Detailed Geologic and Geomorphic Mapping and Characterization of the Lake Mary Fault Zone, Coconino County, AZ

Final Technical Report

NEHRP Project Award No. G19AP00047 – Intermountain West

Award Dates: 09/01/2019 through 03/31/2021

Submission Date: March 31, 2021

P.I.s – Jeri Young Ben-Horin (AZGS – jeribenhorin@arizona.edu) and Philip A. Pearthree (AZGS – pearthre@arizona.edu)

Arizona Geological Survey – AZGS
University of Arizona
1955 E. Sixth Street
Tucson, AZ 85721
PH: 520-621-2470

Research supported by the U.S. Geological Survey (USGS), Department of Interior, under USGS award number G19AP00047. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Abstract

The Lake Mary Fault System (LMFS) is located in Flagstaff, Arizona. Prior to this study, much was unknown related to its slip rate or whether the fault system was still active. The LMFS is a 30-45km long set of normal faults and multiple splays that displace Pliocene-Quaternary lava flows and sediments. Detailed mapping efforts identified offset lava flows, two of which are Quaternary in age, and resulted in the discovery of less active fault strands in the southern portion of the mapping area. In addition, detailed mapping provided the geologic constraints for locating potential paleoseismic sites. The LMFS has segments that have been active for several million years and have a complex faulting history that has resulted in dense fracturing of bedrock, reactivation of older reverse and normal faults, much of which have little vertical offset. The Lake Mary fault which is considered the active strand of the LMFS appears to be a normal fault with near vertical dip and a strike that varies from N60W to N-S. The main trace of the Lake Mary fault has up to 40m of vertical offset of a colluvial deposit with clasts from a Quaternary basaltic lava flow, dated for this study with $^{40}Ar/^{39}Ar$ at 1.17Ma old. Geochemical analyses of volcanic clasts found in the Lake Mary fault footwall corroborated the hand identification showing the clasts' originating from the Qbwc flow. The clasts were analyzed using inductively coupled plasma-mass spectrometry (ICP-MS) for Rare Earth Elements (REEs). ICP-MS data infer 3 different rock types for the 12 samples. X-ray fluorescence (XRF) results are still pending due to malfunctioning instrumentation in the Peter Hooper Geo-Analytical Lab, Washington State University. Slip rate estimates were calculated using $^{40}Ar/^{39}Ar$ dates obtained for this study and the vertical offset measurements of Tob (5.9Ma) and Qbwc (< 1.17Ma) for a slip rate range of 0.022mm/yr to 0.035mm/yr. Three potential paleoseismic sites were located based on the presence of young to moderately young deposits and certainty of the fault's location. Excavations in excess of 2-3 meters will likely be required to expose deposits that may have evidence the most recent event.

Introduction

Flagstaff lies within the Northern Arizona Seismic Belt (inset, Figure 1). This is an area of moderate seismicity with multiple events exceeding M > 5.0 and three earthquakes in the early 1900s between Flagstaff and Grand Canyon estimated at M6 to M6.2 (Bausch and Brumbaugh, 1997). Probabilistic ground motions for the Flagstaff area depicted on current national maps almost certainly underestimates the true hazard. Because little is known about the slip rates and recurrence of Quaternary faults, national probabilistic ground-motion maps did not incorporate the Lake Mary Fault System (LMFS) faults. In addition, the moderately large earthquakes from the early historical record are poorly located and may be underestimated. As a result, current forecasting almost certainly understates the true hazard.

The LMFS is characterized by a well-defined 30-45km long, N-S and NW-SE trending, west and south-facing bedrock scarp (Figure 1). The scarp appears to be geomorphically young, implying the fault is active and capable of ground-rupturing events that could threaten the rapidly growing Flagstaff area. Today, there are approximately 140,000 residents in the greater Flagstaff area, home to approximately 25,000 students of Northern Arizona University, Gore Industries and Flagstaff Medical Center. A large earthquake along any of the numerous Quaternary faults in the region could result in widespread damage, economic losses and loss of life in the Flagstaff area.

This study seeks to improve our understanding of the LMFS by focusing on three main goals:1. Determine if the fault system is still active, 2. Determine the fault's slip rate(s), and 3. Locate sites that could be excavated for future paleoseismic studies. Detailed geomorphic and geologic mapping, combined with geochemical analyses and $^{40}Ar/^{39}Ar$ dating of lava flows resulted in more accurate estimates of the fault system's slip rates, and the location of possible fault excavation sites.

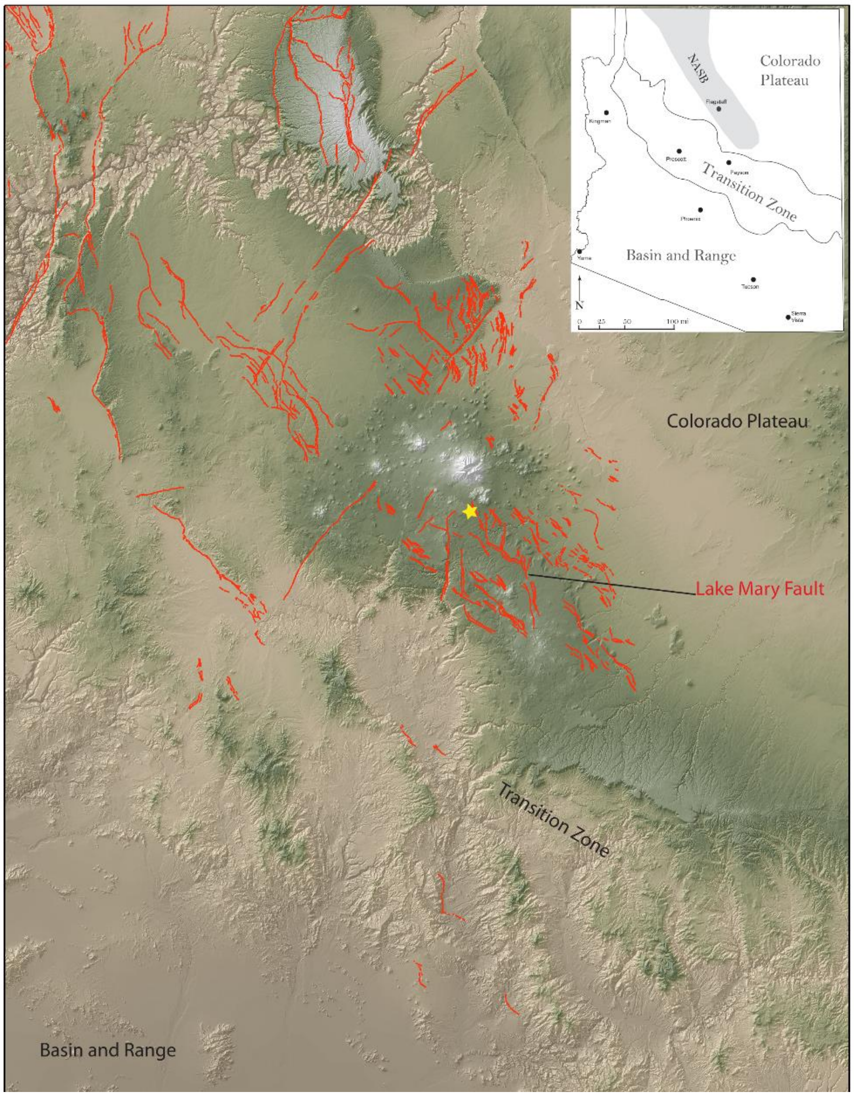

Figure 1: Regional map of young faults in northern Arizona. Inset, upper right shows 3 major physiographic provinces of Arizona and the Northern Arizona Seismic Belt (gray polygon); larger DEM figure with location of Flagstaff (yellow star), Lake Mary Fault System along with multiple Quaternary faults (red lines) throughout this part of Arizona; San Francisco Mountains (white) near center.

Geologic Background

The LMFS includes several fault zones named individually in previous reports – the Lake Mary, Mormon Lake, Drive In, Peaceful Valley, and Switzer fault zones (Pearthree et al., 1996; Pearthree, 1998) (see Figure 2). Along the central part of the LMFS, antithetic faults south of the main fault zone form a narrow, asymmetric graben, with the largest amount of vertical displacement on the eastern and northern side of the graben. The topographic expression of the primary fault zone is a well-defined high escarpment, with bedrock cliffs at the top and along moderately steep colluvial slopes below. Because the mesa above the escarpment dips gently to the NE by 1 to 3 degrees, there are no large drainages in the northeastern footwall and the amount of alluvial deposited along the fault zone is quite limited. Much lower bedrock scarps bound most of the southwest margin of the LMFS graben. The lowest part of the graben floor is covered with young, fine-grained deposits and two artificially dammed reservoirs that supply water to the City of Flagstaff. As noted previously, the northwestern terminus of the fault system is very complex, with numerous N- and NW-trending faults in a splaying pattern. At the southern end of the Lake Mary fault, displacement decreases into a set of low hills, but displacement on the Mormon Lake fault zone increases to the south (Figure 2). Fault orientations varied and can be grouped into four clusters: 1. N-S striking normal faults, 2. NE striking normal faults, 3. N-NW striking normal faults, and 4. NW striking normal faults. Nearly all of the faults have a steep to vertical dip angle. Many are found as sets of faults that make up narrow grabens.

Several lava flows help bracket the activity of the fault zone and were used for offset measurements and slip rate estimates. Nearly all of the flows mapped in this study filled in pre-existing fault grabens and are elongated in outcrop. The exception to this generality is the sheet flow unit Tob, which is the oldest flow both in the map area and in Flagstaff. Tob predates and is contemporaneous with faulting that has a NE and NW conjugate faulting pattern. Younger flows, such as the Pine Grove basalt and the Walnut Creek basalt flows filled preexisting grabens; however, both of these units were subsequently faulted by several NS and NW oriented faults. There many faults that are partially covered by flows which that do not have offsets. Although the complexity in faulting patterns and faulting history is best interpreted using the volcanic flow geology since many of the flows have been dated and have decent offset.

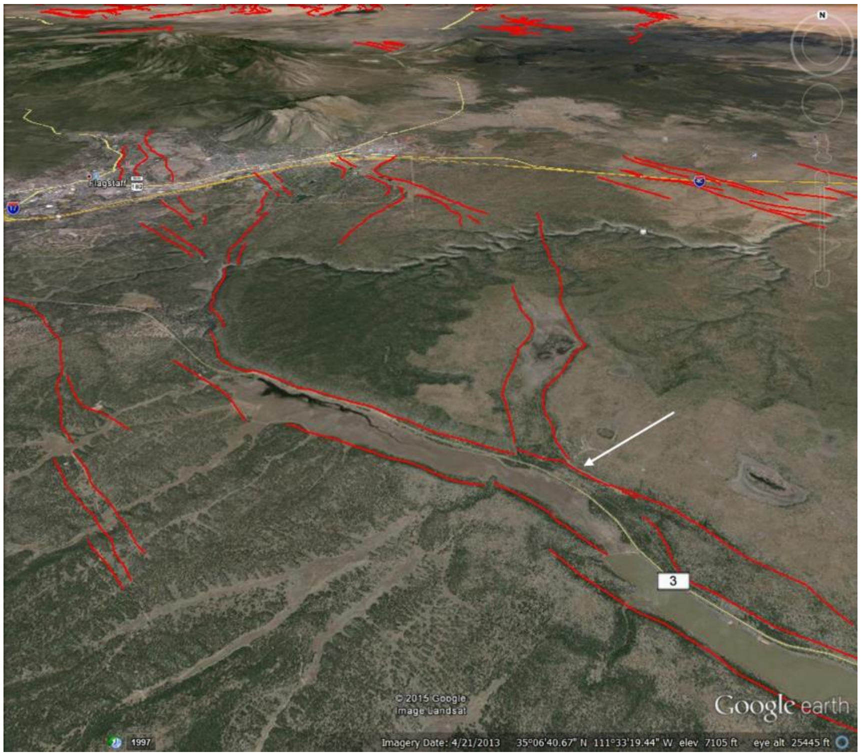

Figure 2: Oblique view of the Lake Mary Fault System trending toward the city of Flagstaff in the upper right of the image. Multiple fault splays have been mapped as Quaternary and are collectively part of the LMFS. Main Lake Mary Fault trace indicated by white arrow, middle of image.

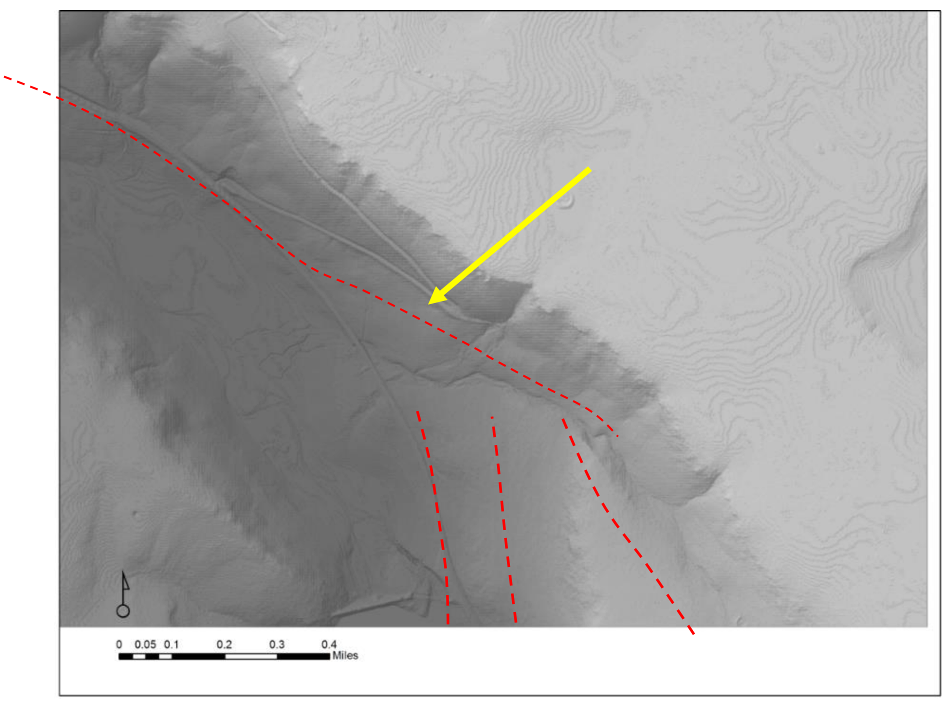

Figure 3: LiDAR base map with multiple mapped fault strands associated with the LMFS. Dense tree canopy made using aerial imagery challenging. LiDAR has vastly improved mapping accuracy and faulting relationships. Yellow arrow indicates the location of a potential paleoseismic site, Site 2.

Methods

This project incorporated three main tasks so that meaningful fault slip rates could be obtained in addition to detailed mapping of offset landforms and location of potential paleoseismic sites. Task 1 was to complete detailed surficial and geomorphic mapping within the specified mapping area. This was accomplished by using LiDAR in the field (over 90 days total), and in the laboratory (150 days) where detailed contact relationships and faults could be delineated. An interactive ArcGIS webmap of the results are published and downloadable from this URL:

https://uagis.maps.arcgis.com/home/webmap/viewer.html?webmap=6bc3d2bf10714b1484601c869d036b55

In addition, the fault exposure along a road cut was analyzed and mapped in detail as part of Task 1 (Figure 3). The road cut could not be "cleaned" and studied up close due to increased instability of overhanging materials from erosion. Previously mapped and dated lava flows were also incorporated into our results so that slip rates over different time spans could be evaluated.

Upon the start of the project, only a quarter of the northwesternmost extension of the mapping area had available LiDAR data. Task 2 was designed to provide detailed topographic data to supplement the lack of LiDAR in the remaining 3/4s of the mapping area using drone flights and structure from motion to create DEMs. Dense tree canopy covers much of the mapping area and limited the extent to which drone flights could be conducted. AZGS had planned to complete multiple drone flights and create cross-sectional topographic profiles to supplement the DEMs generated with NAIP imagery by AZGS; however, 3DEP LiDAR data became available by August 2020. The new 3DEP LiDAR eliminated the need for drone flights as well as the use of the NAIP DEMs which were of low resolution due to tree canopy. Task 2 effectively became retrieval and processing of LiDAR data from the Coconino County Cartography Department.

Task 3 included $^{40}Ar/^{39}Ar$ dating of an offset Quaternary basaltic unit and older late Miocene or Pliocene basaltic units. Three samples were collected from the three different basalt flows and sent to New Mexico Geochronology Research Laboratory in Socorro, New Mexico. The three dates provided a base value for estimating long-term slip rates for the three flows faulted along the LMFS. In addition to dating basalts, AZGS had 12 samples analyzed with X-ray fluorescence and inductively coupled plasma-mass spectrometry for two main purposes. The first purpose was to definitively correlate the Tob unit mapped in the Lake Mary Graben to the Anderson Mesa Tob unit vertically offset by 130 meters. The second purpose to correlate basaltic clasts found in the footwall of the main strand of the LMFS, just north of Lower Lake Mary Dam, to a lava flow on the downthrown side of the fault Several volcanic clasts, subangular to rounded, were found more than 20 to 40 meters above the lava flow from which they were derived. The clasts are thought to have been eroded out of the Qbwc, Quaternary basalt Walnut Creek and were possibly caught up in the fault graben and uplifted with the footwall over time.

Results

The overall goals of this mapping project were to: 1. Determine if the fault system was still active, 2. Determine the fault's slip rate(s), and 3. Locate sites that could be excavated for future paleoseismic studies. Detailed mapping of bedrock, lava flows and surficial and Quaternary deposits provided the context in which fault slip rates were estimated (Figures 4 and 5 and Appendix A, and https://uagis.maps.arcgis.com/home/webmap/viewer.html?webmap=6bc3d2bf10714b1484601c869d036b55). Additionally, collaboration with Dr. Richard Holm, emeritus professor at Northern Arizona University and expert in the volcanic flows in the Flagstaff area, provided two small previously unpublished maps in which he differentiated several flows and had multiple flows dated with K-Ar methods in the 1990s (Richard Holm, personal comm. 2020, and Holm, 1994 and Holm and Shafigullah, 1994). Previous workers had mapped a significant Quaternary flow (here called the Qbwc – Walnut Creek Basalt) as Tertiary in age (Wolfe et. al., 1987). Using an unpublished 1.5mi X 1.5mi map of the area near Lower Lake Mary Dam by Holm (1988) the young flow was determined to be Quaternary, and Qbwc clasts found footwall of the fault were correlated to the Qbwc flow. The clasts were mostly subrounded, but ranged from angular to rounded, thus implying they may have been sourced from a large channel such as Walnut Creek.

The Kaibab Formation (Pk) is found throughout the mapping area and is riddled with fractures and faults that trend mostly NW and NE (Bills, et al., 2000; Wolfe et al., 1987). Many of the faults have only a meter or so of vertical offset, suggesting that deformation is widely distributed along many faults and not been concentrated along a main strand. The exception to this diffuse deformation is along the LMFS paralleling Walnut Creek. This segment, referred to as the Walnut Creek Segment has a vertical throw of approximately 75m or less of the Pk (Figures 4 and 5). The Triassic Moenkopi (Trm) is exposed as thin remnants on the top of Anderson Mesa, just above Walnut Canyon. Along several fault exposures classic Trm red sandstone is seen faulted against Pk. Vertical throw of Trm is approximately 60 meters (Figures 4 and 5). The amount of offset along the Walnut Creek segment suggests that the fault has had concentrated deformation along this segment and may be a reactivated older fault.

An older basaltic sheet flow covers a major portion of the south and central map area (unit Tob 5.9Ma). Tob is faulted and vertically displaced 130 meters from the bottom of Lake Mary to the top of Anderson Mesa. Around 4Ma another basaltic flow emanated from a vent north of the current Mormon Lake, the Pine Grove flow (Tpbf). The Tpbf basaltic flow filled in several fault grabens, and the flow cut off the northern part of Mormon Lake. The Pine Grove flow was subsequently faulted and is vertically offset in several small grabens adjacent to Lake Mary Road. Vertical offset of the Tpbf is approximately 40 meters.

In the southern portion of the mapping area, the 3Ma old Mormon Mountain lava flows are offset along several faults (Holm, 1994). The southernmost extension of the fault could be partially overlain by Pliocene volcanic flows Tydd and Tyb; however there appears to be a lineament that crosses the Tyb flow and could be offset by about 3m. Tyb has a K/Ar age of 3.89 +/-0.01 Ma (Holm, 1994), suggesting this southern fault extension is either very minimally offset or may not have had a ground-rupturing event since the flow’s emplacement. Previous mapping by Holm (1994) indicates that the Tydd and Tyb flows erupted along a northwest trending fault zone and overlie the fault. It is particularly important to determine the full potential rupture length of the LMFS, and if this southern section has not ruptured since the emplacement of the Tyb unit, the rupture length of the LMFS decreases by 15-20km. However, this area is particularly complex given the multiple flows, dikes and vents and it is difficult to discern whether the flows were simply following preexisting faults or if they have been faulted.

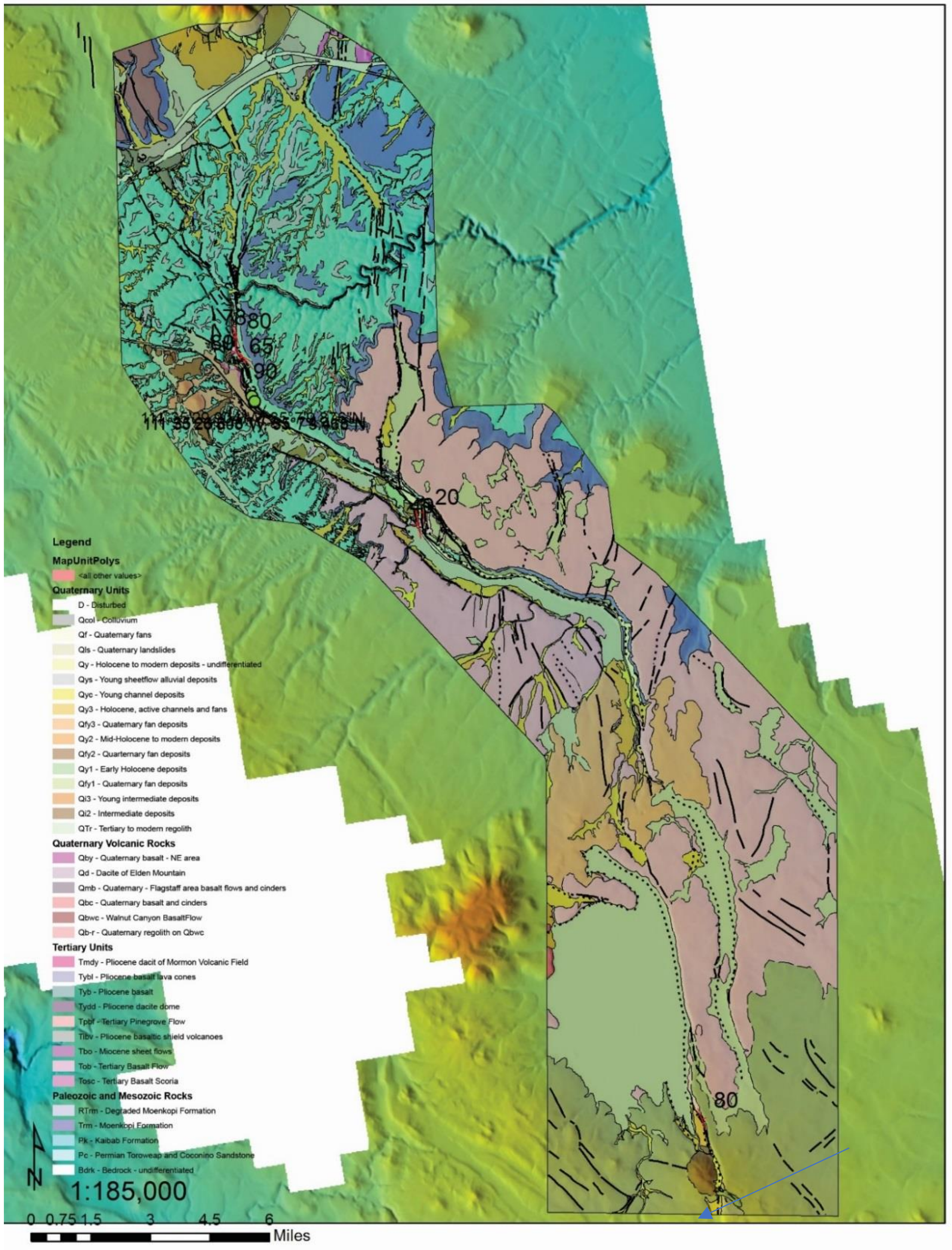

Figure 4:Overview of the completed map area overlain on LiDAR provided by Coconino County. The small green dots represent the cross-section area and the locations of Qbwc clasts found > 40meters above the main Qbwc flow. See Appendix A for detailed map unit descriptions. Blue arrow indicates Tydd/Tyb flows that may overlie the southern extension of the LMFS. Interactive web service with database and map displayed here: https://uagis.maps.arcgis.com/home/webmap/viewer.html?webmap=6bc3d2bf10714b1484601c869d036b55

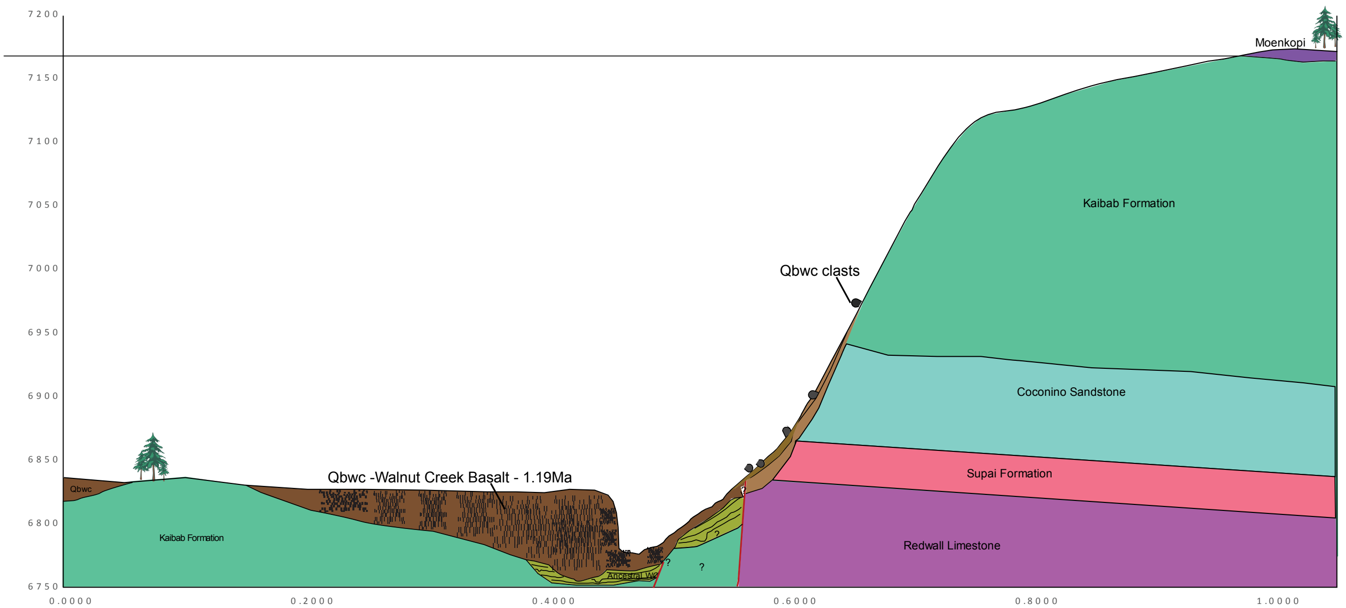

Figure 5: Cross-section showing relationship between Quaternary Walnut Creek basalt, $^{40}Ar/^{39}Ar$ dated at 1.17Ma, and the Lake Mary fault. Qbwc clasts found more than 40meters above the top of the Qbwc flow and may be uplifted in the fault zone. Dark gray circles represent actual clast heights found in the field. View to the NNW.

Volcanic Units and faulting

$^{40}Ar/^{39}Ar$ Dating Results

Previous studies have included K-Ar dating of Tob, Tbo and Qbwc, (Holm and Shafiqullah, 1994 and Wolfe et al., 1959) . Given the higher precision of $^{40}Ar/^{39}Ar$ dating methods, three main volcanic units were redated so that their dates could be used for estimating slip rates. Three volcanic samples were submitted to the Geochronology Laboratory at New Mexico Tech: 1. Tob(s), 2. Tbo (found in the northermost part of the mapping area) and 3. Qbwc. Each one of these units has significant offset histories relevant to determining the rate of faulting for the LMFS. $^{40}Ar/^{39}Ar$ ages for Tbo, Tob(s) and Qbwc are 5.32 +/-0.06Ma, 5.924 +/-0.012Ma and 1.17+/-0.0017Ma, respectively (Figure 6). The Qbwc age has the most significant difference between the previous K-Ar age and current $^{40}Ar/^{39}Ar$ age.

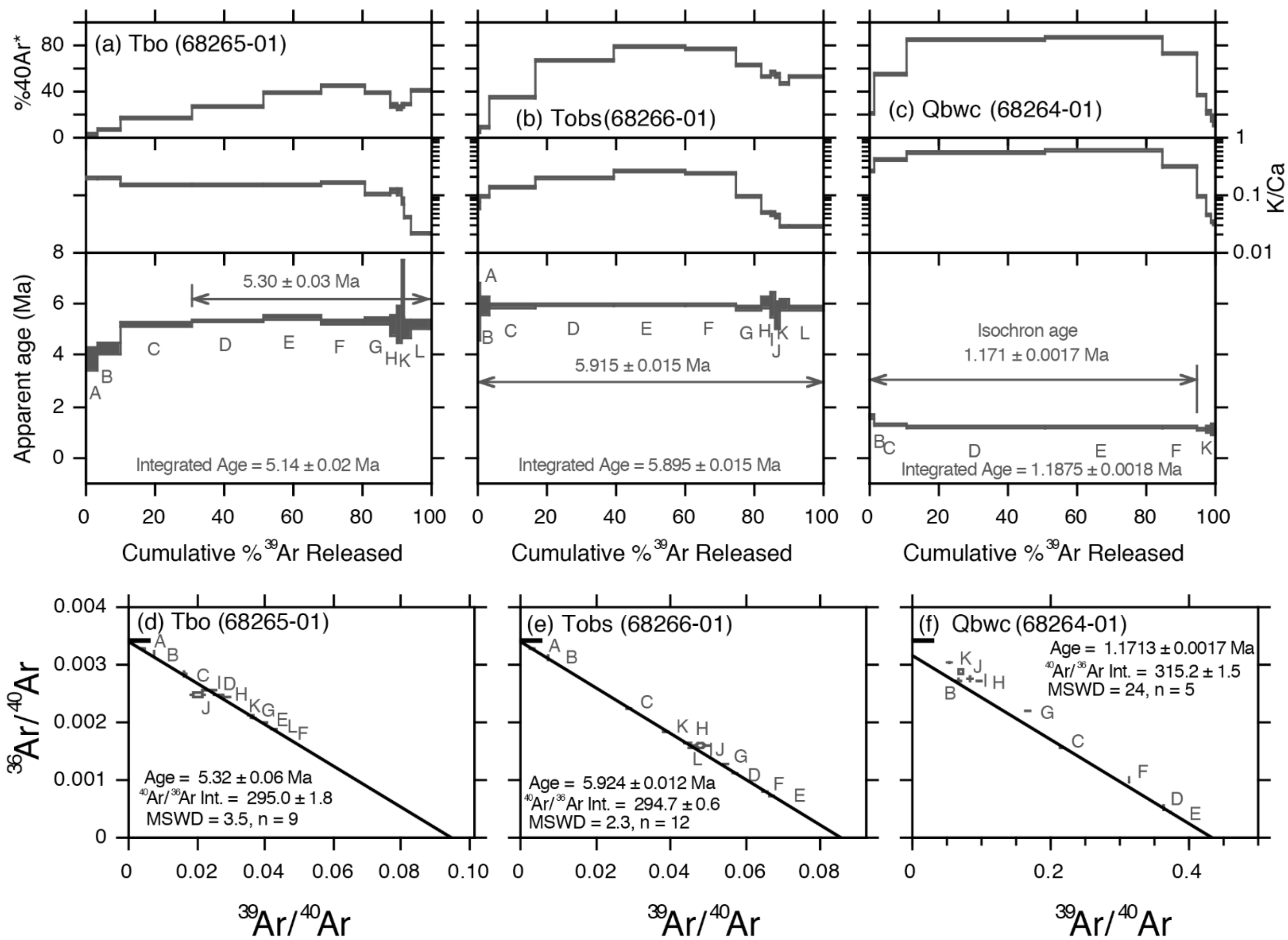

Figure 6: $^{40}Ar/^{39}Ar$ dating results for samples Tbo, Tob and Qbwc by Matt Heizler, New Mexico Tech Geochronology Lab. The oldest sample (Tob) corresponds to the extensive sheet flow basalt in the central and southern portion of the mapping area (vertically offset more than 130m). The youngest sample corresponds to the Walnut Creek basalt (Qbwc), found along the fault scarp near the northern half of the mapping area, and is potentially offset by more than 40m.

Geochemical Analyses

A Quaternary basaltic flow near Lower Lake Mary Dam has an $^{40}Ar/^{39}Ar$ age of approximately 1.17ma. This flow filled in a preexisting fault graben and the ancestral Walnut Creek around this same area. Rounded small boulders and subangular clasts from this flow were identified more than 42 meters above the top of the flow, on the footwall of the main trace of the LMFS (cross section, Figure 5). To determine if clasts were sourced from the Quaternary basalt flow (Qbwc), we collected 10 samples and analyzed their Rare Earth Element concentrations and bulk mineral assemblages. One sample was taken directly from the Qbwc flow for comparison to the 9 samples taken from the fault zone (examples of fault zone clasts in Figure 7). Two additional Tob samples were collected for correlation, one from the bottom of Lower Lake Mary, and the other from the top of Anderson Mesa.

These clasts were identified using hand sample identification by Dr. Holm, as well as Rare Earth Element concentration comparisons (Spider plot Figure). Additionally, the same 10 Qbwc samples are awaiting X-ray fluorescence analyses at the Hooper Geochemistry Laboratory, Washington State. Because of mechanical issues and delayed progress due to covid19, XRF results are still pending. The Spider Plot below (Figure 8) as well as individual REE plots per sample (Figure 9) indicate that samples 1-10 are from the same source, while samples 11 and 12 are from the same source. Raw Rare Earth Element concentration data can be found in Appendix B.

Figure 7: Photographs of two examples of Qbwc clasts found on the footwall of the LMFS, just northeast of the Lower Lake Mary Dam and Walnut Creek intersection. These rounded clasts were greater than 16meters above the top of the Qbwc lava flow.

Table 1:List of samples sent to Washington Univ. Geochemical Laboratory for XRF and inductively coupled plasma-mass spectrometry for correlation and comparison.

	Sample ID	Rock Type	Lat	Long
1	07-13-2020_1	basalt -vesicular; gray;	35.118	-111.5914
2	08-05-2020-_1	clast - rounded basalt	35.11916	-111.59027
3	08-05-2020_2	angular to sub-rounded - basalt from bench	35.11862	-111.58969
4	08-11-2020_1	basalt from Walnut Bench	35.12934	-111.59567
5	08-11-2020_2	basalt	35.0964	-111.5958
6	08-31-2020_1	basalt	35.11941	-111.5916
7	08-31-2020_2	basalt	35.11913	-111.59155
8	08-31-2020_3	basalt - chips from large clast	35.11875	-111.59148
9	08-31-2020_4	reddish, altered basalt	35.1186	-111.59141
10	1_Qbwc	basalt from mapped Qbwc flow	35.11345	-111.587328
11	1_Tob	sheet flow basalt from Anderson Mesa	35.10653	-111.557063
12	10-22-2020_1	Tob- Fine-grained basalt, south of LLM	35.10474	-111.575979

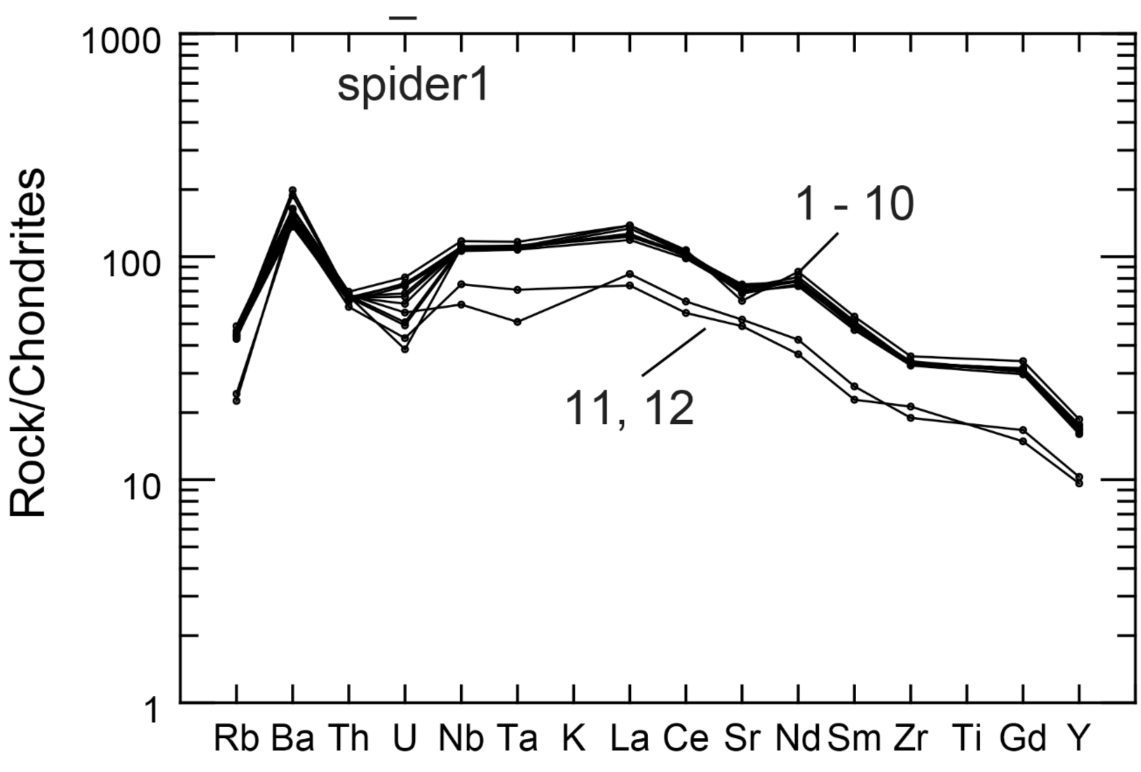

Figure 8: Spider plot with REEs for 12 samples plotted against standard chondrites. Samples 11 and 12 deviate from the REE concentrations shared by samples 1 through 10. Samples 1-9 are from the same lava flow, found in different locations along the fault scarp, up to over 40meters above the Qbwc flow. Sample 10 was taken directly from an outcrop of Qbwc, intact and adjacent to Lake Mary Road.

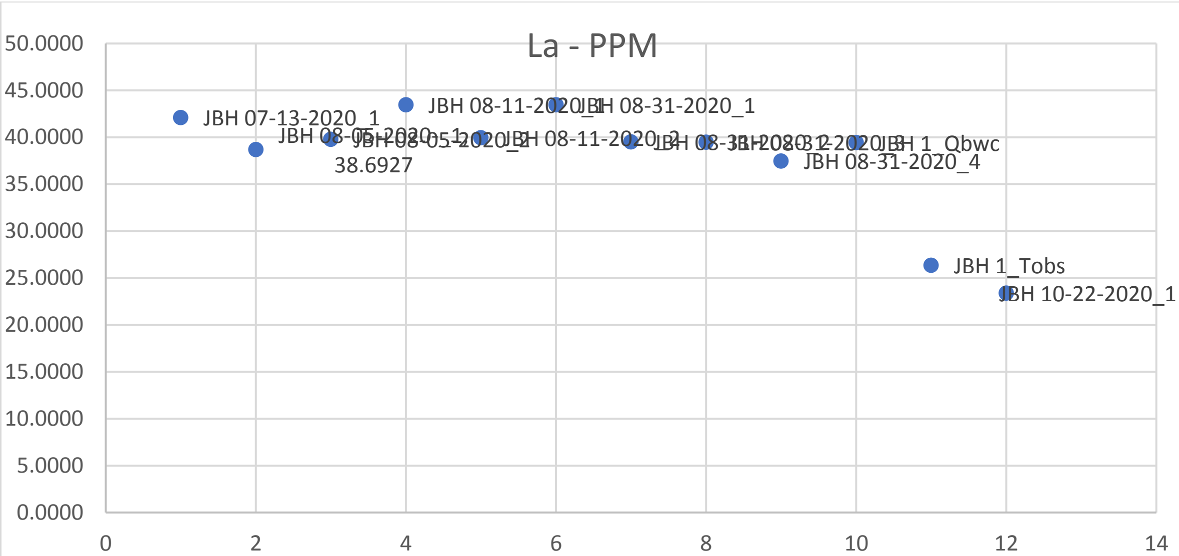

Figure 9: Sample REE of La (Lanthanum) plot for the 12 samples. The two samples in the lower half of the plot (JBH1_Tobs and JBH 10-22-2020_1) were taken from the Tob flow from the bottom of Lake Mary and the top of Anderson Mesa. The remaining samples were from clasts found in the footwall of the fault, some more than 40meters above the top of the Qbwc flow. Sample JBH1_Qbwc was taken directly from the flow for comparison. The 10 samples in the upper portion of the plot are likely sourced from the same flow.

Slip Rate Estimates and Fault Activity

Determining if the fault has generated offset in more recent time is still questionable due to the fault being mostly expressed in bedrock, and landform alteration by logging, road construction, dam building, etc. Along Lake Mary Road, there are multiple dirt roads that parallel the highway. These dirt roads and Lake Mary Road may very well have followed a preexisting bench made by the fault; however, historical maps and photos are too coarse and do not provide information to answer this question. The fault has likely been active during the Quaternary. There are two Quaternary flows that have some vertical offset: Qbwc and Qmb found in the northern part of the mapping area. The fault appears to offset either a thin portion of the Qbwc or a colluvial or channel deposit that contains clasts from Qbwc. The table below summarizes the range in clast heights taken from an area just north of Lower Lake Mary Dam, on the footwall of the main fault. The clasts are likely sourced from Qbwc as indicated by hand sample identification and REE concentrations (Figures 8 and 9).

Qbwc Clast Heights	Clast 1 Low	Clast 2 High
Clast elev.	6890ft	6974ft
Qbwc flow elevation	6835ft	6835ft
feet	55	139
meters	16.76829	42.37805
mm	16768.29	42378.05
slip rate (Qbwc age =1.29Ma)	0.012999	0.032851

Table 2: Example slip rate estimates based on faulted colluvial clasts. Over 15 volcanic rock clasts were found above the main fault, in slope colluvium, and on rock ledges. Several clasts were identified with hand sample identification and geochemical analyses as Qbwc. The

general flow height of the basaltic Qbwc is approximately 6830ft, thus indicating that the subrounded Qbwc found in the footwall could be uplifted several meters.

Using new $^{40}Ar/^{39}Ar$ dating and geochemical analyses of basalt flows completed for this study, we calculated two slip rates, one for the oldest vertically offset unit and one for a young, Quaternary flow unit. The first slip rate uses the 5.9Ma age and 130meters of vertical offset of a sheetflow basalt (Tob) which resulted in a rate of 0.022mm/yr. The second slip rate is based on the new age of the Walnut Creek basalt of 1.17Ma and approximately 16m to 42m of vertical offset, thus equaling 0.013mm/yr to 0.035mm/yr. The table below is a summary of slip rates based on the amount of vertical offset of different flows, with Qmb being the youngest possible unit that has some vertical offset. Confidence in whether the Qmb volcanic flow is offset or simply filled in a preexisting graben is low due to surfaces changes and construction.

Flow Unit	Description	Max. offset (m)	Confid. (1-low to 5-High)	Dating method	Age	Slip Rate	Fault
Tob	**Med. Gray olivine basalt; sheet flow; extensive.**	**130.0**	**5**	**40Ar/39Ar**	**5900000**	**0.022034**	**Main strand LMF**
Tbo	Med. Gray olivine basalt; sheet flow; extensive.	35.0	5	40Ar/39Ar	5300000	0.006604	Switzer strand
Tpbf	Gray olivine basalt; fills older grabens.	42.7	4	K/Ar	4380000	0.009745	So. Segment
Tyd&Tysc	Clinopyxn-olivine basalt; scoria cone and dacite.	3.0	2	K/Ar	3890000	0.000771	Mormon fault
Qbwc	**Splotchy orange, gray, aphanetic olivine basalt.**	**42.0**	**4**	**40Ar/39Ar**	**1170000**	**0.035294**	**Main strand LMF**
Qbc	Gray olivine basalt; erupted through Qbwc flow.	6.1	2	cuts Qbwc	<1.17Ma	< 0.035	West strand LMF
Qmb	Basalt with rough surface and mostly unweathered	3.7	2	K/Ar	150000	0.024667	Splay of LMF

Table 3: Summary table of the main volcanic units that are offset within the study area. Listed from oldest to youngest (Tob is oldest). Vertical offset measurements taken in multiple places. Confidence ranking is largely based on the quality of the correlation of displaced flow surfaces. Slip rates vary per fault segment or strand but strands that appear to still be active have slip rates greater than 0.02mm/yr. Slip rates for Tob and Qbwc offsets (in bold type) have high confidence rankings and are considered more accurate.

Potential Paleoseismic sites

Given the lack of depositional environments along the fault scarp, only three sites were deemed potentially suitable for paleoseismic study along the nearly 35-45km long LMFS. The three sites all have some colluvial and alluvial deposits that may be too young to have a record of the most recent event; however, upon exploratory trenching of the sites, it may be possible to find an event if the trenches exceed the upper, younger deposits. Bedrock may prove to be too shallow at all three sites, thus limiting excavation depths.

From south to north:

1. Site 1 - Fan that crosses fault immediately north of FSR 82E – Cons-Faulting may be too old at this site to have a seismic record in the upper several meters of deposits. Faulting offsets lava flows that are 5.9Ma and 4.38Ma, and fans do not appear to have offset. Pros – faults are well located, deposits appear to be extensive and may have a long record.
2. Site 2 – Cons -Faulting may also be too old to be recorded in these deposits. In addition, road construction for a side road may have removed original deposits,or damaged the faulting record at this site. Pros - Fault crosses FSR 128 and is well located, and potentially cuts a fan apron immediately east and adjacent to the road.
3. Site 3 - Cons – Highly disturbed area due to old road and utility construction, and faults not located with precision. Pros - Walnut Creek where the fault offsets Qbwc clasts in colluvium, immediately adjacent to southernmost offset colluvial clast.

Site 2 appears to be the most favorable location for an exploratory excavation since there is a small apron of alluvial deposits that may cross the fault, and the fault is positively located in this area (Figure 11). Site 3 would likely be the second favorable site since there are young colluvial deposits with clasts from the adjacent Qbwc; however, this site may have multiple strands and the fault is not located with precision. Site 1 is the lowest ranked site since the current landforms do not appear to have evidence of faulting, and faulting along this segment or section appears to be older; hence, excavations would need to be exceedingly deep to reach deposits that may have recorded the most recent event.

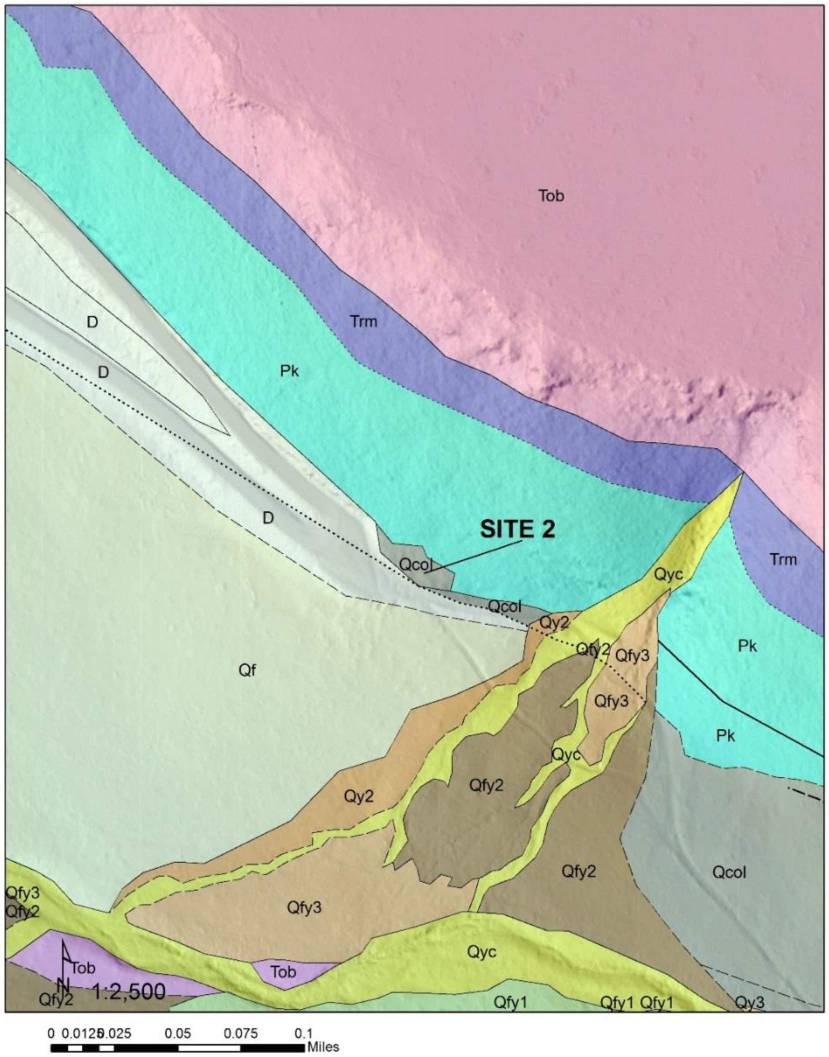

Figure 10: Location of potential paleoseismic excavation site, immediately east of FSR 128 (shown as disturbed polygons). Site 2 could be the most likley location to have a record of an event given the fault is positively located, and there are colluvial deposits. The Qy deposits east of Site 2 may not be offset, but road construction and alteration of the deposits makes it difficult to discern if the fault has offset Qy2 or Qfy2.

Discussion

Detailed mapping efforts reveal a fault system with a long and complex faulting history. Pre-Laramide mostly N-S and N-E striking faults and fractures are posited to be related to the upward propagation of vertical or near vertical structures in Precambrian basement rocks. According to previous studies (Wolfe, et al., 1987, Shoemaker et al., 1978), the propagation of basement fractures was mechanized by Cenozoic tensional tectonics pulling on the western edge Colorado Plateau, thus reactivating Precambrian faults. Most of these reactivated faults trend north and northeast. In the mapping area, the oldest lava flow unit, Tob has multiple sets of NNE faults that are likely related to reactivation of older, deep seated Precambrian faults. During the Laramide, compressional stresses resulted in regional 1-2-degree tilt to the northeast. Anderson Mesa (mostly in the central portion of the mapping area) and McMillan Mesa (in the northernmost part of the mapping area) tilt approximately 1 to 2 degrees to the northeast, which likely is the result of Laramide tectonics; however, both mesas have been significantly faulted within the last 5Ma by Quaternary faults.

Basin and Range extension is likely the mechanism for the Quaternary faults on the Colorado Plateau, including the LMFS. Reactivation of older structures that have made the crust weak and prone to distributed deformation as seen in the highly fracture Kaibab Formation in the study area, could explain the predominately N-S and NW trending combination of fault orientations. Additionally, extension of the Colorado Plateau may have rotated from more east-west extension to the current northeast-southwest direction thus distributing stress along preferred northwest-southeast striking faults, as well as preexisting north-south faults. Several fault zones with cross-fault systems, like Cataract Creek and the Blue Ridge faults can be found on the Plateau. Seismicity and resultant focal mechanisms for both the Cataract Creek and the Blue Ridge fault systems indicate faulting on preferred northwest-southeast normal faults (Brumbaugh, 2008).

Given the low slip rates and the predominately bedrock fault exposures, preservation of ruptures is rare to nonexistent. However, offset of Quaternary lava flows, continued seismicity in the area (Figure 11) and the sharp geomorphic expression of the Walnut Creek Segment of the LMFS suggests this fault system could generate a ground-rupturing earthquake. The active segments of this system is likely 30km long and does not include the southern 15km portion of the LMFS.

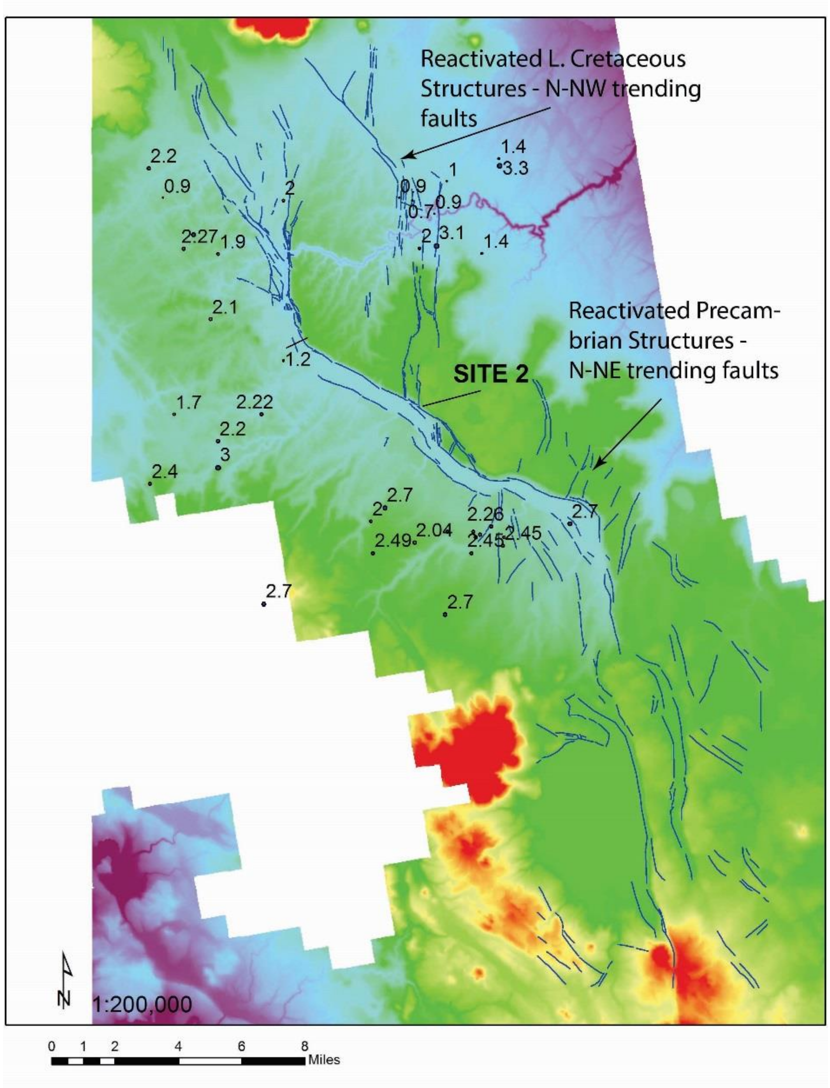

Figure 11: Bare Earth DEM (red is higher elevation, and blue is lowest) with faults overlain (dark blue), 38 earthquakes with labeled Md magnitudes (small numbered dots), and the location of the most favorable potential paleoseismic site, Site 2. Number of earthquakes is a minimum due to intermittent seismic monitoring. Quake dates range from 1997 to present. The mapping area contains faults that generally trend NE, N and NW and may be reactivated structures.

Conclusions

The LMFS is a complex set of faults and fractures that mostly trends north-northwest and is located within the densely populated city of Flagstaff. Detailed mapping and dating of lava flows during this study provide insight into the fault system's activity and potential to generate a ground-rupturing earthquake. Using new 40Ar/39Ar dates, mapped lava flows and offset measurements, the maximum slip rate for the LMFS is approximately 0.035mm/yr. The southern portion of the fault system has had minimal offset in the last 3million years and is not likely a potential source for a large event. The northern 30km of the LMFS is likely active, with low recurrence intervals, based on the offset of a Quaternary basalt flow along the Walnut Creek segment of the LMFS. Three sites were located along the LMFS for potential paleoseismic excavations; however, sedimentation rates are low along the south-facing scarp and may have record of the most recent event (MRE). Without having information on the timing of the MRE, the fault is considered a potential threat and capable of generating a ground-rupture event.

Final Report and Dissemination Efforts

Upon completion of the XRF analysis in the Spring of 2021, AZGS will complete the manuscript and figures for this study and submit them to Geology during the fall of 2021. In addition, a version of this report and mapping database will be made available as an AZGS Open-File report, with announcements sent to Coconino County and the city of Flagstaff. The mapping results are currently published and available for download at:

https://uagis.maps.arcgis.com/home/webmap/viewer.html?webmap=6bc3d2bf10714b1484601c869d036b55

References

Bausch, D.B. and Brumbaugh, D.S., 1997, Flagstaff community earthquake hazard evaluation, Coconino County, Arizona, Internal Report – Arizona Earthquake Information Center, Northern Arizona University, https://aeic.nau.edu/reports/flag.html.

Bills, D.J., Truini, M., Flynn M.E., Pierce, H.A., Catchings, R.D., and Rymer, M.J., 2000, Hydrogeology of the Regional Aquifer near Flagstaff, Arizona, 1994-97, Water Resources Investigations Report 00-4122, USGS.

Brumbaugh, D. S. 2008, Seismicity and tectonics of the Blue Ridge area of the Mogollon Plateau, Arizona, Bull. Of Seism. Soc. Of America, v. 98, no. 3, p. 1527-1534.

Holm, R. F., 1994, Geologic map of the Mormon Lake Quadrangle, Coconino County, Arizona, Contributed Map, Arizona Geological Survey, CM94-C.

Holm, R.F. and Shafiqullah, M., 1994, K-Ar ages of late Cenozoic basaltic rocks in the northern part of the Mormon Volcanic Field, north-central Arizona, Isochron/West, no. 61, July 1994.

Pearthree, P.A., Vincent, K.R., Brazier, R., and D.M. Hendricks, 1996, Plio-Quaternary faulting and seismic hazard in the Flagstaff area, northern Arizona*: AZGS Bulletin* 200, 40 p., scale 1:50,000 and 1:100,000, 2 sheets.

Pearthree, P.A., 1998, Quaternary fault data and map for Arizona: *AZGS OFR* 98-24, 122 p., scale 1:750,000.

Shoemaker, E.M., Squires, R.L., and Abrams, M.J., 1978, Bright Angel and Mesa Butte Fault systems of northern Arizona, in Smith, R.B., and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America.

Ulrich, G.E., Billingsley, G.H., Hereford, E.W., Wolfe, E.W., Nealey, L.D. and Sutton, R.L., 1984, Map showing geology, structure and Uranium deposits of the Flagstaff 1deg x 2deg quadrangle, Arizona: U.S. Geological Survey Miscellaneous Investigations Series, Map 1-1446, scale 1:250,000.

Wells, D. and Coppersmith, K., 1994, New empirical relationshipos among magnitude, rupture length, rupture width, rupture area, and surface displacement, Bulletin of the Seism. Soc. Of Am., v. 84, no. 4, p. 974-1002.

Wesnousky, S., 2008, Displacement and geometrical characteristics of earthquake surface ruptures: Issues and implications for seismic-hazard analysis and the process of earthquake rupture., Bulletin of the Seism. Soc. Of Am., v. 98, n. 4.

Wolfe, E.W., Ulfrich, G.E., Holm, R.F., Moore, R.B., and Newhall, C.G., 1987, Geologic map of the central part of the San Francisco volcanic field, north-central Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-1959, scale 1:50, 000.

Appendix A – Mapping Unit Descriptions and Unit Legend

Quaternary Sedimentary Units/Landforms

RTrm – Tertiary to modern regolith production on bedrock that includes Permian Kaibab Formation, Triassic Moenkopi Formation, Tertiary basaltic sheet flow rocks, and Mormon Mountain volcanic deposits, Quaternary fan deposits; time transgressive due to mixing of older eroded bedrock and soils and continued alteration of regolith in current climate; clay content often high, with some bedrock remnants scatter throughout; regolith can be less than 0.25m to near 1.5m thick or more.

Qb-r – Quaternary to modern regolith production on the Quaternary basalt Walnut Creek flow found adjacent and within Walnut Creek, near Lower Lake Mary Dam. Regolith includes clay and silt and some pebble gravel that includes subangular to subrounded clasts, predominately chert in composition. The presence of chert indicates mixing of weathered Kaibab Formation, which outcrops near the Qbwc and underlies most of the area adjacent to Walnut Creek.

Qys – Quaternary - Holocene to Modern deposits, undifferentiated; deposits include some fine-grained wide-spread deposits associated with mixing from channels and alluvial fans, as well as colluvial slopes.

Qyc – Modern active channels with clay to boulder sized, sub-rounded to rounded clasts; channels typically incise slightly or much older deposits; landform disturbances related to logging, water works projects, roads, etc., are more incised than surrounding, less disturbed landforms;

Qy3- Holocene, active channels and alluvial fan deposits ranging from clay to boulder in size, poorly to moderately sorted in most places.

Qy2 – Mid-Holocene to Modern deposits found along channel flanks and as alluvial fans; channel terraces are relatively low, approximately 0.5m to less than 2.0meters; terrace deposits and fans may infrequently be inundated with modern flood deposits.

Qy1 – Early Holocene – channels and inactive alluvial fan deposits composed of fine-grained silt and sand, and coarser subangular to rounded gravel deposits; deposits are often densely vegetated with grasses, shrubs and some pine.

Quaternary Volcanic Units

Qd - Dacite of Elden Mountain pyroclastic flow breccia and domes – partly exogenous dacite domes of Elden Mountain; massive, jointed dacite flow lobes extend down flanks in most directions (K-Ar ages 0.49 +/-0.06 and 0.57 +/-0.03Ma. The dacite flow associated with the dome has a flat surface, is several meters thick with angular blocks of very light gray dacite and pumiceous dacite in a matrix of unsorted, poorly consolidated, dacitic ash and lapilli with inverse graded bedding in the basal portion.

Qmb – Basalt flows and cinder cones – Medium to dark-gray, yellowish to dark-brown where weathered, 5 to 30m thick basalt flows. K-Ar age of 0.69 +/- 1.41Ma. Found mostly in the northern part of the mapping area, adjacent to main disturbed area associated with I10.

Qbwc – Quaternary basalt flow found near Walnut Creek; Ar/Ar date of 1.2Ma vesicular, basaltic lava flow that flowed into the ancestral Walnut Creek, filled the creek and continued flowing towards the area of what is now Lower Lake Mary Dam;

Tertiary Volcanic Units (Simplified from Holm, 1994)

Tmdy – 3.1 +/-0.6 Ma – Pliocene dacite of the Mormon Volcanic Field;

Tybl -3.89+/- 0.01 Ma – Pliocene basalt lava cones; Parasitic lava cones with dark to medium gray clinopyroxene-olivine basaltic lavas that may carry local plagioclase phenocrysts; flowed into graben of Ashurst Run, bounded by faults;

Tyb – 3.89 +/- 0.01Ma – Pliocene basalt; Small, dark gray, vesicular basalt flows with prominent phenocrysts of olivine and clinopyroxene in equal amounts; Flows are 0.5 to 9m thick at edges;

Tydd – no direct date – Pliocene dacite dome; Light gray to pink dacite forms and endogenous lava dome and small satellite dome that were erupted along the fault that bounds the west side of the graben at the south end of Mormon Lake. Phenocrysts of hornblende and plagioclase are set in a dense to sparsely vesicular hyalopilitic matrix.

Tpbf – 4.38 +/- 0.20 Ma -Tertiary Pinegrove basalt flow

Tibv - 4.38 +/- 0.20 Ma? -Pliocene basalt shield volcanoes; Three overlapping basalt shield volcanoes in the southern part of the mapping area; basalt is medium gray and contains different proportions of olivine, clinopyroxene and plagioclase phenocryst in different volcanoes; each shield is composed of multiple lava flows that range from 1.2m to over 10m thick.

Tob – Recent Ar/Ar date: 6Ma – Miocene – Medium gray lava flows of olivine basalt that underlie low-relief topography in the southern part of the map, and covers Anderson Mesa near the central part of the map; Common olivine phenocrysts are 1-5mm in diameter; plagioclase phenocrysts are uncommon and clinopyroxene is rare; most outcrops have a diktytaxitic matrix; sheet vesicles and cylindrical vesicles seen in outcrop; flows are 3-17m thick.

Tbo – Recent Ar/Ar date: 6Ma -Miocene – identical petrology to the Tob flows but sourced from volcanic vents to the west (Woody Mountain). This flow can be found in the very northern reaches of the mapping area and is bounded by several faults along McMillian Mesa (often referred to as Switzer Mesa). The unit is faulted and offset as multiple topographic steps that trend mostly N-S.

Paleozoic and Mesozoic Bedrock Units

Trm – Lower to Middle? Triassic Moenkopi Formation – In the mapping area, heavily weathered, and eroded light pink to red well-sorted sandstone; found mostly as remnants topping ridges in the western portion of Anderson Mesa, and along the main strand of the Lake Mary Fault System in the central portion of the mapping area. In the central and southern part of the mapping area, the Moenkopi is mostly covered by fans and colluvial deposits and is often in the downthrown block of the main fault. Near the headwaters of Walnut Creek, the Moenkopi Formation is found along the fault and is makes of part of the fault gouge exposed in 2 elongated mining pits.

Pk – Lower Permian Kaibab Formation – Buff, white to gray calcareous sandstone to fossiliferous limestone; beds of fossiliferous limestone and densely bioturbated limestone found several meters below the upper Pk topping beds.

Pc – Permian Toroweap and Coconino Sandstone – Toroweap Formation is mostly 2m or so thick, gray and gray-orange sandy limestone transitioning into buff calcareous sandstone of the Kaibab Formation; Coconino Unit - slightly pink, high-angle cross-bedded, well-sorted sandstone that is faulted along Walnut Creek and contains multiple sets of orthogonal fractures;

Quaternary Units

D - Disturbed
Qcol - Colluvium
Qf - Quaternary fans
Qls - Quaternary landslides
Qy - Holocene to modern deposits - undifferentiated
Qys - Young sheetflow alluvial deposits
Qyc - Young channel deposits
Qy3 - Holocene, active channels and fans
Qfy3 - Quaternary fan deposits
Qy2 - Mid-Holocene to modern deposits
Qfy2 - Quarternary fan deposits
Qy1 - Early Holocene deposits
Qfy1 - Quaternary fan deposits
Qi3 - Young intermediate deposits
Qi2 - Intermediate deposits
QTr - Tertiary to modern regolith

Quaternary Volcanic Rocks

Qby - Quaternary basalt - NE area
Qd - Dacite of Elden Mountain
Qmb - Quaternary - Flagstaff area basalt flows and cinders
Qbc - Quaternary basalt and cinders
Qbwc - Walnut Canyon BasaltFlow
Qb-r - Quaternary regolith on Qbwc

Tertiary Units

Tmdy - Pliocene dacit of Mormon Volcanic Field
Tybl - Pliocene basalt lava cones
Tyb - Pliocene basalt
Tydd - Pliocene dacite dome
Tpbf - Tertiary Pinegrove Flow
Tibv - Pliocene basaltic shield volcanoes
Tbo - Miocene sheet flows
Tob - Tertiary Basalt Flow
Tosc - Tertiary Basalt Scoria

Paleozoic and Mesozoic Rocks

RTrm - Degraded Moenkopi Formation
Trm - Moenkopi Formation
Pk - Kaibab Formation
Pc - Permian Toroweap and Coconino Sandstone
Bdrk - Bedrock - undifferentiated

Figure 12: Symbols and colors for mapped units. Map database can be viewed and downloaded here: https://uagis.maps.arcgis.com/home/webmap/viewer.html?webmap=6bc3d2bf10714b1484601c869d036b55

APPENDIX B

Rare Earth Elemental Concentrations for 12 volcanic samples

Sample ID	La ppm	Ce ppm	Pr ppm	Nd ppm	Sm ppm	Eu ppm	Gd ppm	Tb ppm	Dy ppm	Ho ppm	Er ppm	Tm ppm
JBH 07-13-2020_1	42.1176	83.8290	10.9696	46.8624	9.6075	2.9805	8.8457	1.2406	6.8504	1.2770	3.2582	0.4491
JBH 08-05-2020-_1	38.6927	82.6833	10.6414	44.9448	9.4842	2.9188	8.6874	1.2365	6.6174	1.2588	3.1261	0.4374
JBH 08-05-2020_2	39.7978	83.1387	10.8323	46.1857	9.3813	3.0306	8.5852	1.2389	6.6640	1.2650	3.1758	0.4415
JBH 08-11-2020_1	43.4830	87.1312	12.0393	51.1623	10.3523	3.2795	9.5334	1.3709	7.3385	1.3909	3.5125	0.4854
JBH 08-11-2020_2	39.9708	81.3995	10.7960	46.4032	9.4448	3.0099	8.8080	1.2480	6.8148	1.3121	3.2480	0.4556
JBH 08-31-2020_1	43.4836	85.1783	11.4672	48.4090	9.8391	3.0766	8.7890	1.2672	6.8867	1.2755	3.1840	0.4442
JBH 08-31-2020_2	39.5008	83.7703	10.9074	46.3215	9.5155	3.0730	8.7897	1.2476	6.7525	1.2689	3.1742	0.4371
JBH 08-31-2020_3	39.4701	83.3591	10.8512	46.3803	9.3669	3.0188	8.5136	1.2405	6.6528	1.2573	3.1463	0.4474
JBH 08-31-2020_4	37.4797	79.7702	10.3245	43.9955	9.0112	2.8972	8.3223	1.1768	6.4345	1.2362	3.0450	0.4217
JBH 1_Qbwc	39.4398	82.8218	10.7833	45.9531	9.2359	3.0286	8.5743	1.2382	6.6608	1.2675	3.0691	0.4458
JBH 1_Tobs	26.3757	51.1788	6.2927	25.3245	5.0306	1.5825	4.6725	0.6952	3.9393	0.7684	2.0403	0.3054
JBH 10-22-2020_1	23.4081	45.4646	5.5637	21.8106	4.3839	1.4819	4.1552	0.6415	3.7371	0.7111	1.8722	0.2911
JBH 08-05-2020-_1	38.4742	81.7943	10.5390	44.3693	9.2773	2.9407	8.5418	1.2352	6.6110	1.2344	3.1039	0.4209

Sample ID	Yb ppm	Lu ppm	Ba ppm	Th ppm	Nb ppm	Y ppm	Hf ppm	Ta ppm	U ppm	Pb ppm	Rb ppm	Cs ppm
JBH 07-13-2020_1	2.6051	0.4058	715.4814	3.2790	37.8516	34.2300	4.3423	2.1713	0.6433	4.4812	14.9709	0.0983
JBH 08-05-2020-_1	2.5321	0.3669	545.8699	3.2236	37.6757	32.5128	4.3621	2.2153	0.9948	4.1960	15.4730	0.0834
JBH 08-05-2020_2	2.6106	0.3873	562.4126	3.2829	38.7245	33.5641	4.3938	2.1901	0.9775	4.0002	15.9140	0.1298
JBH 08-11-2020_1	2.8296	0.4229	624.8183	3.4786	41.1324	37.2359	4.7086	2.3292	1.0521	4.3457	17.1300	0.0965
JBH 08-11-2020_2	2.5963	0.3959	582.5052	3.2828	38.3354	35.2690	4.4020	2.2017	0.8593	4.1259	15.4079	0.0578
JBH 08-31-2020_1	2.5520	0.3690	618.2843	3.3319	38.3985	35.0253	4.4073	2.2071	0.5046	4.3201	15.5475	0.0789
JBH 08-31-2020_2	2.5907	0.3887	588.6621	3.3518	38.7683	33.6753	4.4293	2.2179	0.6577	4.0666	14.9762	0.0959
JBH 08-31-2020_3	2.5998	0.3835	560.4683	3.3205	39.0105	33.3973	4.5001	2.2429	0.8948	4.2548	16.2741	0.1778
JBH 08-31-2020_4	2.4828	0.3676	519.2698	3.1517	37.1112	32.0092	4.1765	2.1462	0.9584	3.9605	15.3287	0.0799
JBH 1_Qbwc	2.5429	0.3783	753.9031	3.3086	38.1344	33.3397	4.3199	2.1854	0.7978	4.2921	15.6674	0.1065
JBH 1_Tobs	1.8450	0.2934	585.2730	3.3819	21.3516	20.5905	2.5551	1.0185	0.7279	4.8853	7.8811	0.0845
JBH 10-22-2020_1	1.6943	0.2669	540.4828	2.9774	26.3380	19.2276	2.8579	1.4198	0.5619	3.7648	8.4594	0.0553
JBH 08-05-2020-_1	2.5007	0.3855	545.2350	3.2016	37.5434	32.3313	4.3093	2.2068	1.0302	4.1733	15.3464	0.0917

Sample ID	Sr ppm	Sc ppm	Zr ppm
JBH 07-13-2020_1	776.6750	21.7465	184.8873
JBH 08-05-2020-_1	752.6283	21.2325	184.3668
JBH 08-05-2020_2	825.8705	21.8035	189.8395
JBH 08-11-2020_1	696.8237	22.7766	200.3776
JBH 08-11-2020_2	766.6259	22.3926	186.6565
JBH 08-31-2020_1	794.5284	21.6532	186.8065
JBH 08-31-2020_2	804.3534	21.8402	186.7264
JBH 08-31-2020_3	800.0858	22.2808	189.4755
JBH 08-31-2020_4	769.9939	20.8871	182.4209
JBH 1_Qbwc	806.7177	21.6717	187.3808
JBH 1_Tob	574.3049	30.3474	105.5481
JBH 10-22-2020_1	536.7118	29.2225	118.7443
JBH 08-05-2020-_1_R	743.0866	21.4266	185.1448