to their small size (e.g., minor lava flows) but are still important findings to add in the YVF stratigraphy.

Further updates regard the splitting of the LCT in this region. The LCT in the Madison Junction area was originally mapped as lower-member A, upper-member A, and member B (Christiansen, 2001), this area being the only place where LCT lower-member A was reported. These members were earlier divided based on welding intensities, crystallinity measurements, and the presence of amphibole in member A. However, field observations show a lack of amphibole in all the LCT deposits in the Madison Junction area. Instead, crystallinity, lithics, pumice and fiamme types and counts and EPMA are used here to identify five packages, with lower lithic-rich ignimbrites grading upward to densely-welded, devitrified, crystal-rich ignimbrites. Splitting the LCT in the Madison Junction area into discrete packages highlights the variability in near-vent eruptive styles and compositions.

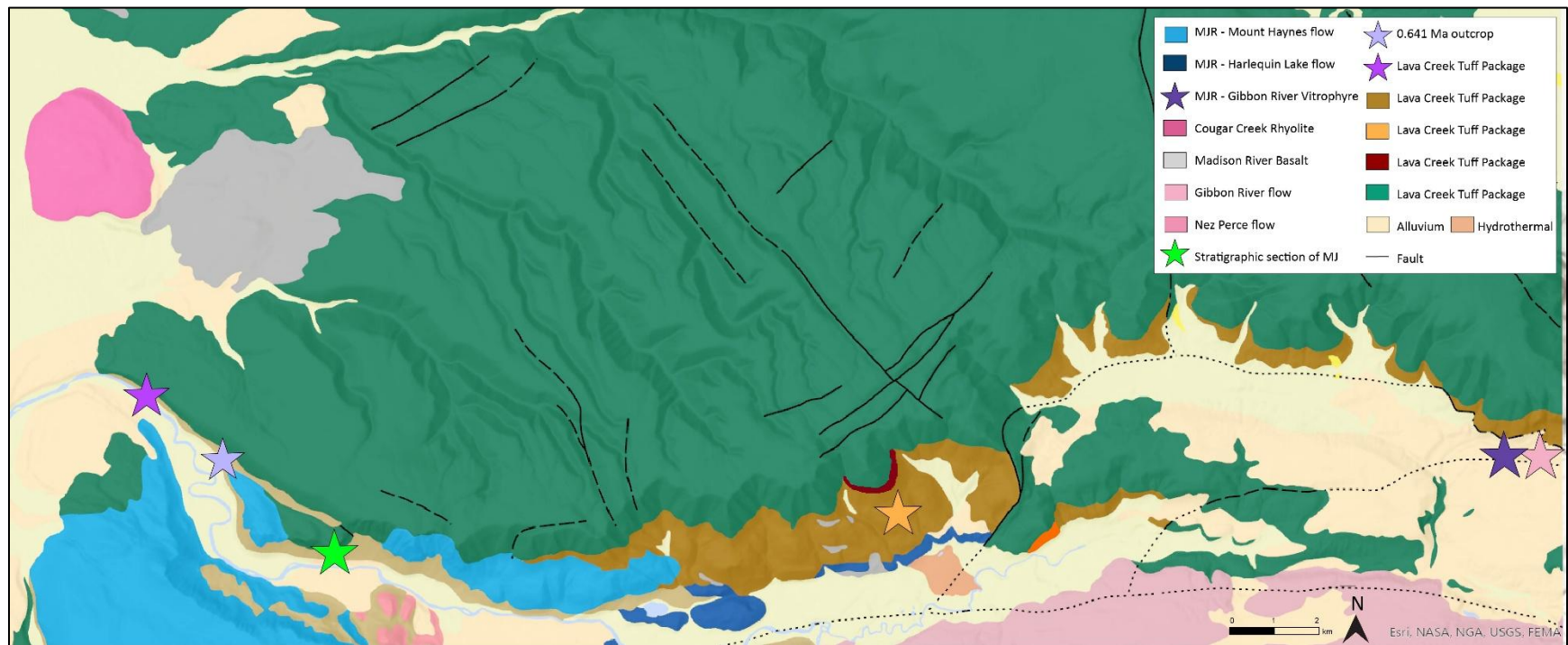


Figure 16. An updated geologic map of the Madison Junction area. Geologic units marked in stars are added to the areas that they would be mapped in but are too small to be included.

LCT

The five field packages determined through field observations reflect changes in eruptive dynamics and welding intensities through the Madison Junction area. From stratigraphic low to high, these LCT packages range from lithic- and pumice-rich – containing black and gray rhyolite lithics and red lava lithics, indicating ignimbrite ripping through preexisting rhyolitic eruptions – to lithic-poor and fiamme-rich – reflecting a stable, densely-welded upper ignimbrite (Figure 17). The black and gray lithic-rich ignimbrite and the fiamme-rich upper ignimbrite are the dominant LCT packages in the Madison Junction area, divided by field descriptions, whole-rock geochemistry, and EPMA analyses (Figure 17). Other systems (e.g. Lascar Volcano, Chile (Calder et al., 200) and Campi Flegrei, Italy (Gallo et al., 2023)) show a similar stratigraphic relationship, with basal deposits that rip through preexisting lava flows, preserving them as lithics in their lower stratigraphy. These ignimbrites eventually stabilize to become densely-welded and lithic-poor, representing much of the eruption. This highlights that the Madison Junction region preserves an important transition in the LCT eruption progression.

Field observations from this study suggest that mapped LCT upper member A and member B are the same ignimbrite package, which contrasts with Christiansen (2001) field observations. Whole-rock geochemistry and EPMA data confirms that mapped A versus B ignimbrites are geochemically the same, lying within the least evolved, highest whole-rock Ba-Sr/Rb population. Further, their physical and petrologic features are also the same, with a correlated flow spanning their division, covering a majority of the Madison Junction area (Figure 16, 17).

Although this crystal-poor, lithic-rich to crystal- and fiamme-rich stratigraphy matches the Christiansen (2001) description of the LCT lower- and upper-member A, EPMA analyses separate the stratigraphy into two separate magmatic populations, the lithic-rich lower population includes low values for barium in sanidine, whereas and the fiamme-rich upper population includes significantly higher barium in sanidine concentrations (Figures 14, 17). These two distinct populations suggest a highly evolved magma cap fed the lower ignimbrite, with a lesser evolved magma feeding the upper fiamme-rich cap. The distinct grouping of these two units suggest that they erupted at intervals rather than representing a zoned magmatic system being tapped (Figures 14, 15). We can infer, however, that magma from the upper part of the chamber erupted first, followed by magma from the lowest part of the chamber (Wolff et al., 2020).

Evidence of activity just before the LCT eruption can be seen throughout the Madison Junction region, with a local stratigraphic section in the Mount Jackson area reflecting a lava flow with two conformable, short explosive pulses and hot, frequent recycled clasts preserved in the lowest LCT stratigraphy. Continued analyses on these findings, including whole-rock geochemistry and $^{40}\text{Ar}/^{39}\text{Ar}$ dating on recycled lithics can assist in the validity of early LCT activity not documented elsewhere.

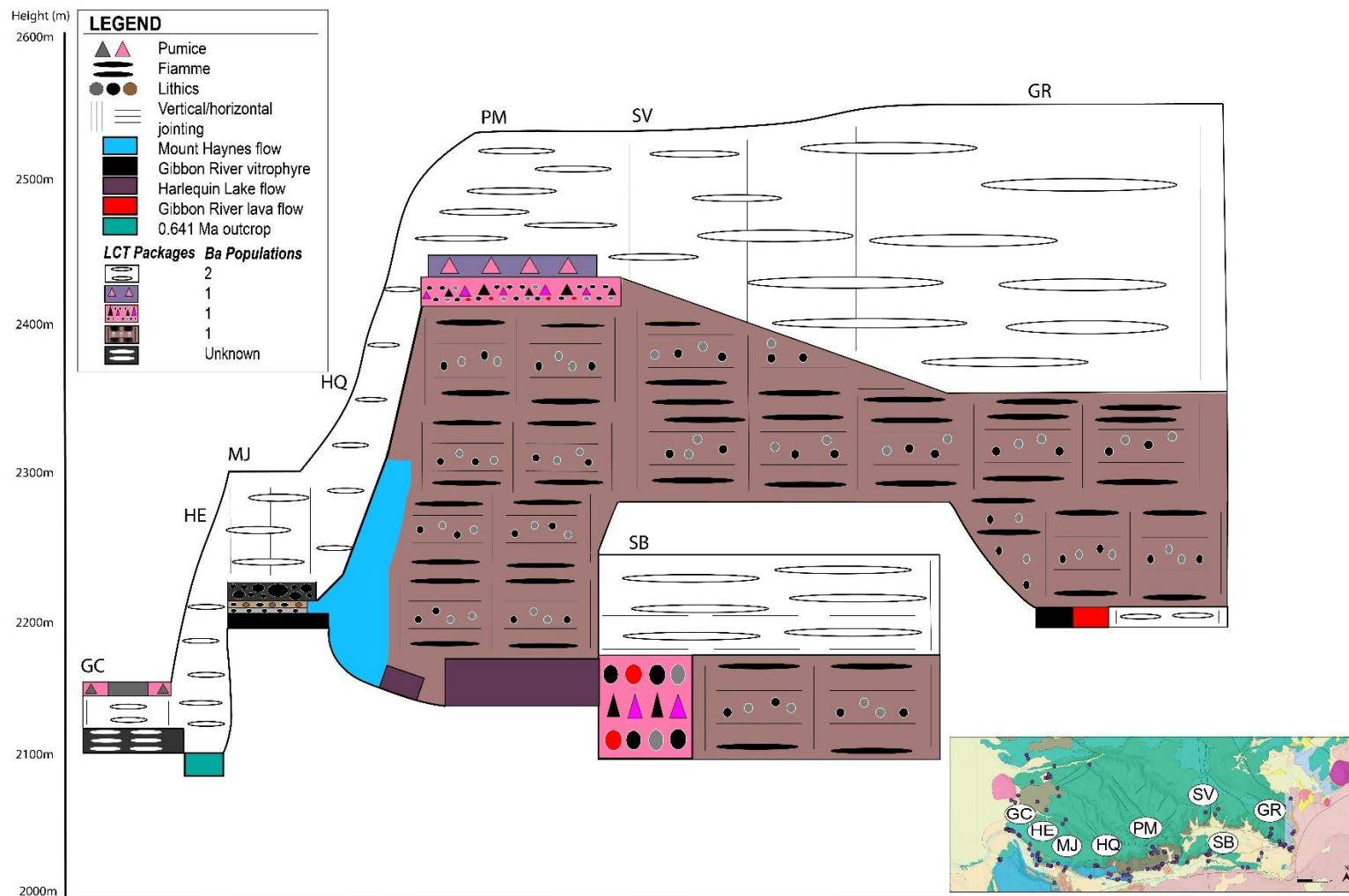


Figure 17. Simplified stratigraphic cross section of the south-facing cliffs of the Madison Junction area, with each locality labeled from west to east: GC – Gneiss Creek, HE – History Exhibit, MJ – Mount Jackson, HQ – Harlequin Lake, PM – Purple Mountain, SV – Secret Valley, GR – Gibbon River, and SB – Slump Block. Colors of each outcrop (purple, brown, white, black, and pink) reflect their outcrop colors.

MJR

The Harlequin Lake and Mount Haynes flows of the MJR are broadly mapped accurately in the Madison Junction area (Figures 16, 17), with a small correction for the Gibbon River vitrophyre, which was previously mapped as LCT member A. Petrologic descriptions, whole-rock geochemistry, and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the Harlequin Lake flow agree with previous studies (Troch et al., 2017). These findings also agree with what is known of the Mount Haynes flow; however, the varying crystal counts attributed to this flow in the valley-separated Mount Jackson and Mount Haynes sections (17 vs 56 crystals per 100 cm²) require $^{40}\text{Ar}/^{39}\text{Ar}$ dating to determine the true age of the lava flow.

The Harlequin Lake flow includes one of the highest Ba-Sr/Rb ratios and EPMA Ba-in-sanidine concentrations of all units in the Madison Junction area, whereas the Mount Haynes flow lies within the first, most evolved LCT population. The Gibbon River vitrophyre overlaps in Ba space with the Mount Haynes flow, meaning both units include sanidines that crystallized from a magma with similar Ba concentrations. There is a possibility that the Gibbon River vitrophyre unit erupted prior to the Mount Haynes flow as a precursory explosive eruption which led into the Mount Haynes flow. The Gibbon River vitrophyre includes amphibole, which would require a high-temperature, high-pressure, water-enriched source, where water-enriched magmas are more susceptible to produce explosive eruptions (Bardintzeff and Bonin, 1987). Interestingly, amphibole is absent in the Harlequin Lake and Mount Haynes flows. The presence of amphibole in the Gibbon River vitrophyre and the lack of it in the Mount Haynes flow suggests that although these flows may have come from a similar system, they may not be from the same magma body. These findings update the frequency of events in the MJR eruptions, with an explosive phase of the MJR between two effusive, geochemically separate lava flows. Future

work exploring the geochemistry of these units more in depth could help refine these initial findings.

Complexities

The preserved stratigraphy in the Mount Jackson section (Figures 5, 6) is unmappable due to its small size but records an important transition for the MJR to LCT timeline. The lower, crystal-rich lava flow (Figure 5) erupted effusively, allowing for recrystallization to occur during cooling to create spherulites. The lava flow's Ba-Sr/Rb ratios lie between the two LCT populations, but closer to the second (higher Ba, less evolved) LCT population. The lower, gray ash layer contains black clasts of the lower lava flow, suggesting proximal venting. The upper, brown ash layer contains black, brown, and gray clasts that vary in petrologic descriptions and geochemical analyses, suggesting that this layer may have had a higher eruption energy to preserve three different, larger clast types; however, their size also suggests proximal venting. These two ash layers, along with the presence of clasts of the lower lava flow in the overlying basal vitrophyre, indicate that the entire stratigraphic section likely pre-dated or occurred during the onset of LCT volcanism. Receiving $^{40}\text{Ar}/^{39}\text{Ar}$ dates of the lower lava flow will resolve this question.

Whole-rock analysis of the local 0.64 Ma lava flow outcrop in the History Exhibit section lies within the first, most evolved Ba population of the LCT, but its petrological descriptions and age do not lie within the LCT. EPMA analysis on single sanidines may shed light on the origin of this lava flow, and where it fits in the stratigraphy between the MJR and the LCT. There is also

potential that the age results from the lower lava flow in the Mount Jackson section will shed light into the origin and stratigraphic placement of this lava flow.

The proposed rheomorphic upper ignimbrite exposure in the Gneiss Creek section is the only sample that represents the third Ba-Sr/Rb LCT population. Its petrologic descriptions and geochemical signatures indicate a hotter ignimbrite. As a local rheomorphic ignimbrite of minimal size, it likely will not be considered into remapping efforts but it is important to include in the stratigraphy of the LCT, as it represents evidence of a local, extremely hot ignimbrite that is less evolved than the underlying ignimbrites. Conducting EPMA on sanidines separated from this sample in the future would add to evidence of a third population of LCT ignimbrites.

The local lava flow in the Gibbon River section (Figure 9B) has two separate ages, both of which lie within error of the determination for the Gibbon River flow (Wooton, 2010). There are two possibilities to which this could have occurred: 1) This outcrop could be related to a glacial kame with its semi-rounded shape. A later glacial event could have reworked this outcrop with two different aged lava flows, explaining the two separate age populations or 2) Their errors overlap, and could be one age population if dated again. Further research is required to determine this answer.

CONCLUSIONS

Remapping in the Madison Junction area has identified several LCT packages and lava flow units that add to the complexity of the LCT and the MJR eruptions. Most of these new findings are local, highlighting the importance of remapping the Yellowstone Volcanic Field in a finer detail. The Gibbon River vitrophyre unit, a new explosive eruption within the MJR, is local enough that it is unmappable, but will significantly refine our understanding of the MJR framework. The new vitrophyre unit of the MJR is informally named “Gibbon River vitrophyre” in this paper. Its close Ba-Sr/Rb ratios and Ba concentrations to the Mount Haynes flow suggest they may have originated from the same system. The 0.64 Ma lava flow in the History Exhibit section predates the LCT but geochemically relates to the earlier lower Purple Mountain packages. This lava flow may represent a ‘leak’ of magma that erupted before the onset of the LCT. Age results from a complete stratigraphic section preserving a lower lava flow beneath a known LCT package will further test this hypothesis. For the future of remapping the Yellowstone Volcanic Field, detailed field observations, whole-rock Ba-Sr/Rb ratios, sanidine separate EPMA data, and $^{40}\text{Ar}/^{39}\text{Ar}$ dating will aid in determining the number of units in a field area as well as distinguishing packages within the LCT. The general agreement between whole-rock Ba-Sr/Rb ratios and Ba-in-sanidine concentrations means that the crystal cargo accurately reflects the melt, which is a helpful indicator for future remapping.

Applying these varied methods in the Madison Junction area has identified that the LCT erupted as five packages tapped from two to three separate magma bodies. These packages begin with lithic and pumice-rich, crystal-poor, evolved ignimbrites, and end with fiamme- and crystal-rich, less evolved ignimbrites, overall representing two petrological and geochemically different

ignimbrite populations. Each of these methods has proved valuable in distinguishing the LCT from the MJR, with less information gained from the Ba-Sr/Rb ratios and EPMA data in the Mount Haynes and Gibbon River vitrophyre units. From this I conclude that whole-rock and single-crystal compositional space cannot always distinguish Yellowstone rhyolites (e.g., the MJR from the LCT).

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APPENDICES

APPENDIX A

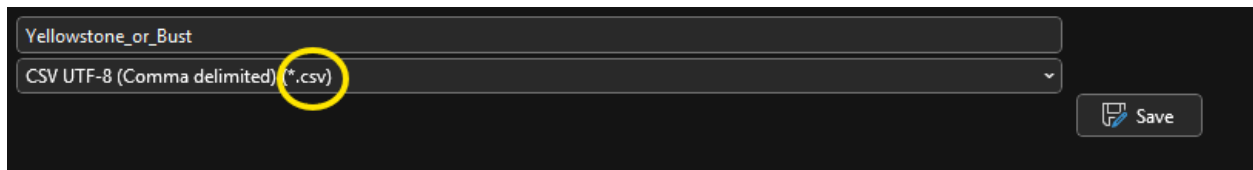
DOWNLOADING THE GEODATABASE

*** These instructions were written in November 2024, using ArcGIS Pro version 3.3. If you are using a different version of ArcGIS Pro, there may be subtle differences.**

**** Edits and additions added in May 2025, using ArcGIS Pro version 3.4.**

I. Prepare Raster Information/Data

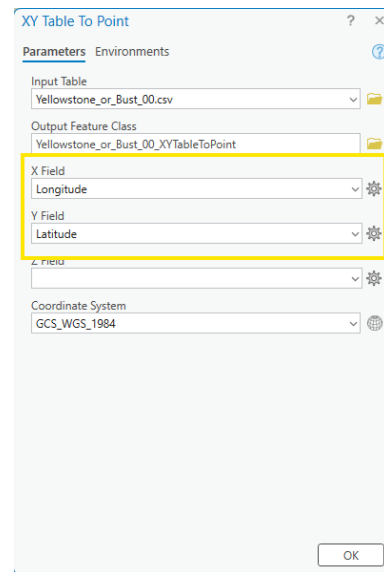
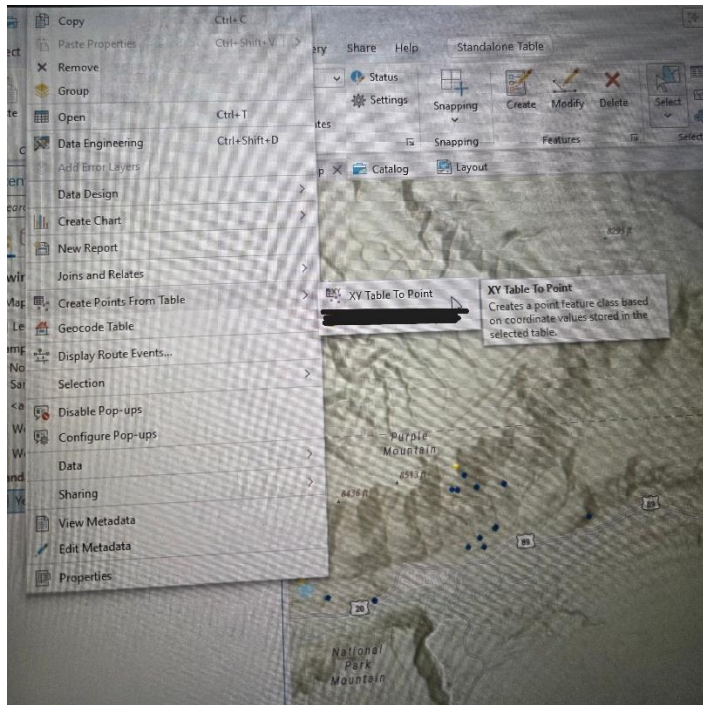
1. In an Excel spreadsheet prepare data needed to input into ArcGIS Pro
2. Customize columns as needed. Make sure to label two columns longitude and latitude respectively, ensure coordinates are input correctly.
3. Save spreadsheet as a .csv file.



II. Add to ArcGIS Pro

1. Open ArcGIS Pro, click on map, name project, click OK.
2. Click on Map in the ribbon, click on Add Data, click on Browse
3. Navigate to where your .csv file is, choose it, then click OK.
4. Or drag your .csv file to the Contents Pane on the left side of the map
5. Under Standalone Tables, right click on your .csv file

- Click on Create Points from Table, click on XY Table to Point



- In the X Field, choose Longitude
- In the Y Field, choose Latitude
- Click OK

III. Geodatabase

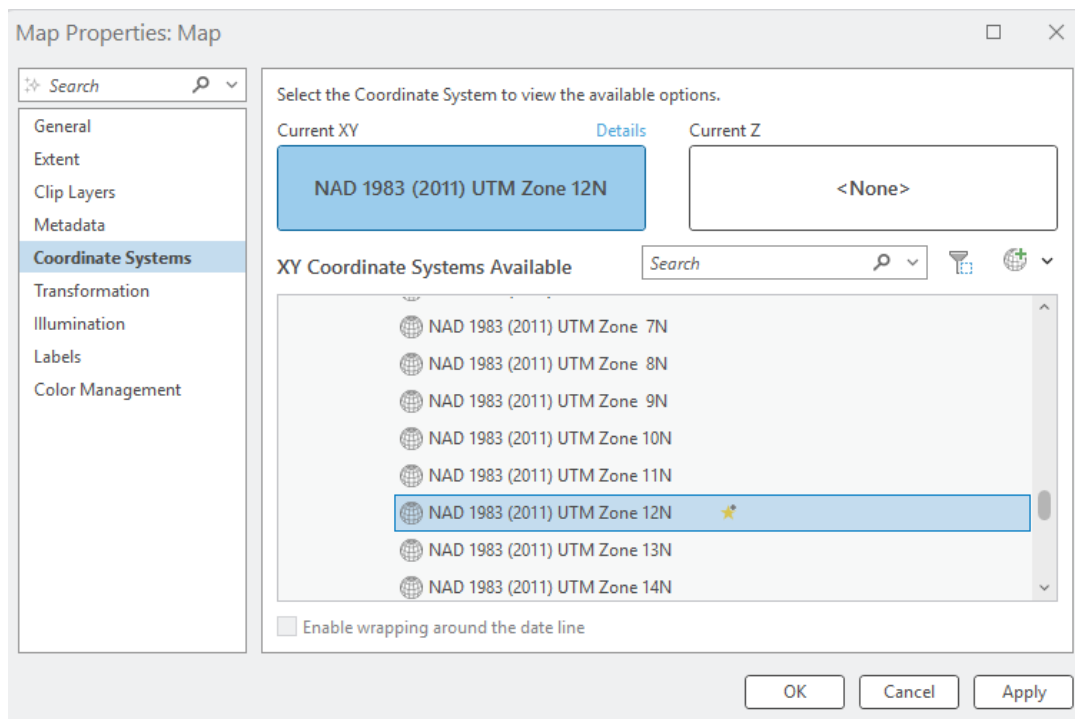
1. In ArcGIS Pro, open your project
2. In Catalog Pane, right click on a folder, choose New, File Geodatabase, name geodatabase.
3. Right click on new geodatabase, choose New, Feature Class, and name it.
4. Add fields (the following are what I used for Yellowstone or Bust, which are also the titles of my columns in my .csv file).
 - a. Waypoint, Text
 - b. Sample, Text
 - c. Sample_name, Text
 - d. Date, Date Only
 - e. Time, Text
 - f. Weather Text
 - g. Long, Double
 - h. Lat, Double
 - i. Elvation (m), Long
 - j. Outcrop_desc, Text
 - k. Relevant_papers, Text

*Every text has a length of 8000

IV. Adjust Projection

1. Right click on Map in the Contents Pane.

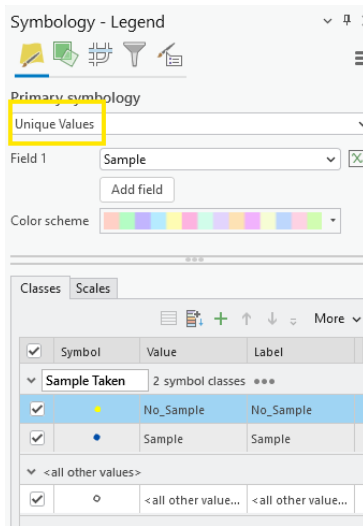
2. Click on Properties
3. Click on Coordinate Systems
4. Click on Projected Coordinate System
5. Scroll down to click on UTM
6. Scroll down to click on North America
7. Scroll down to click on NAD 1983 (2011)
8. Scroll down to click on NAD 1983 (2011 UTM Zone 12N)



NOTE: 5 through 8 are for Montana and Wyoming, if your research area is in a different state or part of the world, Google search what projection coordinate system would best display your research area.

V. Symbology

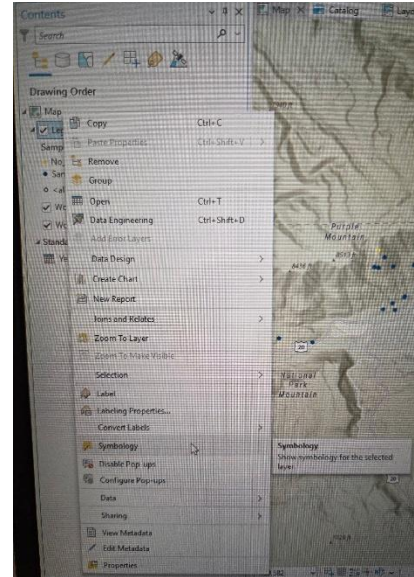
1. Right click on your _XYTableToPoint (under Map in the Contents Pane).
2. Click on drop down menu under Primary symbology
3. For two types of symbols for the map, i.e. No_Sample,



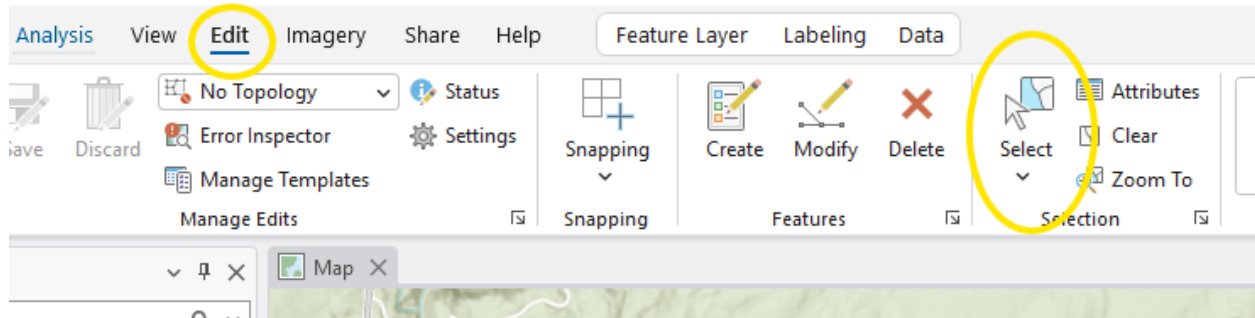
Sample, choose Unique Values

4. Field 1, choose title from column headers from your .csv file

5. Choose a Color Scheme, you can also change colors by right clicking the symbols in the Contents Pane

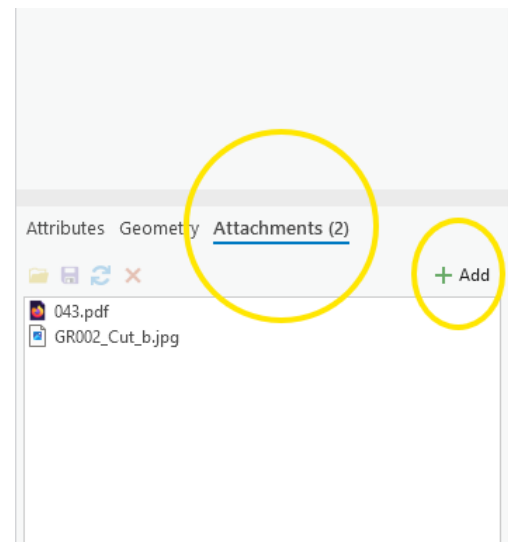


VI. Adding attachments to attributes



Click on Edit in ribbon

1. Click on Select
2. Choose a point on map, right click it
3. Click Attributes
4. Click on Attachments
5. Click add
6. Add files desired
7. Click Save within the Edit ribbon
8. Repeat steps 3 through 8 as needed



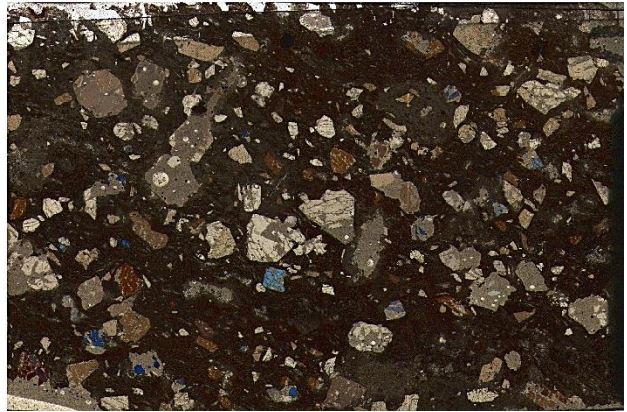
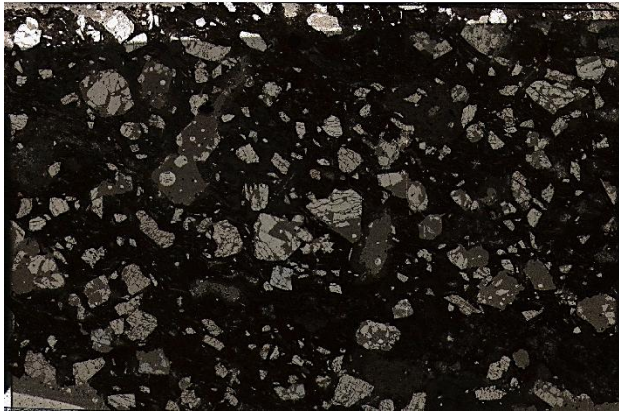
NOTE: If you want to view PDFs export/convert them to .jpg format prior to adding.

This was written by Lynne Gormley with help from Frank Dougher, MSU Instructor, Land & Environmental Sciences, and ChatGPT.

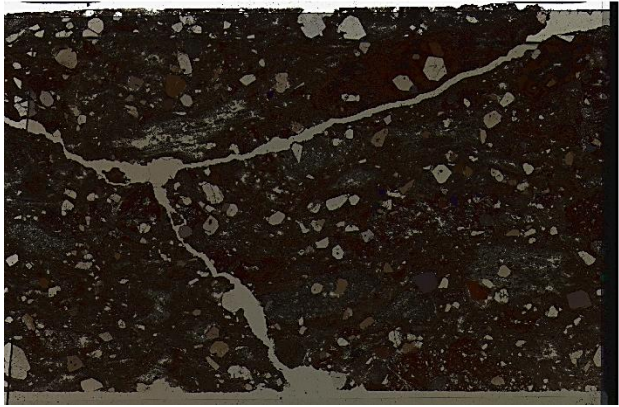
APPENDIX B

THIN SECTION SCANS

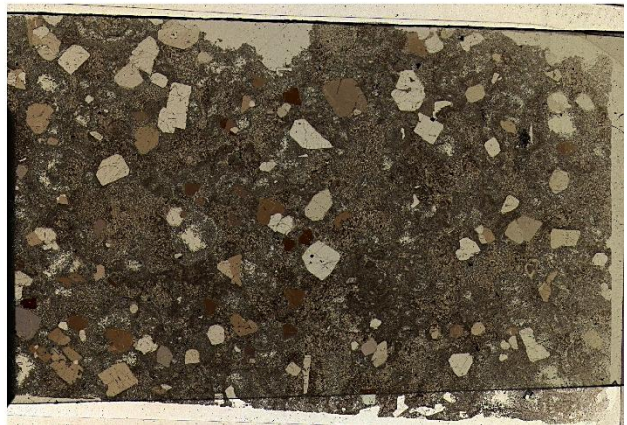
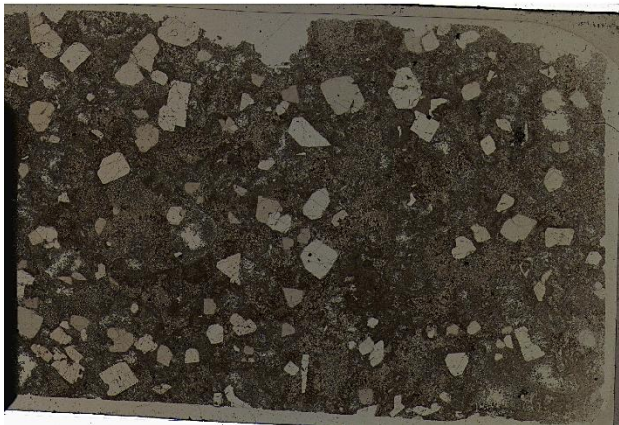
25_GC004 – Lower Gneiss Creek LCT



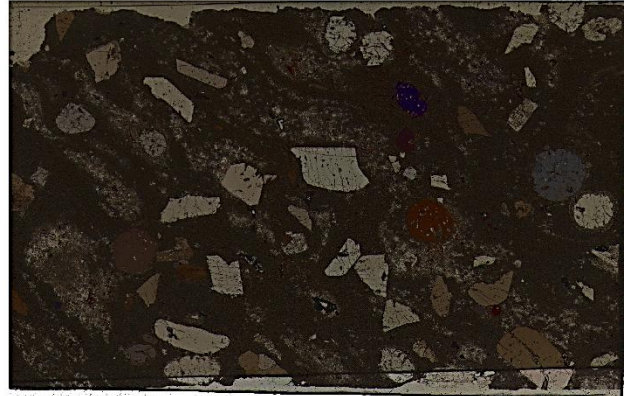
24_GR004 – Lower Gibbon River LCT



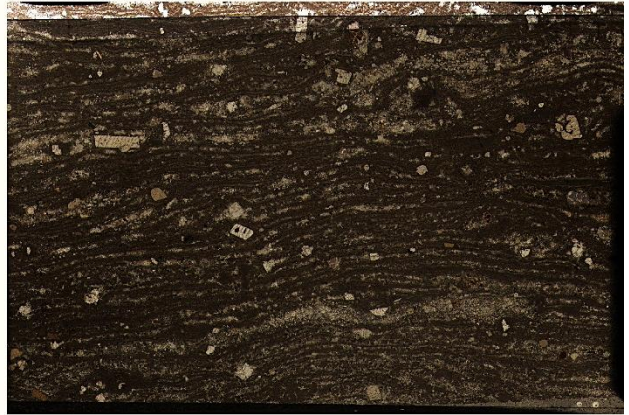
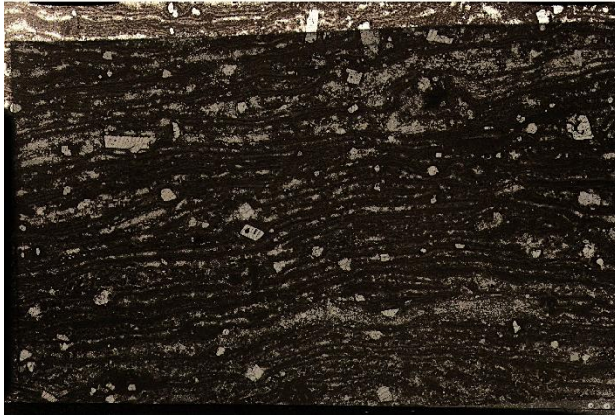
24_HE001 – History Exhibit lava flow 0.64 Ma



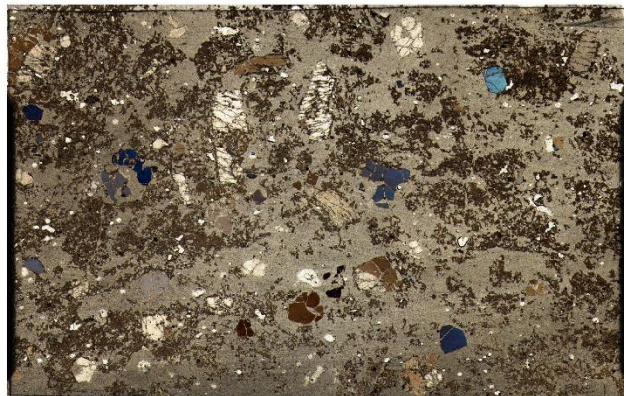
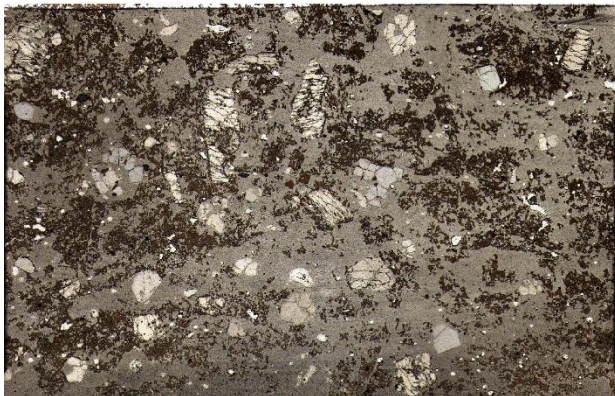
24_HQ001 – Harlequin Lake flow MJR



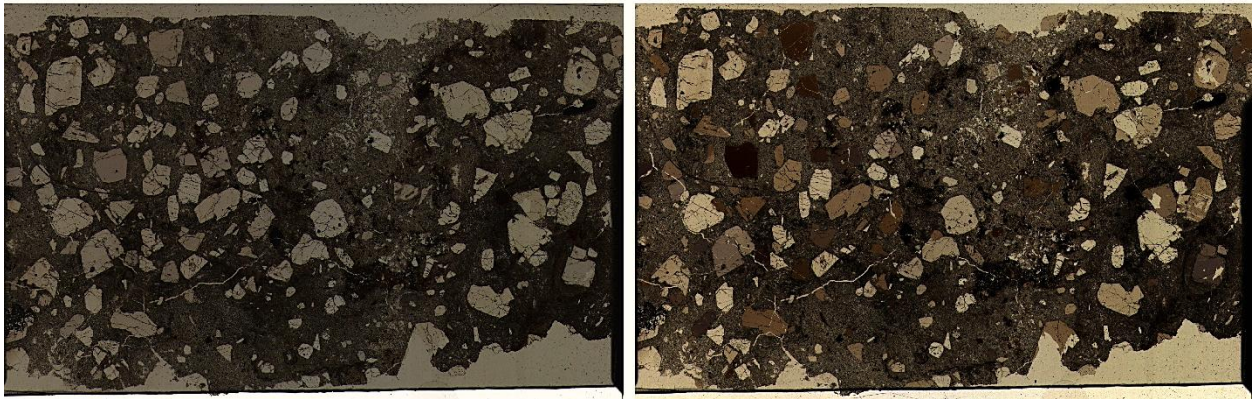
25_MH004 – Mount Haynes flow MJR



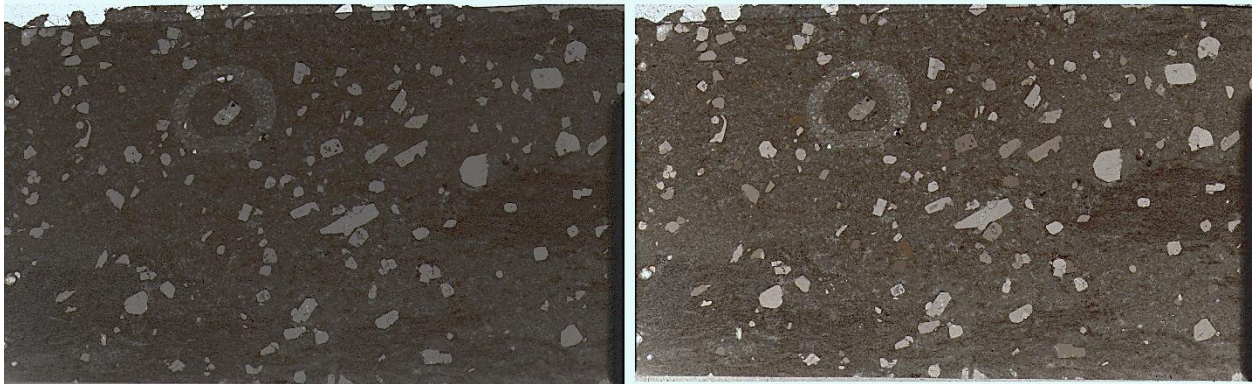
25_MJ002 – Unmapped lower lava flow of the Mount Jackson section



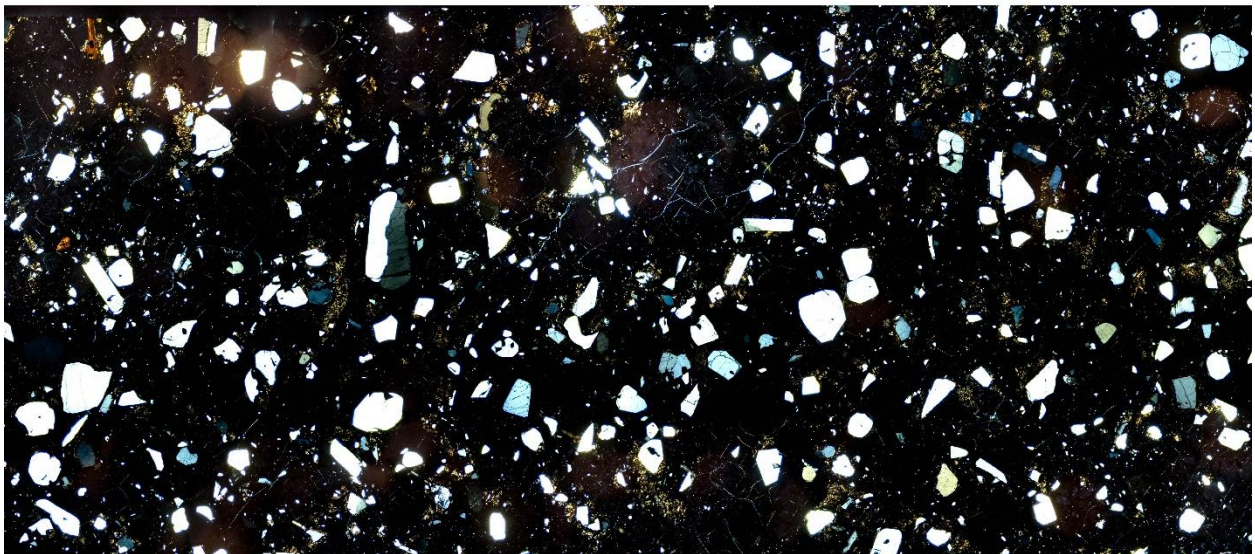
24_PM001 – Purple Mountain LCT



24_PM005 – Lower Purple Mountain LCT



YELL22-GR05 - Gibbon River Vitrophyre



APPENDIX C

ARGON-ARGON DATA FROM SAMPLES IN THE MADISON
JUNCTION AREA (SUPPLEMENTARY DATA ITEM 1)

APPENDIX D

WHOLE-ROCK GEOCHEMISTRY FROM SAMPLES IN THE
MADISON JUNCTION AREA (SUPPLEMENTARY DATA
ITEM 2)

APPENDIX E

ELECTRON PROBE MICROANALYSIS DATA FROM
SAMPLES IN THE MADISON JUNCTION AREA
(SUPPLEMENTARY DATA ITEM 3)

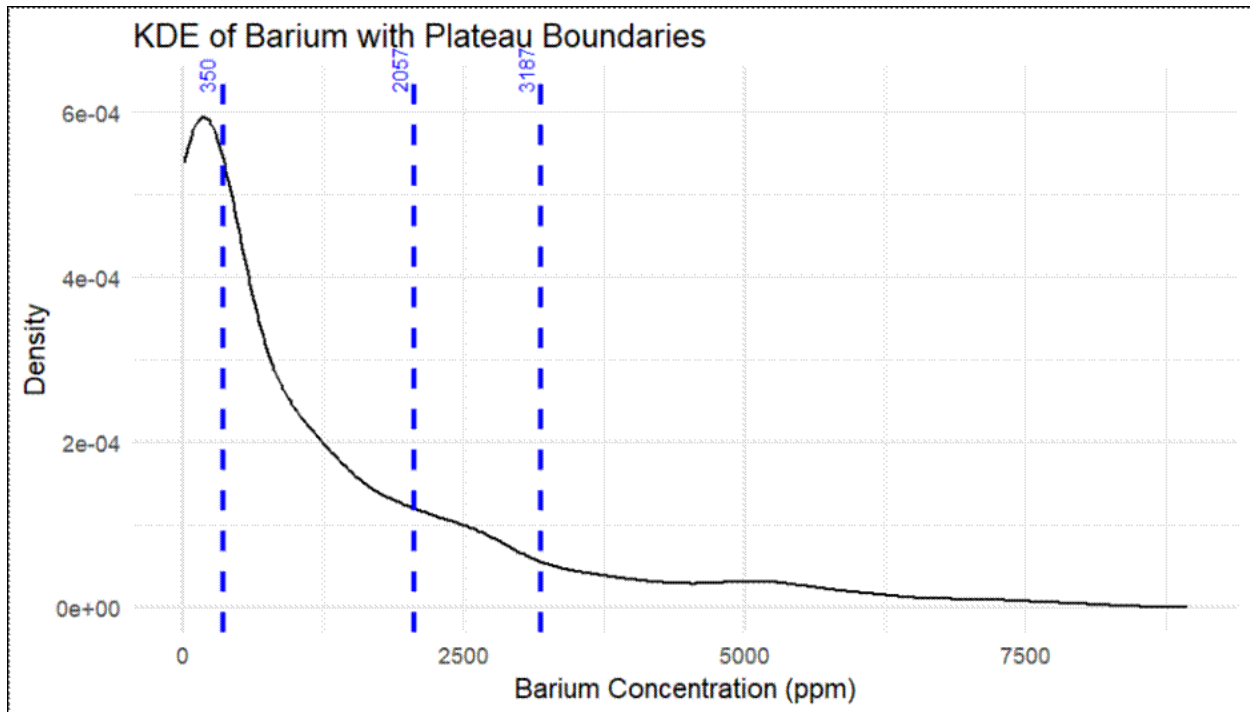


Figure 18. Kernel Density Plot of all samples analyzed for EPMA from the Madison Junction area. Barium concentration in ppm is on the x-axis. Density on the y-axis represents the concentration of data points at a certain barium concentration, where a higher density means more samples are grouped at that concentration. Vertical lines were made from RStudio code to determine the detection limit (DL) for barium in a single sample within the Madison Junction area, including two lines for determining a plateau of Barium in the system.