Physical volcanology and geochemistry of Upsal Hogback
Volcano, Fallon, Nevada, USA

by

Erika Anderson

A thesis submitted to the Faculty of Graduate and Postdoctoral
Affairs in partial fulfillment of the requirements for the degree of

Master of Science

in

Earth Sciences

Carleton University
Ottawa, Ontario

© 2014, Erika Anderson

Abstract

Upsal Hogback volcano is a tuff cone built up from phreatomagmatic eruptions that is located near the city of Fallon, Nevada. It is composed of indurated basaltic ash and lapilli tuff with abundant basaltic bombs. The edifice consists of the north complex (1 vent), and the south complex (3 vents). The edifice has also been severely eroded by glacial Lake Lahontan, obscuring the original morphology of the volcano, making it look similar to a tuff ring and not a tuff cone. Geochemical analysis of bomb samples from Upsal Hogback show that the north and south complexes are geochemically distinct but still have a similar asthenospheric mantle source. The magma supplying the volcano originated from a spinel peridotite or low percent garnet mantle source. Neighboring volcanic centers, Soda Lakes and Rattlesnake Hill, also have similar mantle sources and also are volcanic types on the phreatomagmatic spectrum.

Acknowledgements

Thank you to my supervisor, Brian Cousens, for his guidance and instruction. Thanks to Mike Jackson for help with sample preparations. Many thanks to Peter Jones for his direction on the electron microprobe. Thank you to Rhea Mitchell and Dan Stepner for all their help with the isotope geochemistry and my incessant questions. Thanks to Jordan Zak for his great help in the field and his work on Soda Lakes. Also thanks to Bruce Pauly and Chris Henry for their input and help in the field. Thank you to Alana Mackinder and Chris Rogers for helping with all the little things. Thanks to Mike Boyles for teaching me scientific skills that will always come in handy. Thank you to Thomas Cullen for all his help with fixing computer problems. Thanks to the staff in the Earth Sciences. A big thank you to the graduate students in the Earth Sciences for all the discussions about our projects and ideas we had, great for inspiration!

Table of Contents

Abstract.....	ii
Acknowledgements	iii
Table of Contents	iv
List of Figures.....	vii
List of Tables	xvii
List of Appendices.....	xix
1 Chapter: Physical Volcanology of Upsal Hogback Volcano, Fallon, Nevada, USA	
.....	20
1.1 Introduction	20
1.2 Geological Setting	22
1.2.1 The Phreatomagmatic Spectrum	29
1.2.1.1 Cinder Cones	29
1.2.1.2 Tuff Rings	30
1.2.1.3 Tuff Cones	32
1.3 Observations and Data.....	32
1.3.1 Large Scale Morphology.....	32
1.3.2 Field Observations	33
1.3.2.1 Textures	37
1.3.2.2 Palagonitization	41
1.3.2.3 Structural Measurements	44
1.3.2.4 Petrography.....	47
1.3.2.4.1 Bomb Samples.....	47
1.3.2.4.2 Tuff samples	56

1.3.3	Post Eruptive Effects.....	63
1.4	Discussion	70
1.4.1	North versus south complexes	70
1.4.1.1	Vent Placement.....	70
1.4.1.2	Comparisons of complexes.....	71
1.4.2	Upper and Lower Edifice.....	72
1.4.2.1	Evidence for Subaerial and Subaqueous Eruptions.....	74
1.4.3	Type of Volcano.....	74
1.4.3.1	Comparisons with other volcanism in the Carson Sink.....	77
1.4.4	Lake Lahontan Interactions.....	80
1.4.4.1	Syn-Eruptive Effects.....	80
1.4.4.2	Post-volcanic Effects	80
1.4.4.2.1	Tufa Precipitation.....	80
1.4.4.2.2	Erosion.....	81
1.4.4.2.3	Slumping	82
1.4.4.2.4	Shoreline deposits.....	84
1.4.4.2.5	Mud cracks	84
1.4.4.3	Timing of Eruption	85
1.4.5	Map	87
1.4.6	Risk to Fallon.....	89
1.5	Conclusions	91
2	Chapter: Geochemistry of Upsal Hogback, Fallon, Nevada, USA.....	92
2.1	Introduction	92
2.2	Geological Setting	94
2.2.1	Age of Upsal Hogback.....	100
2.3	Methods	101

2.3.1	Major and Trace Element Geochemistry	101
2.3.2	Isotope Geochemistry	103
2.3.3	Microprobe Analysis	108
2.4	Results	109
2.4.1	Major Element Geochemistry	109
2.4.2	Trace Element Geochemistry	118
2.4.3	Isotope Geochemistry	127
2.4.4	Microprobe Analysis	129
2.4.4.1	Plagioclase	129
2.4.4.2	Olivine	135
2.4.4.3	Spinel	137
2.5	Discussion	139
2.5.1	Upsal Hogback Magma Evolution	139
2.5.2	Comparisons with other volcanic centers	149
2.5.2.1	Comparisons with volcanism in the Carson Sink	149
2.5.2.2	Buffalo Valley Volcanic Field	159
2.5.2.3	Miocene-Pliocene Ancestral Cascades Arc	161
2.5.2.4	Tahoe-Truckee Volcanic Field	164
2.5.2.5	McClellan Peak	167
2.5.3	Source of Magma	168
2.6	Conclusions	169
3	Chapter: Summary of Conclusions	171
	Appendices	174
	References	249

List of Figures

Figure 1: Upsal Hogback (circled in red) near Fallon, Nevada, USA. Soda Lakes and Rattlesnake Hill are circled in yellow. The photo is from Google Maps (2012) by TerraMetrics (2012).	21
Figure 2: Close up of Upsal Hogback volcano in the map by Morrison (1964). The purple demarcates Upsal Hogback deposits and edifice.	23
Figure 3: Geothermal Areas near Fallon Nevada from Olmsted et al. (1986), with Upsal Hogback and Soda Lakes circled in red.	28
Figure 4: The phreatomagmatic spectrum illustrating the amount of water involved with each type of volcanism and the amount of energy produced, from Wohletz et al. (1983).	28
Figure 5: Cross section of a tuff ring and tuff cone, highlighting the difference in topographic relief between the two types of volcanoes from Wohletz et al. (1983).	31
Figure 6: The big hogback and little hogback, showing the high topographic relief and steep dips found in the southern complex.	34
Figure 7: Basaltic bomb sample from Upsal Hogback, note a rhyolite clast in the upper right corner of the bomb.	34
Figure 8: Large flow banded rhyolite block that is a common type of lithic block found in the tuffs.	36
Figure 9: Exceptionally large tertiary volcanic block on the side of the north edifice that has tufa precipitated all around it.	36
Figure 10: Ash tuff sample with cross bedding from the north complex (Sample 12-UH-31).	38

Figure 11: Palagonitized mud cracks on top of the upper edifice of the north complex. .	39
Figure 12: Bomb sag impact structure in the lower part of the edifice at Upsal Hogback.	40
Figure 13: Armored lapilli in the lapilli tuff of the little hogback, one example of armored lapilli circled.	40
Figure 14: Top of the big hogback looking down at the little hogback, both showing the distinctive orange color of palagonite.....	42
Figure 15: Aerial photograph from the United States Department of Agriculture (USDA) (2010) showing the distinction between the lower unpalagonitized part of the edifice lined in red, and the upper palagonitized part of the edifice of the south complex.	43
Figure 16: Tuff blocks right next to one another with completely different dips. To the right, lies another flat lying tuff block.	45
Figure 17: Aerial photograph from the USDA (2010) with structural measurements superimposed upon it, showing the haphazard strikes and dips of the tuff blocks.	46
Figure 18: Steeply dipping lapilli tuff overlying flat lying lapilli tuff in the lower parts of the southern edifice.	48
Figure 19: Lapilli tuff dipping two different ways over lying ash tuff that is almost flat lying, at the southern end of the two smaller vents of the south complex.	48
Figure 20: Location of bomb samples from Upsal Hogback. The photograph is from the USDA (2010).	49
Figure 21: Contact between two different glass types in the bomb sample 12-UH-01 under plane polarized light. The darker glass at the bottom has less microlites, while the lighter glass on top has abundant microlites.	51

Figure 22: Anhedral plagioclase phenocryst from sample 12-UH-01 in plane polarized light with three zones, the middle one has a dissolution texture. Plagioclase microlites surround it in a dark glass matrix.....	52
Figure 23: Heavily fractured olivine phenocryst in plane polarized light from sample 12-UH-05.	52
Figure 24: Glomeroporphyritic olivine and plagioclase phenocryst in plane polarized light in sample 12-UH-08.....	54
Figure 25: Spinel phenocryst from bomb sample 12-UH-05 in plane polarized light.....	54
Figure 26: Basaltic tertiary volcanic block covered in an Upsal Hogback bomb in sample 12-UH-43, the tertiary volcanic is the bottom half.	55
Figure 27: Location of tuff samples from Upsal Hogback. The photograph is from the USDA (2010).	57
Figure 28: Sample 12-UH-44 is an example of cross bedding seen in an ash tuff in the lower part of the edifice.	58
Figure 29: Sample 12-UH-21 with ash mass circled in red.	58
Figure 30: Ash tuff of sample 12-UH-34 with one large lapilli clast with pervasive palagonitization throughout the tuff. It comes from the upper part of the edifice of the north complex.	59
Figure 31: Sample 12-UH-45 also from the upper portion of the north complex shows rinds of palagonite (circled in red).....	59
Figure 32: Sample 12-UH-38, a heavily palagonitized lapilli tuff sample with a tufa clast within it.	60

Figure 33: Subhedral olivine phenocryst from a lapilli with lighter glass from sample 12-UH-17, with spinel circled in red within the olivine. The photo was taken in plane polarized light.	62
Figure 34: Palagonite rim on a light glass lapilli in sample 12-UH-39 from the upper part of the edifice of the south complex.	62
Figure 35: Tufa precipitated from Lake Lahontan on the side of the large hogback, following the vertical surface.	64
Figure 36: Rare tufa precipitation (with arrow pointing to it) on a horizontal surface, underneath a layer of ash tuff.	65
Figure 37: Sample 12-UH-09 shows carbonate cement holding the lapilli tuff together made of subrounded clasts.	66
Figure 38: Aerial photograph from the USDA (2010) showing the asymmetrical morphology of the vents (arrows pointing to vent locations). Note that none are completely circular.	67
Figure 39: Shorelines, on the west side of the edifice between the north and south complex, seen on aerial photographs from the USDA (2010) showing a cross cutting relationship (circled).	68
Figure 40: Wave cut terrace from wave action by Lake Lahontan with tufa precipitated onto the vertical surface.	69
Figure 41: Ash tephra at Soda Lakes with cross bedding.	78
Figure 42: Palagonitized lapilli tuff at Upsal Hogback.	78
Figure 43: Sinter deposits at Rattlesnake Hill.	79

Figure 44: The regions circled in red are the areas with the most slumping at Upsal Hogback. The photograph is from the USDA (2010).....	83
Figure 45: Lake levels of Lake Lahontan through time (Morrison, 1964; Rhodes et al., 2000). Altitude of GPS station from Blewitt et al. (2009) at Upsal hogback is demarcated in red.	86
Figure 46: Updated geomorphological map of Upsal Hogback in the Carson Sink.....	88
Figure 47: Upsal Hogback (circled in red) north of the city of Fallon in Nevada, USA. Soda Lakes and Rattlesnake Hill are circled in yellow. Photo is from Google Maps (2012) and TerraMetrics (2012).....	93
Figure 48: Geothermally active areas near Fallon, Nevada, from Olmsted et al. (1986), with Upsal Hogback and Soda Lakes circled in red.	97
Figure 49: Map of Western Nevada, showing the locations of the TTVF, the ACA in purple, McClellan Peak Basalts, and the volcanism in the Carson Sink., while the BVF is in the yellow box in the inset (Cousens et al., 2012).	99
Figure 50: Bomb sample localities for geochemistry at Upsal Hogback. The photograph is from the USDA (2010).....	102
Figure 51: Tuff sample localities at Upsal Hogback. The photograph is from the USDA (2010).....	110
Figure 52: Discrimination diagram based on LeBas et al. (1986) showing that both the north and south complexes are basaltic.	111
Figure 53: Discrimination diagram for alkalic and thoeiitic basalts (Winchester and Floyd, 1976).....	112

Figure 54: Al_2O_3 concentration is higher in south complex samples compared to the north complex. The error represents a 1-sigma value.	112
Figure 55: The south complex has less MgO than the north complex. The error represents the 1-sigma.....	114
Figure 56: Fe_2O_3 concentrations versus SiO_2 . The error represents the 1-sigma on the analyses.	114
Figure 57: Na_2O content is higher in the south complex compared to the north complex. The error is the 1-sigma of the analyses.	115
Figure 58: CaO is slightly higher in the south complex compared to the north complex. The error is the 1-sigma of the analyses.	115
Figure 59: The south complex is more enriched in K_2O than the north complex. The error is the 1-sigma of the analyses.	116
Figure 60: The south complex has higher TiO_2 content than the north complex. The error is the 1-sigma of the analyses.	116
Figure 61: P_2O_5 content is higher in the south complex over the north complex. The error represents the 1-sigma of the analyses.....	117
Figure 62: $\text{Mg\#}$ versus $\text{CaO}/\text{Al}_2\text{O}_3$ for Upsal Hogback samples.....	119
Figure 63: The south complex is more enriched in Ba than the north complex. The error is the 1-sigma of the analyses.	119
Figure 64: Sr shows more variability but is more enriched overall in the south complex compared to the north complex. The error is the 1-sigma of the analyses.	120
Figure 65: Rb is more enriched in the south complex than the north complex. The error represents the 1-sigma of the analyses.....	120

Figure 66: Zr is less enriched in the north complex compared to the south complex. The error is the 1-sigma of the analyses.....	121
Figure 67: The south complex is less enriched in Cr than the north complex. The error is the 1-sigma of the analyses.	121
Figure 68: Ni is more enriched in the north complex compared to the south complex. The error is the 1-sigma of the analyses.....	122
Figure 69: Sc is slightly less enriched in the south complex compared to the north complex. The error represents the 1-sigma of the analyses.	122
Figure 70: V concentration is the same for both the north and south complex. The error is the 1-sigma of the analyses.	123
Figure 71: Normalized incompatible element plot of the north and south complex, normalized to primitive mantle (Sun and McDonough, 1989).	126
Figure 72: Normalized incompatible element plot focused on REE (Sun and McDonough, 1989).	126
Figure 73: BSE photograph of zoned plagioclase phenocryst from Sample 12-UH-01.	130
Figure 74: BSE photograph of an alternating zoned plagioclase phenocryst next to zoned olivine phenocrysts.	131
Figure 75: Mineral content in phenocrysts between the north and south complex of the Upsal Hogback edifice.	133
Figure 76: Mineral content of phenocryst between the upper and lower unit.	134
Figure 77: Mineral content of phenocrysts comparing bomb samples to tuff samples. .	134
Figure 78: BSE photograph of a zoned olivine phenocryst with a spinel inclusion from sample 12-UH-34.....	136

Figure 79: BSE photograph of a spinel phenocrysts next to an olivine phenocryst in sample 12-UH-17.....	138
Figure 80: The south complex is enriched in MREE and LREE compared to the north complex.....	140
Figure 81: The south complex is more enriched in LILE and REE than the north complex.	140
Figure 82: Normalized REE pattern (Sun and McDonough, 1989) after 20% fractional crystallization is removed from the south complex.	142
Figure 83: Mixing curve between bomb samples from Upsal Hogback and tufa. The Sr error is smaller than the symbols, and the Nd error represents the 2-sigma of the analyses.	146
Figure 84: The samples from north and south complex have a large range in $^{87}\text{Sr}/^{86}\text{Sr}$ and less in $^{144}\text{Nd}/^{143}\text{Nd}$ (Zindler and Hart, 1986). The analytical uncertainty is smaller than the symbols.	146
Figure 85: Upsal Hogback is more constrained in $^{144}\text{Nd}/^{143}\text{Nd}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ values (Zindler and Hart, 1986). The analytical uncertainty is smaller than the icons.....	147
Figure 86: Upsal Hogback shows a range in mantle components in a $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ plot (Zindler and Hart, 1986). The analytical uncertainty is smaller than the symbols.	147
Figure 87: Upsal Hogback plots near EMII in a $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ (Zindler and Hart, 1986). The analytical uncertainty is smaller than the symbols.	148
Figure 88: Normalized incompatible element plot for Rattlesnake Hill, SLB, and SLDC (Sun and McDonough, 1989).....	150

Figure 89: $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{144}\text{Nd}/^{143}\text{Nd}$ plot for the volcanism in and neighboring the Carson Sink (Zindler and Hart, 1986).....	152
Figure 90: $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{144}\text{Nd}/^{143}\text{Nd}$ plot for the volcanism in the Carson Sink and neighboring it (Zindler and Hart, 1986).....	153
Figure 91: $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ plot for the mantle components of the volcanism in and around the Carson Sink (Zindler and Hart, 1986).....	154
Figure 92: Volcanism in and around Carson Sink plot near EMII in $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ plot (Zindler and Hart, 1986).	155
Figure 93: LREE versus MREE for the other volcanism in and near the Carson Sink. .	157
Figure 94: LILE versus REE for the volcanism in and around the Carson Sink.	158
Figure 95: Normalized incompatible element plot of the BVF (Sun and McDonough, 1989).	160
Figure 96: Normalized incompatible element plot for the samples from the Ancestral Cascade arc (Sun and McDonough, 1989).	163
Figure 97: Normalized incompatible element plot of samples from the TTVF and McClellan Peak (Sun and McDonough, 1989).	165
Figure 98: Close up of geomorphological map of Upsal Hogback edifice.....	207
Figure 99: Close up of the edifice with structural measurements.....	208
Figure 100: Close up of geomorphological map of north complex of Upsal Hogback..	209
Figure 101: Close up of geomorphological map of the south complex of Upsal Hogback.	210
Figure 102: Structural measurements of the north complex.	211
Figure 103: Structural measurements of the south complex.....	212

Figure 104: Close up of structural measurements around the hogback area.	213
Figure 105: Close up of west side of the south complex with structural measurements.	214
Figure 106: Close up of structural measurements of the east side of the south complex.	215

List of Tables

Table 1: Location of structural measurements and location of samples.	177
Table 2: Thin section petrography of the Upsal Hogback bomb samples.	184
Table 3: Thin section petrography of lapilli and ash samples from Upsal Hogback.	190
Table 4: Petrography of lapilli and ash tuff slabs.	199
Table 5: Location of sample stations.	217
Table 6: Major element geochemistry analyzed by the OGS.	219
Table 7: Trace element concentrations for Upsal Hogback bomb samples.	220
Table 8: Nd isotopes analyzed at Carleton University.	226
Table 9: Corrected Pb isotope values.	226
Table 10: Sr isotopes analyzed at Carleton University.	227
Table 11: Nd and Sr isotopes for the tufa sample from Upsal Hogback.	227
Table 12: Major element analytical uncertainty for samples sent to the OGS lab with three replicate analyses.	228
Table 13: Trace element analytical uncertainty for samples sent to the OGS lab with six replicate analyses.	228
Table 14: Analytical uncertainty for isotopes analyzed at Carleton University. The Nd analytical uncertainties come from 115 replicate analyses. The Sr analytical uncertainties come from 79 replicate analyses. The Pb analytical uncertainties are from 56 replicate analyses.	229
Table 15: Calculated Nd and Sr concentrations in the tufa sample.	230
Table 16: Plagioclase phenocrysts and microlites electron microprobe analysis.	231
Table 17: Olivine phenocrysts electron microprobe analysis.	235

Table 18: Electron microprobe analysis of spinel phenocrysts.	238
Table 19: Pyroxene in groundmass and phenocryst analyzed by electron microprobe..	239
Table 20: Glass electron microprobe analyses.....	240
Table 21: Other electron microprobe mineral analyses.	241
Table 22: Tufa microprobe analysis of sample 12-UH-38.	243
Table 23: Anorthite content of plagioclase phenocrysts and microlites.	243
Table 24: Forsterite content of olivine phenocrysts analyzed by electron microprobe. .	245
Table 25: Fractionation model for north complex magma to south complex magma.	247
Table 26: Mixing model between the bomb samples and the tufa sample.	248

List of Appendices

Appendix A Physical Volcanology	174
A.1 Chapter 1 Abstracts.....	174
A.2 Sample and Measurement Stations.....	177
A.3 Petrography.....	184
A.4 Updated Map.....	207
Appendix B Geochemistry.....	216
B.2 Sample Locations.....	217
B.3 Geochemistry.....	219

1 Chapter: Physical Volcanology of Upsal Hogback Volcano, Fallon, Nevada, USA

1.1 Introduction

Upsal Hogback is a volcano located north of the city of Fallon, in the Carson Sink of western Nevada, USA (Figure 1). It is a type of phreatomagmatic volcano that erupted during the history of glacial Lake Lahontan. A phreatomagmatic eruption is a high-energy explosive volcanism that involves a water component (Wohletz et al., 1983). The three phreatomagmatic volcanic end members are cinder cones, tufa cones, and tufa rings, which involve a decreasing amount of water respectively. These high-energy eruptions could be very dangerous for population centers surrounding them. The type of phreatomagmatic eruption at Upsal Hogback is unknown, and its proximity to the city of Fallon means it could be a great risk to the population. Fallon is also the site of a Naval Air Force Base, with the Top Gun training facility, which means heavy damage to military aircraft could occur if there was a future eruption.

The eruptions at Upsal Hogback created an edifice composed of lapilli and ash tuff with abundant olivine- and plagioclase-phyric basaltic bombs. The tuff is indurated and the upper edifice has significant palagonite alteration. The volcano has been severely eroded by the effects of Lake Lahontan. It consists of several vents that can be divided into the north and south complex. The north complex consists of only one vent, while the south complex has up to three possible vents. Previously, the volcano was mapped by Morrison (1964), where the focus of his study was the sedimentary geology of the Carson Sink. Morrison proposed four to seven possible vents. Our field investigations of Upsal

Figure 1: Upsal Hogback (circled in red) near Fallon, Nevada, USA. Soda Lakes and Rattlesnake Hill are circled in yellow. The photo is from Google Maps (2012) by TerraMetrics (2012).

Hogback show that this is not the case, therefore the map of Upsal Hogback needs to be updated. (Figure 2) The age of Upsal Hogback is also poorly constrained, as different authors place the volcanism at various times within the Carson Sink Quaternary depositional history (e.g.: Morrison, 1964; Fultz et al., 1983).

Older volcanism in the area includes the Miocene-Pliocene Ancestral Cascade arc and Pliocene-Pleistocene Tahoe-Truckee volcanic field to the east of the Carson Sink by the Nevada-California border, representing lithospheric melts mixed with melts from the mantle wedge caused by the subduction of the Juan de Fuca plate (Cousens et al., 2008, Cousens et al., 2011). To the west of the Carson Sink is the Buffalo Valley volcanic field, formed by asthenospheric intraplate magmatism (Cousens et al., 2012). Thus, western Nevada exhibits an evolution of volcanism from subduction-driven volcanism in the west to asthenospheric intraplate volcanism in the east.

The goals of this study are to: 1) Ascertain the type of phreatomagmatic volcanism at Upsal Hogback, 2) Characterize the volcanic deposits and volcanic history, 3) Create a new map of the volcano, 4) Constrain the age of volcanism at Upsal Hogback, 5) Establish the volcanic risk to Fallon.

1.2 Geological Setting

Upsal Hogback is located in the Carson Sink just north of the city of Fallon, Nevada. The Carson Sink sits on the boundary of several geological regions. First, it lies

on the transition between the Sierra Nevada and the Great Basin, a zone of extension that leads to lithospheric thinning (Ormerod et al., 1988; Cousens et al., 2011). The Carson Sink also lies on the edge the Walker Lane, a northwest trending zone of dextral shear (Fauls and Henry, 2008). The Carson Block of the Walker Lane, where the Carson Sink is situated, is cut by sinistral faults. It also lies within the Humboldt Lineament, a northeastern trending zone of lithospheric thinning, where there is high heat flow and northeastern trending faults (Louie et al., 2004).

The age of Upsal Hogback has not been well constrained. A $^{40}\text{Ar}/^{39}\text{Ar}$ total gas age by Shevenell et al. (2005) dated a volcanic bomb sample at 0.60 ± 0.09 Ma, but it did not produce plateau or isochron, leading to an imprecise date. It is possible there was inherited argon from the mantle present in the sample. The deposits from Upsal Hogback “intertongue” with the Wyemaha Formation, which infers that the eruptions took place between 30,000 and 40,000 years ago (Olmsted et al., 1984). Fultz et al. (1983) state that the volcano lies above the Wono Ash bed, which has been stratigraphically age determined at 25,000 years. Tufa that has precipitated onto the volcanic edifice has been dated by ^{14}C at $11,100 \pm 100$ and $8,600 \pm 200$ years (Benson et al., 1992; Broecker and Kaufman, 1965). The oldest ^{14}C date at $11,100 \pm 100$ years is the best youngest age constraint, since the edifice had to be present at this time for the tufa to be precipitated onto it. This constrains the age of the volcano to between 25,000 and 11,100 years old.

Morrison (1964) did a comprehensive study of the geology of the Carson Sink with a focus on the sedimentary history near Fallon for the United States Geological

Survey (USGS). The oldest rocks in the Carson Sink are Tertiary in age, and are basaltic and dacitic volcanic rocks from Rainbow Mountain. Dacitic and rhyolitic volcanism from Eagle Mountain followed afterwards and further volcanism occurred in the Truckee River area afterwards creating silicic tuff. Sedimentation also occurred during this time and afterwards, some composed of tuffaceous sediments, leading to the conclusion that volcanism may have been continuous with sedimentation. Subsequently, the Bunejug Formation was deposited, consisting of up to 400 ft of mafic and andesitic lava flows, capped by olivine phyric basaltic flows. During this time period, extensive faulting in the Carson Sink occurred, and during the Pleistocene. Formation of precursor lakes to Lake Lahontan may have begun fill after deposition of the Bunejug Formation.

The Carson Sink was part of one of the basins that formed the glacial lake called Lake Lahontan. According to Benson and Thompson (1987) Lake Lahontan covered much of northeastern Nevada. It can be divided into seven subbasins: Smoke Creek-Black Rock Desert, Pyramid Lake, Carson Desert, Buena Vista, Walker Lake, Honey Lake, and the Winnemucca Dry Lake. The Carson Sink is in the Carson Desert subbasin. The Carson Desert was first inundated between 45 ka and 50 ka, when Walker Lake spilled over. At 20 ka, the lake level was at 1265 m above current sea level. The maximum lake level was at 1330 m above sea level at 13.5 ka. After this high stand, the lake started to desiccate and lake levels dropped by 100m in approximately 1000 years.

During the Quaternary, the Paiute Formation was deposited, comprising of alluvium and colluvium (Morrison, 1964). The Cocoon soil was subsequently deposited,

demarking the Cocoon Interval. This soil horizon is conformably overlain by the Lahontan Valley Group, which was deposited within the existence of glacial Lake Lahontan. Initially, storm deposits of the Eetza Formation accumulated, and are composed of “lacustrine sand, clay, and tufa”. During a desiccation period for the lake, the Wyemaha Formation was deposited, and is composed of eolian sand, gravel, silt and clay. The Churchill soil was then deposited on top of the Wyemaha Formation. Another highstand of Lake Lahontan then occurred, during which the Sehoo and Indian Lakes Formation were deposited. The Sehoo Formation is composed of lacustrine gravel and sand in the near-shore environment and silt and clay in deeper water settings. During mid-Sehoo time, the Harmon School soil was deposited. The Indian Lakes Formation is comprised of alluvium and colluvium, including eolian sand, lacustrine silt, clay and some volcanic sand. After the complete desiccation of Lake Lahontan, the Turapah Formation was deposited, consisting of eolian sand. The Fallon Formation was deposited last, resulting from sedimentation from intermittent shallow lakes and desiccations.

Two other volcanic centers are located in the Carson Sink: Soda Lakes and Rattlesnake Hill (Figure 1). Soda Lakes comprises Soda Lake and Little Soda Lake to its southeast. Both are typical maars that are less than 6 ka because of the lack of tufa precipitated on the edifice, indicating that it post-dates Lake Lahontan, (Zak, 2013; Cousens et al., 2012), though Rhode et al. (2000) postulate that a residual lake could have been present as late as 2000 years ago. Both Soda Lake and Little Soda Lake are composed of unindurated lapilli and ash tephra with thin laminations, and trachybasaltic bombs (Zak, 2013). Rattlesnake Hill is situated in the town of Fallon, and is a 1 Ma

volcanic neck (Shevenell et al., 2005). It is composed of massive gray lava capped by a red basaltic trachyandesitic spatter vent (Zak, 2013). All rocks on Rattlesnake Hill are partially coated with tufa from Lake Lahontan.

The Carson Sink area around Fallon is the site of many geothermal fields, studied by Olmsted et al. (1986), reflecting the high heat flow in the area (Figure 3). One of these areas is called the Upsal Hogback geothermal field, and is situated just north of the volcanic edifice. There is a high thermal gradient at the surface of the field that is caused by the low albedo of the eroded, dark lapilli remnants from the Upsal Hogback. Another deeper geothermal gradient occurs below the surface geothermal field, which is surmised to come from lateral flow from the nearby Soda Lakes geothermal area via faults (Olmsted et al., 1984). Olmsted et al. (1984) also studied the Soda Lakes geothermal area, which is located between Upsal Hogback and Soda Lakes. It has a stronger temperature gradient than the Upsal Hogback geothermal field. The geothermal activity originates from convective upflow and shallow lateral flow along faults in the area. There is a geothermal plant at Soda Lakes utilizing the energy from the Soda Lakes geothermal field. There is also another geothermal plant called Stillwater just east of the city of Fallon.

Volcanism further from the Carson Sink is more variable. To the east are the Ancestral Cascade Arc and the Tahoe-Truckee Volcanic Field (TTVF). Cousens et al. (2008) explored the Ancestral Cascade arc volcanism near the Lake Tahoe area. There, it consists of lava flows, debris flows, and collapsed lava domes. This volcanism ranges

Figure 3: Geothermal Areas near Fallon Nevada from Olmsted et al. (1986), with Upsal Hogback and Soda Lakes circled in red.

Figure 4: The phreatomagmatic spectrum illustrating the amount of water involved with each type of volcanism and the amount of energy produced, from Wohletz et al. (1983).

from basaltic to dacitic in composition. The source of magma is from melting lithospheric mantle as well as from fluid-driven melting of the mantle wedge resulting from the subducting Juan de Fuca plate. According to Cousens et al (2011), the TTVF is primarily composed of cinder cones, lava flows, and pillow lavas, and includes a tuff ring at Skylandia Beach. The TTVF is post arc volcanism deriving from asthenospheric upwelling causing lithospheric melting at the trailing edge of the subducting Juan de Fuca plate. Northeast of the Carson Sink, by the city of Battle Mountain, lies the Buffalo Valley Volcanic Field (BVF) in the north east Fish Creek Mountains. Studied by Cousens et al. (2012), the BVF is composed of alkalic basalt and trachybasalt flows and cinder cones that are 4.05 to 0.95 Ma in age.

1.2.1 The Phreatomagmatic Spectrum

Upsal Hogback has been previously described as a tuff ring (Morrison, 1964), but this may not be the case. The eruptions occurred during the history of Lake Lahontan, thus it is possible that there could have been a large water component to the eruptions. There are three types of volcanoes that lie on the phreatomagmatic spectrum, with differing ratios of water/magma interaction (Figure 4). These endmembers are cinder cones, tuff rings, and tuff cones with increasing amounts of water/magma interaction respectively (Wohletz et al., 1983).

1.2.1.1 Cinder Cones

According to Wohletz et al (1983), cinder cones form with little involvement of water, thus is less explosive than the others. The deposits from cinder cones are from

ballistic emplacement with a small component of ash. Walker and Croasdale (1971) describe the eruptive style of cinder cones as strombolian with deposits that are thickly bedded and well sorted. Spatter is also very common, as well as red alteration of the deposits.

1.2.1.2 Tuff Rings

Wohletz et al. (1983) describe the differences between tuff rings and tuff cones. Structurally, the topographic relief between the two is different, with tuff cones having a much higher edifice (Figure 5). Tuff rings are the product of interaction with groundwater and ascending magma with very shallow dipping slopes. As the magma comes in contact with the groundwater, the conversion to steam leads to an explosive eruption. The deposits associated with tuff rings are from pyroclastic surges and consist of un-indurated and thinly bedded (1-5 cm) deposits. They form by explosion breccia and flow surges. This flow surge is considered hot and dry emplacement. Tuff rings are characterized by slopes of less than 12°, and have craters that extend below the normal topographic ground level. Tuff rings are also not indurated and have almost no palagonitization.

Along the phreatomagmatic spectrum, there are also maars that are fairly similar to tuff rings, and the terms are sometimes used interchangeably. White (1991) proposes that the difference between tuff rings and maars is the amount of “magma vesiculation, eruptive flux rates, water source and supply rate”. Maars also contain more lithic fragments in their deposits than tuff rings. In maars, the elevation of the base of the crater is below the original ground level.

Figure 5: Cross section of a tuff ring and tuff cone, highlighting the difference in topographic relief between the two types of volcanoes from Wohletz et al. (1983).

1.2.1.3 Tuff Cones

In contrast tuff cones are the products of magma interaction with shallow surface water (Wohletz et al., 1983). Tuff cones have craters that are above ground level, have deposits thicker than 100m, bedding between 1 cm and 1 m, and have vent dips greater than 25°. The formation of the edifice starts out the same as tuff rings, yet there is an additional phase of emplacement by pyroclastic surges where clasts get incorporated into steam laden surges that travel short distances. The steam condenses within the tephra when it deposits. This implies cooler and wetter emplacement than a tuff ring. White (1991) states that distinguishing features of tuff cones are bomb sags, and a lower unpalagonitized edifice with an upper palagonitized edifice. This lower edifice was emplaced subaqueously, leading to low bedding angles and coarse-grained deposits. The upper edifice was emplaced subaerially, has steeper bedding angles, is weakly bedded and coarse-grained, and has abundant water within the tuff.

1.3 Observations and Data

1.3.1 Large Scale Morphology

Vents mapped by Morrison (1964) were investigated in the field. The two vents identified on the northwest corner of the main complex is in fact a wind blowout. Another proposed vent north of the north complex identified by 2010 air photographs from the United States Department of Agriculture (USDA) was also found to be a circular set of sand dunes. The horst mapped by Morrison due south of the main edifice was also investigated, and although visible in air photographs, it is a low dune covered in basaltic lapilli fragments eroded from Upsal Hogback. These lapilli fragments are found in the

area surrounding the main edifice, and are wind-scattered material from the original vents. From air photos, there are three possible vents in the south that are part of the edifice, as well as one vent in the north and field work confirms that these are all potential vents. None of the vents identified have full circular edifices instead they display asymmetrical topography.

The north complex has a lower topographical relief than what is observed at the south complex. The south complex includes Big Hogback, from which Upsal Hogback gets its name, a large slump block that tilts 28° south towards a possible vent center. The Big Hogback is around 40 meters long, 15 meters wide, and 10 meters high. Next to it is a smaller slump block, called the Little Hogback, with a similar steep dip toward the same possible vent. The Little Hogback is approximately 15 meters long, 5 meters wide, and 5 meters high. Both hogbacks are palagonitized lapilli tuffs. The hogback shows the largest topographic relief on the volcano (Figure 6). At the top of the north complex, similar large scale slump blocks are found, with palagonitization, but have smaller dip angles in a smaller range than the large range seen in the top part of the southern complex's edifice.

1.3.2 Field Observations

The edifice at Upsal Hogback is composed of lapilli tuff, with some occurrences of ash tuff. The lapilli are basaltic with olivine and plagioclase phenocrysts. The majority of the edifice has been covered with sand blown from the Carson Sink, leading to field observations being important in determining the original morphology of Upsal Hogback.

Figure 6: The big hogback and little hogback, showing the high topographic relief and steep dips found in the southern complex.

Figure 7: Basaltic bomb sample from Upsal Hogback, note a rhyolite clast in the upper right corner of the bomb.

Two types of tuff are present in the edifice at Upsal Hogback, lapilli and ash tuffs. The lapilli tuff dominates both the north and the south complex, and is made up of small subrounded to angular basaltic lapilli clasts that are indurated to form beds. The clasts are also olivine- and plagioclase-phyric. Lapilli tuff beds can vary in thickness from 1-2 cm to more than 10 cm and are palagonitized in the upper part of the edifice (described below). The ash tuffs are very fine grained with fine laminations that sometimes have cross bedding (described below) and are indurated. They occur most frequently in the lower part of the edifice in both the north and south complex, and are not palagonitized.

Basaltic bombs are common in both the lapilli and ash tuffs, and are found in the lower and higher reaches of the edifice (Figure 7). These bombs vary in size, from 6 cm to 50 cm in diameter, and some show aerodynamic surface features. The bombs include plagioclase and olivine phenocrysts, with rare megacrysts of either mineral.

The most easily identifiable lithic fragment found is flow-banded rhyolite (Figure 8). They appear more frequently in the south complex than the north complex. Large blocks of rhyolite up to a 0.5 m in diameter are found on top of the edifice, covered in tufa. A rhyolite xenolith was dated at 6.3 ± 0.3 Ma (Fultz et al., 1983). Plagioclase-rich Tertiary basaltic volcanic rocks are also commonly seen as blocks that can get quite large and create bomb sags. Blocks have a large range in size, from 6 cm to 1.5 m in diameter. Some of the larger ones sit above the tuff and are covered in tufa (Figure 9). Some of these large blocks even form a line along the eastern side of the southernmost vent of the south complex.

Figure 8: Large flow banded rhyolite block that is a common type of lithic block found in the tuffs.

Figure 9: Exceptionally large tertiary volcanic block on the side of the north edifice that has tufa precipitated all around it.

1.3.2.1 Textures

Cross bedding was rarely seen in the field, and only in two samples of tuff. The cross-bedding was observed in the lower outcrops of both complexes. The cross-bedding was only present in ash tuffs and not observed in lapilli tuffs. The cross-stratified units were never associated with palagonitization (Figure 10).

Mud cracks were observed in a 2.3 cm thick layer along the highest unit of the north east of the north complex. The mud cracks only occurred in this one layer along the north vent. The layer consists of ash-sized particles. This layer also displays the characteristic orange color of palagonite. The layer is only 2.3 cm thick (Figure 12).

Bomb sags are seen throughout the ash and lapilli tuffs. Bomb sags are impact structures consisting of impressions made in the tuff due to the ballistic force of the erupted bomb (Walker and Croasdale, 1971). These structures can only occur subaerially, or within a few meters of water, due to the drag of water on the bomb reducing the bomb's speed and impact force. The bomb sags are seen in both the lower and higher reaches of the edifice. The bomb sags observed at Upsal Hogback were created by both bombs and large blocks (Figure 12).

Armored lapilli are also seen within the deposits of Upsal Hogback. According to Wohletz et al. (1983), armored lapilli consist of lapilli that are coated in layers of volcanic dust, indicating a wet environment. The ash layers of the armored lapilli are

Figure 10: Ash tuff sample with cross bedding from the north complex (Sample 12-UH-31).

Figure 11: Palagonitized mud cracks on top of the upper edifice of the north complex.

Figure 12: Bomb sag impact structure in the lower part of the edifice at Upsal Hogback.

Figure 13: Armored lapilli in the lapilli tuff of the little hogback, one example of armored lapilli circled.

palagonitized at Upsal Hogback (Figure 13), showing an orange rind around the basaltic lapilli.

1.3.2.2 Palagonitization

Both north and south vent complexes of Upsal Hogback are palagonitized at the top. Pauly et al. (2007) indicate that palagonite is an alteration product of hot basaltic glass with water. The process of palagonitization is the hydrothermal alteration of sideromelane, in which the glass is dissolved and hydrated to form palagonite, smectites, and zeolites. Many factors can affect the extent of palagonitization including: heat, the chemistry of the water, composition of the initial sideromelane, and location. The palagonite rind on the basalt depends on the duration of alteration and the temperature. Palagonite is clearly observed because of its distinctive orange color that occurs throughout the upper lapilli tuffs. The brighter color occurrences of palagonite indicate the alteration occurred at “lower, ambient temperatures” (Stroncick and Schminke; 2002). The palagonite at Upsal Hogback is bright orange (Figure 14), and is most distinctively seen at the Big Hogback.

Both complexes also show a lack of palagonitization in the lower part of their edifices. Some does occur in a few layers within the lower portion, but the characteristic orange color does not pervade the whole lower edifice. This makes it distinguishable from the upper parts of the edifice, which has distinctive palagonite alteration throughout it (Figure 15). This palagonitization seen in the upper parts of the edifice occurs in both the north and south complexes. The palagonitization is especially seen around the

Figure 14: Top of the big hogback looking down at the little hogback, both showing the distinctive orange color of palagonite.

Figure 15: Aerial photograph from the United States Department of Agriculture (USDA) (2010) showing the distinction between the lower unpalagonitized part of the edifice lined in red, and the upper palagonitized part of the edifice of the south complex.

hogback area and the south east side of the north complex. The smaller vents of the southern complex show less palagonitization than the two major vents forming the south and north complex.

1.3.2.3 Structural Measurements

Nearly two hundred structural measurements were taken in order to help ascertain the original vent locations. In an ideal setting, the inner vent would have a concentric set of steep dips, and the outside of the vent would have radiating shallow dips. A prime example of this is seen in the edifice at Soda Lakes. However, this was rarely observed at Upsal Hogback.

The lower part of the edifice commonly exhibits lower dips than seen in the upper part of the edifice. The outcrops of lower edifice were more continuous than those seen in the higher parts of the structure, thus the dips were similar to each other on a large scale. In some areas of the south and north complex, the dips were more variable, especially in the east part south complex and a small portion of the west part of the north complex. It was expected that the upper edifice would also have low dips that radiated around the vents. But in fact, when measured, the dips in the upper part of the edifice are randomly orientated. In the field, it was observed that two blocks of lapilli tuff right next to each other could be dipping at dramatically different angles and in different directions (Figure 16). This was especially observed around the hogbacks, since there is much more preservation of tuff blocks in that area (Figure 17).

Figure 16: Tuff blocks right next to one another with completely different dips. To the right, lies another flat lying tuff block.

Figure 17: Aerial photograph from the USDA (2010) with structural measurements superimposed upon it, showing the haphazard strikes and dips of the tuff blocks.

Isolated blocks of lapilli tuff are scattered throughout the upper edifice, and most have tufa precipitated along the outer margins of the blocks. Most of the isolated blocks are found in the higher parts of the edifice of Upsal Hogback and especially in the south complex on the southernmost vent. Sections of the lower part of the edifice that exhibits isolated slump blocks occur in the east of the south complex and the west of the north complex. The blocks on average are around 5 meters by 5 meters. Isolated blocks that are the only outcrops that form the upper part of the edifice in the south complex are by the hogback, these show dips in entirely random directions.

Slumping is seen along the outer edges of the lower part the main vents, where gently dipping tuff deposits have a steeply dipping tuff overlying it on the side of the outcrop (Figure 18). The tuff was very similar petrographically throughout. The slumping is frequently seen on the smaller northwestern vents of the southern complex. There is one instance of extensive slumping at the end of the outcrop of the westernmost vent of the southern complex, where the slumping of lapilli tuff occurs on both east and west sides of the outcrop the meter wide outcrop. The lapilli tuffs dip to both the east and west and are observed lying overtop a flat lying ash tuff (Figure 19).

1.3.2.4 Petrography

1.3.2.4.1 Bomb Samples

Eighteen basaltic bomb samples were taken from the north and south complex (Figure 20). In thin section, these samples are all similar and are olivine and plagioclase phryic basaltic bombs. The amount of plagioclase and olivine phenocrysts varied from

Figure 18: Steeply dipping lapilli tuff overlying flat lying lapilli tuff in the lower parts of the southern edifice.

Figure 19: Lapilli tuff dipping two different ways over lying ash tuff that is almost flat lying, at the southern end of the two smaller vents of the south complex.

Figure 20: Location of bomb samples from Upsal Hogback. The photograph is from the USDA (2010).

sample to sample: plagioclase being between 5 and 20%, and olivine was between trace and 20%.

Glass types are variable but still similar to one another. Differing glass types are seen within individual bomb samples, though some have a crystallized fine-grained groundmass. It is common to see two types of glass within one bomb, and these are distinguishable by color (Figure 21). The darker glass has fewer microlites and vesicles than the lighter glass, though there are some instances of the opposite. Sample 12-UH-37 has a coarser grained groundmass compared to the rest of the samples, where pyroxene and olivine make up some of the groundmass.

Plagioclase phenocrysts were abundant in the basaltic bombs. They sometimes showed chemical zoning, as well as zones with sieve texture usually in the second zone (Figure 22). The crystal shapes of the phenocrysts are euhedral to anhedral. The phenocrysts are commonly embayed. Plagioclase microlites are also abundant in all bomb samples but do vary in the glass types, except 12-UH-33, which has a smaller amount than the others.

Olivine phenocrysts can be zoned but this is apparent only under the microprobe. The phenocrysts are subhedral to anhedral, very rarely with euhedral crystal boundaries (Figure 23). The phenocrysts are sometimes embayed, but less commonly than in plagioclase phenocrysts. Many of the olivine phenocrysts are heavily fractured.

Figure 21: Contact between two different glass types in the bomb sample 12-UH-01 under plane polarized light. The darker glass at the bottom has less microlites, while the lighter glass on top has abundant microlites.

Figure 22: Anhedral plagioclase phenocryst from sample 12-UH-01 in plane polarized light with three zones, the middle one has a dissolution texture. Plagioclase microlites surround it in a dark glass matrix.

Figure 23: Heavily fractured olivine phenocryst in plane polarized light from sample 12-UH-05.

Glomeroporphyritic olivine and plagioclase phenocrysts are common in the bomb samples (Figure 24)

There are trace amounts of spinel in some of the samples (Figure 25). The spinel is commonly associated with olivine phenocrysts in the samples. It is frequently in the glass neighboring the olivine phenocrysts, crystallized in contact with the olivine, or even within the olivine crystal itself. It is rarely found within plagioclase, and the spinel phenocrysts' crystal shape is euhedral to subhedral.

Calcite is frequently seen lining fractures and vesicles of the bomb samples. The calcite is likely related to tufa precipitated from brines from Lake Lahontan while the sample was submerged during higher lake levels. The thin sections were cut from the freshest interior part of the samples but still include traces of calcite, showing that the brines easily penetrated the relatively porous volcanic rocks.

Sample 12-UH-43 is bomb ejecta that is cored by what is most likely a Tertiary volcanic lithic fragment (Figure 26). The glass of the Upsal Hogback lava is darker than the Tertiary volcanic core. The sample has much more abundant plagioclase phenocrysts and only trace olivine. The olivine phenocrysts have more alteration than the olivine phenocrysts observed in Upsal Hogback basalts.

Figure 24: Glomeroporphyritic olivine and plagioclase phenocryst in plane polarized light in sample 12-UH-08.

Figure 25: Spinel phenocryst from bomb sample 12-UH-05 in plane polarized light.

Figure 26: Basaltic tertiary volcanic block covered in an Upsal Hogback bomb in sample 12-UH-43, the tertiary volcanic is the bottom half.

1.3.2.4.2 Tuff samples

Tuff samples were taken from the upper and lower edifices of both north and south complexes (Figure 27). Tuff samples were cut into slices, epoxied, polished, and sprayed with lacquer in order to bring out textures in the tuff. The grain sizes are variable, but range from ash to large lapilli. The lapilli range from subrounded to angular clasts. Lithic fragments are observed in most samples although most are too small to identify with accuracy, but can be characterized as fragments of rhyolite, smaller fragments of the larger blocks seen in the tuff, or granite.

Cross-bedding is only seen in two samples, 12-UH-31 and 12-UH-44, and only seen in thin layers (Figure 28). The clasts are primarily ash sized in these two samples, with rare lapilli sized clasts. The cross-beds are 4 to 7 cm thick and unpalagonitized. In ash tuff sample 12-UH-21, small round masses of ash are observed (Figure 29).

Palagonitization is seen mainly in samples from the upper portion of the edifice. The orange color is pervasive throughout the ash tuff (Figure 30), and around the lapilli fragments (Figure 31). The samples from the lower parts of the edifice have some occurrences of palagonite, usually observed in one layer, or only around a few lapilli clasts.

One sample, 12-UH-38, has a tufa clast in it, which is uncommon (Figure 32). This is the only time that a piece of tufa has been observed in a tuff sample. In the field tufa was only observed precipitated onto tuff blocks and within fractures, and never within

Figure 27: Location of tuff samples from Upsal Hogback. The photograph is from the USDA (2010).

Figure 28: Sample 12-UH-44 is an example of cross bedding seen in an ash tuff in the lower part of the edifice.

Figure 29: Sample 12-UH-21 with ash mass circled in red.

Figure 30: Ash tuff of sample 12-UH-34 with one large lapilli clast with pervasive palagonitization throughout the tuff. It comes from the upper part of the edifice of the north complex.

Figure 31: Sample 12-UH-45 also from the upper portion of the north complex shows rinds of palagonite (circled in red).

Figure 32: Sample 12-UH-38, a heavily palagonitized lapilli tuff sample with a tufa clast within it.

a tuff itself as a clast. Unusual amphibole crystals were also seen in 12-UH-38 with the electron microprobe, which were also not observed in any other tuff or bomb sample. The sample is also very palagonite rich.

Thin Sections

The lapilli fragments in the tuffs are more variable than the bomb samples. All lapilli are olivine and plagioclase phyric basalts, but the glass differs from that of the bombs. It is common to see multiple types of glass in the same tuff sample. Some lapilli are a dark glass, with a differing amount of microlites, which resemble the glass present in the bomb samples. But the glass that is most common in the lapilli samples is a pale brown glass (Figure 33), which was not present in the bomb samples.

Olivine and plagioclase phenocrysts as well as microlites are also present in both types of glass lapilli. The olivine and plagioclase phenocrysts are similar in texture and abundance as the bomb samples described above. Spinel is also seen associated with the olivine phenocrysts as in the bomb samples.

Palagonite is seen in several tuff samples (Figure 34). It is commonly found as a rind around the lapilli, and interstitially between them. Occasionally it appears to be altering the lapilli glass itself. Palagonite can be seen in both upper and lower units, but is more pervasive in samples from the upper part of the edifice.

Figure 33: Subhedral olivine phenocryst from a lapilli with lighter glass from sample 12-UH-17, with spinel circled in red within the olivine. The photo was taken in plane polarized light.

Figure 34: Palagonite rim on a light glass lapilli in sample 12-UH-39 from the upper part of the edifice of the south complex.

1.3.3 Post Eruptive Effects

Tufa is deposited all the way to the top of the volcanic edifice. Eroded remnants of tufa are also located on the flattened tops of the edifice. Tufa is generally only observed deposited on vertical or subvertical surfaces (Figure 35). It is rare to see tufa precipitated along a lapilli layer (Figure 36). Calcite is common within the tuff samples due to infiltration of Lake Lahontan waters into the pore space of the tuffs. The calcite is found in the interstitial space around the lapilli and also precipitated onto the lapilli. Unusually, 12-UH-09 has been completely cemented by calcite. The sample has subrounded grains and the tuff is not grain supported but cement supported (Figure 37).

Aerial photographs of Upsal Hogback show that the vents are topographically asymmetrical (Figure 38). None of the vents form a complete circular structure. Shoreline deposits as well as wave cut terraces occur on the outside margins of the edifice. A series of crosscutting shoreline deposits can be seen on aerial photographs on the western side of the edifice between the north and the south complex (Figure 39). These deposits were impossible to distinguish while standing on them in the field. Wave cut terraces are seen around the edge of the southern vent (Figure 40) and can be continuous for 100 meters. Tufa is usually observed precipitated on the vertical sides of the wave cut terraces.

Figure 35: Tufa precipitated from Lake Lahontan on the side of the large hogback, following the vertical surface.

Figure 36: Rare tufa precipitation (with arrow pointing to it) on a horizontal surface, underneath a layer of ash tuff.

Figure 37: Sample 12-UH-09 shows carbonate cement holding the lapilli tuff together made of subrounded clasts.

Figure 38: Aerial photograph from the USDA (2010) showing the asymmetrical morphology of the vents (arrows pointing to vent locations). Note that none are completely circular.

Figure 39: Shorelines, on the west side of the edifice between the north and south complex, seen on aerial photographs from the USDA (2010) showing a cross cutting relationship (circled).

Figure 40: Wave cut terrace from wave action by Lake Lahontan with tufa precipitated onto the vertical surface.

1.4 Discussion

1.4.1 North versus south complexes

1.4.1.1 Vent Placement

Upsal Hogback has been divided into the north and south complex. The previous map by Morrison (1964) shows several vents that are wind blowouts or sand dunes upon further investigation. In aerial imagery the edifice appears to be two circular vents at first glance. In fact, closer inspection of the air photographs reveals four possible vents that comprise Upsal Hogback. Three comprise the southern complex, and combined look like a circular shape. But it is more likely that the Hogbacks are demarking a mostly eroded large vent to the south of the complex. All four of these vents do not form a complete circular edifice.

The north complex comprises of one large vent. This can be clearly seen the aerial photographs. The two vents mapped by Morrison (1964); one to the north of the vent and one to the west, are in fact wind blow outs and not vents. The large vent is has the largest portion of its circular edifice intact out of all the vents at Upsal Hogback.

The south complex is comprised of three vents. The largest is situated on the southernmost part of Upsal Hogback. It is similar in size to the vent in the north complex. Both Big Hogback and Little Hogback demarcate the inside edge of the vent that would continue to the south if it had not been eroded away by Lake Lahontan. Lake Lahontan most likely eroded away two thirds of the structure. The two other vents are to the north

east of the large vent. They are significantly smaller but similar in size to one another, and do not have the palagonitized upper part of the edifice seen in the other vents.

1.4.1.2 Comparisons of complexes

The north complex is clearly composed of one large vent that forms two thirds of a full vent. In the north complex, the dips range from 0 to 36°. The south complex is comprised of three vents. The largest is the southernmost vent, and is composed of both lower unpalagonitized edifice, and upper palagonitized edifice. The two other vents are to the northwest of the large one. These two vents only have unpalagonitized edifices. The south complex has a higher range in dips compared to the north complex with dips that range from 0 to 90°, though the smaller vents only have a range from 0 to 44°.

Both complexes are very similar, the only major difference being the higher topographic relief shown in the south complex compared to the north complex. They both erupted and were built up as tuff cones. The north complex does have the steep dips that are seen in the hogback area of the south complex, but they are less frequent. The upper part of the edifice of the north complex is not as steeply dipping as the upper edifice in the south complex. There are also far fewer slump blocks than what is observed at the hogback area. Cross stratification is seen more abundantly in the north vent yet is still rare. In contrast, the south complex shows far more slumping than the north complex, and in consequence has much more tufa since there are more vertical surfaces for it to precipitate on.

The palagonitization of the upper edifice in both complexes indicate a similar lake level, which may indicate that the north and south eruptions occurred very close in time. Morrison (1964) states that the north complex is younger since more of the circular edifice is intact, this may be more arbitrary since less of the upper part of the edifice is present in the north complex and it has lower topographic relief. This may be a reflection of more erosion by Lake Lahontan, making the north complex older, or another possibility is that less eruptive material was erupted above the water line. There is no definite field relationship that supports whether the north or south complex erupted first.

1.4.2 Upper and Lower Edifice

Using the field observations, the deposits at Upsal Hogback can be divided into the upper edifice and the lower edifice. The upper edifice is characterized by pervasive palagonitization. The dips in the upper edifice are more variable from 0 to 90°, and can be described as random, and are steeper than those observed in the lower edifice. Tufa is more commonly seen precipitated on the upper edifice, which may be because there are more vertical surfaces and fractures for it to precipitate on.

The lower unit of the edifice does have occurrences of palagonitization but it is not pervasive and only occurs in individual layers. Ash tuffs are also more common in the lower edifice than the upper edifice, though lapilli tuffs are still dominant in both. Cross stratification also only occurs in the lower unit, which may be a reflection that more ash-sized tuffs are found in the lower unit. The dips of the tuffs in the lower edifice are

generally shallower (0-24° in areas with no slumping) than what is seen in the upper edifice (0-90° dips).

Both the upper and lower units both are primarily composed of basaltic lapilli. Both units have plagioclase and olivine phenocrysts, with some spinel. The major differences between the two is the lack of pervasive palagonitization in the lower unit, its shallower dips compared to the upper unit, and the lower unit also has more ash tuffs than the upper unit.

The difference in deposition and textures are primarily due to the location below or above water for the unit, which is discussed further below. There is no evidence that the upper unit and the lower unit represent different eruption events, though they most likely represent some of the different stages of the eruption of a tuff cone. Most of the lower unit is in place since far less slumping is observed, while majority of the upper unit is not in place since slumping is observed. No significant unconformity is seen in the deposits, which would occur if there was a long break in between eruptions leading to significant erosion by Lake Lahontan. It is possible that since the lower unit is more intact than the upper unit, there was a short hiatus in eruptions where lake levels changed. This is unlikely; since both the upper unit and the lower unit do have slumping, and the differences in erosion between the two units can be explained by high lake levels affected the upper edifice more than the lower edifice. The upper edifice could have also protected the lower unit from erosion since it overlies it.

1.4.2.1 Evidence for Subaerial and Subaqueous Eruptions

Since the lake level at the time of the eruptions of Upsal Hogback is unknown, it is important to characterize depositional features as subaerial or subaqueous. Bomb sags and armored lapilli are seen throughout the ash and lapilli tuffs. Since both of these can only occur subaerially, or in the instance of bomb sags only within a few meters of water, it shows that where these textures occur, the structure was at or above lake levels.

The differences in palagonitization between the upper and lower units, distinguishes the subaqueous and subaerial eruptions. According to White (1991), the lower unit that is unpalagonitized and shallow dipping represents the submarine parts of the eruption, while the palagonitized steeply dipping upper unit represents the growth of the structure above the water levels.

1.4.3 Type of Volcano

The low topographic relief of Upsal Hogback makes its cross section look much more like a tuff ring than any of the volcanoes on the phreatomagmatic spectrum, like cinder cones and tuff cones. This may be misleading, as Upsal Hogback shows attributes characteristic of a tuff cone. It has the lower unpalagonitized edifice, as well as an upper palagonitized one, that is considered very characteristic of tuff cones according to White (1991). The lower edifice would have been under shallow water or erupted in a dry lake in order for no palagonitization to occur. Based on White's (1991) description, tuff cones are characterized by lower unpalagonitized edifices with shallow bedding that are emplaced underwater, with an upper edifice that is palagonitized with steep bedding that

occurs subaerially. This description of a tuff cone fits exactly with what is observed at Upsal Hogback, with the upper unit showing palagonitization and steep dips and the lower unit that has shallow dips and no palagonitization. There is also evidence of subaerial emplacement as seen by bomb sags and armored lapilli. Armored lapilli are also considered characteristic of tuff cones. This suggests that the edifice must have been at least partially emplaced above lake levels or in shallow water. This also shows that the lake level was fairly shallow when the eruptions occurred. The edifice was then built as the eruptive material piled up and breached lake surface levels.

The potential morphology of a tuff cone can be seen with the Big Hogback. The steep dip angle and size of the hogback make it possible that it was part of a much larger edifice than that observed today. Evidence of this includes the flat top of the edifice and the broken up tufa remnants found therein, an unlikely morphology to occur due to an eruption. The hogback is so large that it is unlikely that wave action from Lake Lahontan moved it, but it is possible that it did slide down slope, as collapse structures are common in tuff cones and tuff rings (Wohletz et al., 1983).

There is rare evidence of surge deposits, which occur in tuff rings, and rarely in tuff cones. The occurrence of ash tuffs in the lower edifice as well as rare cross bedding, compliments the fact that tuff cones and tuff rings have similar beginning stages of emplacement (Wohletz et al., 1983). The cross stratification is characteristics of surge beds according to Wohletz and Sheridan (1983). Cross stratification can occur in the thinly bedded deposits of tuff rings or the thickly bedded deposits of tuff cones. The

thinly bedded deposits occur underneath the thickly bedded deposits of tuff cones. This deposition is seen occasionally in the rare cross-bedded ash tuffs of the lower unit.

According to Wohletz et al. (1983) tuff cones have three stages of eruptions. They begin with explosion breccia at the first stage, then thin beds deposited by inflated surges, and lastly pyroclastic emplacement by surges and pyroclastic falls. The beginning stages would be seen in the lower unit at Upsal Hogback, while the magma first comes into contact with groundwater. The last stage is clearly represented at Upsal Hogback by the upper unit, showing the steeply dipping beds deposited by pyroclastic falls and pyroclastic wet surges, when more surface water comes into contact with the magma. This type of eruption leads to massive poorly bedded tuffs that are indurated by palagonite with some thin laminations of ash whose texture can be obscured by palagonitization. There is very rare cross-bedding. In the upper unit at Upsal Hogback, there is thick bedding and steeply dipping beds, but they are not characterized as massive. The thick bedding would be from the pyroclastic falls. The upper unit is extensively indurated and palagonitized. There is also only cross-bedding in the lower unit. There may be overlap between the two units for the stages of the eruption, because the distinguishing factor between the two units is the subaerial versus subaqueous eruptions. This change occurs when the edifice gets built up above the water, which may not completely reflect a change in water availability.

The eruptive style would be considered surtseyan for tuff cones according to Wohletz and Croasdale (1971). The eruption type is named after the Surtsey tuff cone off

the coast of Iceland. A surtseyan eruption occurs when water has access to the vent, comparable to the proposed conditions during the eruptions at Upsal Hogback with the shallow water of Lake Lahontan. It differs from a strombolian type eruption, common for cinder cones, which does not involve water. Surtseyan deposits are finer grained, thinly bedded, and palagonitized compared to a strombolian type. Armored lapilli and bomb sags are also frequent in deposits from surtseyan eruption.

1.4.3.1 Comparisons with other volcanism in the Carson Sink

The characteristics of Upsal Hogback can be compared with observations at Soda Lake, a characteristic maar, neighboring the volcano. Soda Lakes has very little topographic relief, and shows a characteristic shallow dip away from the crater, but very steep inner walls. Soda Lakes is mostly composed of ash tephra (Figure 41), with some lapilli and bombs, showing a more explosive eruption compared to Upsal Hogback, where there is primarily lapilli tuff (Figure 42). There is also a large amount of cross bedding in the ash tephra at Soda Lakes, which is typical of surge deposits. This implies that Soda Lakes erupted either during a very low stand in Lake Lahontan history, or after the lake had dried up (Zak, 2013).

Rattlesnake Hill, dated at 1 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ total gas age (Shevenell et al., 2005), would have erupted before Lake Lahontan occurred. Therefore there was no water/melt interaction, so the volcanism produced a cinder cone. The volcanism was not explosive enough to create the small lapilli and ash sized clasts seen at Upsal Hogback and Soda

Figure 41: Ash tephra at Soda Lakes with cross bedding.

Figure 42: Palagonitized lapilli tuff at Upsal Hogback.

Figure 43: Sinter deposits at Rattlesnake Hill.

Lakes. No bedding or surge deposits are observed at Rattlesnake Hill, as there is only sinter observed at the top of the edifice (Figure 44).

1.4.4 Lake Lahontan Interactions

1.4.4.1 Syn-Eruptive Effects

Due to Upsal Hogback being in fact a tuff cone, it shows that water was present during the eruption of the volcano. The water would have added explosivity to the eruptions when it came in contact with the vent. Eruption into a lake would have also meant that the part of the edifice that was emplaced underwater would not be palagonitized, and this is represented as the unpalagonitized lower edifice. The water would also have some effect on deposition since it would exert more drag on the clasts than air.

1.4.4.2 Post-volcanic Effects

1.4.4.2.1 Tufa Precipitation

Since the eruptions at Upsal Hogback were during the history of Lake Lahontan, lake levels higher than the edifice have occurred. Evidence of this is that tufa has precipitated up to the top of the volcanic edifice. The tufa could not be there unless the edifice was present beforehand. The top of the edifice is flat and littered with plates of thin tuff beds and tufa, which would be unlikely to occur from an eruption but more likely from erosion due to wave action. The tufa that is precipitated onto the edifice at Upsal Hogback and Rattlesnake Hill can be contrasted to the lack of tufa on the edifice at

Soda Lakes (Zak, 2013). Therefore it is much more likely that Soda Lake erupted after Lake Lahontan dried up, and groundwater is the major factor in maar eruptions. Also, the tephra would have been easily eroded due to wave action, if there were later high stands of Lake Lahontan.

The sample 12-UH-09 is a calcite cement-supported lapilli tuff with rounded lapilli clasts. This sample is likely to be reworked due to wave action by Lake Lahontan and then cemented together due to precipitation from the brines. Sample 12-UH-38 is also unusual because it has a tufa clast within the lapilli tuff. The unusual mineralogy of it also indicates that it may have been reworked by wave action.

1.4.4.2.2 Erosion

A great amount of erosion is due to wave action from Lake Lahontan. One can see this through an aerial view of Upsal Hogback, showing that the proposed vents are asymmetrical, likely due to small inlets being carved out by wave action from the lake. It is quite possible that the edifice was much taller but has since been eroded after the eruptions, as the top of most of the edifice is completely flattened. There is also a thin layer of broken up tufa and lapilli deposited on top of the sediments at Upsal Hogback. Wave cut terraces also occur frequently at Upsal Hogback, where the edges have tufa precipitated onto them.

There is a lot less of the upper unit left intact on both the north and the south edifices. One reason could be that there was a lot less volume of the upper edifice

compared to the lower edifice, thus comparatively after erosion there is far less of it than the upper edifice. Another reason could be that the upper edifice experience more wave action erosion compared to the lower unit, since the upper unit protected it as it sits over top of the lower unit.

1.4.4.2.3 Slumping

Slumping has occurred either during the eruptions or afterwards. The large blocks comprising of the Big Hogback and Little Hogback suggest that slumping occurred during the eruption as slumping is frequent on the inside of the vents during the eruption (Wohletz et al., 1983). The hogbacks are also very large which would make it unlikely that the lake's wave action moved them. The other smaller tuff blocks are much more likely the product of lake erosion. The abundance of differing dip directions in the smaller blocks situated next to one another shows that it could not be a primary deposition feature. Undercutting from wave action could have caused the slumping. Slump blocks are commonly covered in tufa on all vertical surfaces, showing that these were separated from the edifice for a time. Therefore, the slumping must have occurred due to erosion from wave action from Lake Lahontan, as the surface around the slump blocks would be filled with tuff during an eruption. The slump blocks with drastic differences in dip angle to one another also support that these blocks are boulders moved by Lake Lahontan action (Figure 44). It is probably that wave action that eroded away most of the upper unit at Upsal Hogback.

Figure 44: The regions circled in red are the areas with the most slumping at Upsal Hogback. The photograph is from the USDA (2010).

The outcrops in the lower units of the smaller vents of the southern complex described above show steeply dipping lapilli tuff that is deposited on flat lying lapilli tuff (Figure 19). The lapilli tuff dips in both east and west overtop the flat lying ash tuff. Frequently in the lower unit, steeply dipping tuff is seen on the outside edge of a generally flat lying lapilli tuff outcrop. It is possible that the steeply dipping lapilli tuff was plastered on the underlying tuff after being blasted from the vent, maybe even when another vent erupted. But the more likely possibility is that wave action from Lake Lahontan undercut the lapilli deposit that then broke off the edge of the vent and now overlies the rest of the lapilli tuff.

1.4.4.2.4 Shoreline deposits

Shoreline deposits occur frequently around the edifice at Upsal Hogback. These deposits are from the lake as they follow the topological contour of the edifice, representing lacustrine deposits of rock and sediment left by the wave action of the lake on the edifice. The cross cutting shoreline deposits seen on the west side of the edifice between the north and south complexes (Figure 39). This shows that lake levels have varied significantly since the formation of the Upsal Hogback edifice.

1.4.4.2.5 Mud cracks

The mud cracks seen in the upper edifice of the north complex are the product of reworking due to Lake Lahontan. It is possible that this was a product of reworking and erosion, as it is very fine grained, compared to being a wet ash layer that was desiccated.

It could be potential reworking on an exposed ledge after rain and desiccation in the Carson Sink. This could have occurred during any time during Lake Lahontan history, though it seems to be along a continuous layer. The layer is also orange in color showing palagonitization, but this could be because the individual particles were palagonitized before reworking.

1.4.4.3 Timing of Eruption

The lower unit of Upsal Hogback is evidence that Lake Lahontan most likely was present during the eruptions since there is a lack of palagonitization proving that the eruption was subaqueous, and that the lake was not in a desiccation phase. Using the ages of the dated tufa that is 11.1 ka and that Upsal Hogback lies above the Wono ash bed dated at 25 ka (Benson et al., 1992; Fultz et al., 1983), the eruptions must have occurred between those two dates. The elevation of the GPS station at Upsal Hogback is 1230 m (4035.4 ft) above sea level (asl), which is lower than some other portions of the upper edifice (Blewitt et al., 2009). Morrison (1964) (Figure 45) describes three highstands in during Seho time. Rhode et al. (2000) postulates that highstands for Lake Lahontan occurred around 10.5 ka at 1235 m asl, which may have completely covered the edifice, while Morrison (1964) has a highstand after that at 1277.1 m. Rhode et al. (2000) lake level estimations do not go very far back in time, but they postulate a lake level highstand at 12 ka. Between the two highstands, the low stand is a complete desiccation, so the eruption at Upsal Hogback likely occurred either during the lake level lowering or when the lake levels began to rise again, placing the eruptions between 10.5 and 12 ka, though the tufa dated is at 11.1 ka. Morrison (1964) has a drop in lake level during Thinolite

Figure 45: Lake levels of Lake Lahontan through time (Morrison, 1964; Rhodes et al., 2000). Altitude of GPS station from Blewitt et al. (2009) at Upsal hogback is demarcated in red.

recession time, which Rhode et al. (2000) date at 15-18 ka, to well below 1230 m asl. It is possible that the eruptions occurred before this time as the lake levels were dropping, or after this while the lake levels were rising again. This estimates the timing of eruptions between 15 and 18 ka. Until further constraints are made on dating highstands of Lake Lahontan, the eruptions can only be hypothesized to occur either between 11-18 ka.

1.4.5 Map

The updated geomorphological map (Figure 46) of the Upsal Hogback area has several different units mapped:

Sand- This unit is the eolian sand forming dunes that cover most of the Carson Sink.

Lapilli over sand- This unit is characterized by the eroded basaltic lapilli remnants that are deposited on the surface of the sand or remnants of eolian deposits as sand is winnowed out compared to the denser basalt lapilli. These clasts have been eroded from the Upsal Hogback edifice, and give the sand a darker color that is readily observed in the aerial photographs.

Lower Unit- As described above, the lower unit is the lower parts of the edifice, characterized by indurated ash and lapilli tuffs with abundant basaltic bombs. It has occurrences of palagonitization.

Upper Unit- The upper unit, as described above, is primarily indurated lapilli tuff with abundant plagioclase and olivine phyric basaltic bombs. The upper unit is characterized by its pervasive palagonitization throughout the unit.

Figure 46: Updated geomorphological map of Upsal Hogback in the Carson Sink.

Reworked edifice- This unit represents the area of the edifice that has no outcropping of either the lower or upper unit, where sand from the Carson Sink and reworked eroded remnants of the edifice cover the Upsal Hogback.

The map differs from the map by Morrison (1964) in many ways. The number of vents is reduced from 5 to 4, eliminating the vents from west of the north complex and dividing the northern vent of the south complex into two vents. The units differ because this is a geomorphological map, so the Wyemaha and Sehoo Formations are grouped together as sand. The lapilli that overlie the sand were marked as such. The edifice is broken up into the parts where outcrops occur into the palagonitized upper unit and unpalagonitized lower unit, and the rest mapped as reworked edifice.

1.4.6 Risk to Fallon

In Fallon, there is the nearby Naval Air Force Base, with the prestigious Top Gun Training Facility. This would make another eruption very disastrous and costly. The tectonic setting of the area around Fallon could lead to further magmatism in the future. The shearing in the Walker Lane, extension in the Great Basin, as well as lithospheric thinning in the Humboldt Lineament that led to the magmatism of Upsal Hogback, are still in effect. It is unlikely that Upsal Hogback would erupt again, as tuff cones are considered monogenetic (Wohletz et al., 1983). Soda Lakes is also very young, possibly less than 6 ka (Cousens et al, 2012), which means the area is still active and that the Quaternary magmatic centers do not overlap. There is also geothermal activity in the

area, though it may be associated with extensional faults in the Great Basin like other nearby geothermal fields in Nevada (Faulds et al., 2006).

Another eruption in the Carson Sink would be unlikely to produce a tuff cone similar to Upsal Hogback, since Lake Lahontan has dried up, leaving the Carson Sink as a desert. Therefore the eruptive style would be dependent on the amount of groundwater involved in an eruption. With little groundwater, potential magmatism would form a cinder cone. It is more likely to have an eruptive style closer to a tuff ring or a maar, like Soda Lakes, if there is abundant groundwater present. The geothermal activity in the area indicates that there is still ample groundwater in some areas of the Carson Sink.

An eruption in the Carson Sink would have serious ramifications for the area around Fallon. Overall, an eruption would put people in danger, especially in the city of Fallon. It would also have potential to disrupt the local economy. An ash plume from an explosive eruption like a tuff ring or cone would be disastrous to the Naval Air Force Base, putting the Top Gun Training Facility in the danger zone, and costly equipment could be damaged by the ash. An ash plume would also affect air traffic in the southwestern United States, which could have serious consequences to the economy. The city of Fallon itself would also be affected both infrastructure impacts of lapilli and ash falls, and medical effects to the local population.

1.5 Conclusions

The field characteristics of Upsal Hogback demonstrate that the volcano is a tuff cone. Upsal Hogback has the characteristic palagonitized upper edifice and lower unpalagonitized edifice, due to emplacement that was at first subaqueous and as the edifice was built up, breached the water air surface and began to be emplaced subaerially. The evidence of subaerial eruption is abundant bomb sags and armored lapilli. Due to extensive erosion from Lake Lahontan, the volcano now has an edifice morphology similar to a tuff ring, leading to the past interpretations that it was a tuff ring.

The difference in morphology between the three volcanic centers in the Carson Sink can be attributed to differing lake levels during the history of Lake Lahontan. The explosive eruption at Soda Lakes indicates that there was groundwater interacting in the system leading to an increase in fragmentation of the magma. Rattlesnake Hill has the least amount of water-magma interaction, as a spatter cone. Upsal Hogback has the most water/melt interaction on the phreatomagmatic spectrum. There is more water-magma interaction than Rattlesnake Hill and Soda Lakes. This can be seen through the amount of fragmentation seen in between the three volcanoes: lapilli (Upsal Hogback), ash (Soda Lakes), and spatter (Rattlesnake Hill). Any further eruption in the Carson Sink would depend on the amount of groundwater, and could produce a tuff ring or a cinder cone.

2 Chapter: Geochemistry of Upsal Hogback, Fallon, Nevada, USA

2.1 Introduction

Upsal Hogback, a Quaternary phreatomagmatic volcanic center located 18 km north of the city of Fallon, Nevada (Figure 47), derives its name from its massive, steeply dipping block of lapilli tuff located at the southern edge of the structure. It consists of several proposed volcanic vents with low topographical relief. These vents can be divided into the north complex, consisting of one vent, and the south complex, made up of three vents. The volcano can also be divided into the lower edifice and the upper edifice. The major difference between the two is that the upper edifice is heavily palagonitized, and the lower edifice has no palagonitization. Two other major volcanic centers neighbor Upsal Hogback: the 1 Ma Rattlesnake Hill center (Shevenell et al, 2005) and the Holocene Soda Lakes complex that includes Soda Lake and Little Soda Lake. A producing geothermal field is associated with area surrounding Soda Lakes (Olmsted et al., 1986).

Little characterization has been made of the volcanological or geochemical signature(s) of Upsal Hogback. Understanding the volcanological history of the volcano is complicated by possible modification of the structure by glacial Lake Lahontan. The proximity of three young volcanoes to the town of Fallon, and the nearby naval air station, constitutes a volcanic hazard that requires evaluation. Identifying the source of magma for this young volcano is an important factor in understanding the tectonic setting of volcanic activity in the Fallon region.

Figure 47: Upsal Hogback (circled in red) north of the city of Fallon in Nevada, USA. Soda Lakes and Rattlesnake Hill are circled in yellow. Photo is from Google Maps (2012) and TerraMetrics (2012).

The project's goals are to: 1) characterize the geochemical signature(s) of Upsal Hogback, 2) compare the geochemical signatures between the north and the south complex, 3) identify the source of magma, and 4) compare the geochemistry at Upsal Hogback to other volcanic centers in the area.

2.2 Geological Setting

Upsal Hogback is located within the southern Carson Sink, a major fault-bounded valley defined by the Stillwater Range to the east, the Humboldt and Truckee Ranges to the northwest, and the Sierra Nevada to the west. The Carson Sink is located at the confluence of several tectonic trends. The Carson Sink is on the boundary between the extension in the Great Basin and the Sierra Nevada block, a region characterized by thinning of the crust due to shearing from accommodation of the rotating Sierra Nevada block (Unruh et al., 2003). The extension in the Great Basin caused by accommodation of movement of the Pacific block relative to the Sierra Nevada block has also led to volcanism in Nevada (Colgan and Henry, 2009; Cousens et al., 2012). According to Faulds and Henry (2008), the Walker Lane is a northwestern trending zone of dextral shear that crosses the Carson Sink. The Carson Block of the Walker Lane, where Upsal Hogback is situated, includes northeast trending sinistral faults. The Walker Lane accommodates the movement of the Sierra Nevada relative to the movement of the Great Basin and has localized lithospheric thinning (Faulds and Henry, 2008; Unruh et al., 2003). Also, the Humboldt Lineament cross cuts the Carson Sink. It is a northeastern trending zone of lithospheric thinning (Louie et al., 2004), high heat flow, and northeast trending faults (Faulds and Henry, 2008).

Upsal Hogback is situated in the Carson Sink. Other than the volcanic centers of Soda Lakes and Rattlesnake Hill described below, the Carson Sink is primarily a sedimentary basin. Morrison (1964) did a comprehensive study of the southern part of the Carson Sink near Fallon. The ages of the local volcanic rocks range from Tertiary to Quaternary. The oldest Tertiary rocks are the basaltic and dacitic rocks of Rainbow Mountain. After this volcanism came rhyolitic and dacitic volcanism of the Eagle House. Afterwards volcanism in the Truckee area occurred, described further below, and sedimentation in the Carson Sink occurred during this time. Some of the sedimentation is described as tuffaceous leading Morrison (1964) to believe volcanism continued until late Truckee time. One hundred and twenty-two meters of mafic and andesitic lava were deposited forming the early Bunejug Formation, that later became composed of olivine basalts. Extensive faulting also occurred during this time. Sedimentation was dominant during the Quaternary in the Carson Sink. Most of the formations deposited consist of lacustrine and eolian sediments. Morrison (1964) states that some of the Quaternary sediments could be up to 305 m thick in certain areas. Uplift occurred in the Carson Sink during the early Pleistocene as well as faulting.

The Carson Sink was one of the basins comprising glacial Lake Lahontan during the Pleistocene. According to a study by Benson and Thomson (1987), Carson Sink was first inundated between 45 and 50 ka, when the nearby Walker Lake spilled over. By 20 ka, the lake level was at 1265 m above sea level (asl). The highest stand in of Lake Lahontan occurred at 13.5 ka at 1330 m asl. A thousand years later, desiccation caused

lake levels to be at a high of 1230 m asl. During the highest stands, Lake Lahontan covered most of northwestern Nevada. A side effect of the presence of Lake Lahontan was tufa precipitation, which is a carbonate precipitate. It is observed on Upsal Hogback, all the way to the top of its edifice. It is also seen on neighboring volcanic center, Rattlesnake Hill, and is found as a deposit on many of the Tertiary volcanic rocks outcrops surrounding the Carson Sink. Upsal Hogback has been heavily modified due to wave action by Lake Lahontan, leading to shoreline deposits and wave cut terraces.

Soda Lakes is a neighboring volcanic center to the southwest of Upsal Hogback. It consists of Soda Lake and Little Soda Lake to the southeast of it. These are considered to be maars that are <6000 years old (Cousens et al., 2012). They consist of unindurated lapilli and ash tephra that are trachybasaltic in composition (Zak, 2013). Tufa has not been precipitated onto its edifice. In contrast, Rattlesnake Hill is a volcanic neck to the southeast of Upsal Hogback, near the heart of the city of Fallon. The ~1 Ma (Shevenell et al., 2005) volcanic center is also basaltic trachyandesitic (Zac, 2013; Cousens et al., 2012) and is composed of blocky gray lavas and red volcanic spatter. Tufa has been deposited all the way to the top of the edifice.

Olmsted et al. (1986) note that Upsal Hogback has a geothermal area associated with it, north of the edifice (Figure 48). The high surface thermal gradient is caused by the albedo from eroded lapilli fragments from the edifice. A deeper geothermal area below the surface geothermal high, north of the edifices of Upsal Hogback and

Figure 48: Geothermally active areas near Fallon, Nevada, from Olmsted et al. (1986), with Upsal Hogback and Soda Lakes circled in red.

Soda Lakes, is from lateral flow from the nearby Soda Lakes geothermal area according to Olmsted et al. (1984). Soda Lakes has a stronger geothermal gradient than what is found at the Upsal Hogback geothermal area and comes from convective upflow and shallow lateral flow along faults. There are active geothermal plants at Soda Lakes, at Steamboat Hills west of Fallon, and at Stillwater east of Fallon. The numerous geothermal plants reflect the high heat flow around the Carson Sink and Upsal Hogback.

West of Upsal Hogback in the northern Sierra Nevada is the Lake Tahoe and Reno region which has young volcanism for the area from 28 to 1 Ma (Cousens et al., 2008). These volcanic rocks are part of the Ancestral Cascade arc, which stretches from British Columbia, Canada, to California and Nevada, USA. The Ancestral Cascades arc volcanism around Lake Tahoe consist of lava flows, debris flows, and collapsed lava domes that are basaltic to dacitic in composition. The source of magmatism is melting lithosphere mantle as well as fluids coming from a subducting slab driving melting of the mantle wedge.

The younger rocks in the Lake Tahoe and Truckee River area studied by Cousens et al. (2011) represent post arc volcanism from 2.6 to 0.92 Ma (Figure 49). They include intermediate to mafic, mildly alkaline lavas. Cinder cones, lava flows, and pillow lavas form the Tahoe-Truckee volcanic field (TTVF). One volcanic center in the TTVF is the Skylandia Beach tuff ring. The northeastern part of the TTVF is situated on the Carson Range, and is composed of lavas of 3.15 to 1.43 Ma age. They represent a transition from the volcanism from Ancestral Cascade arc to the post-arc volcanism of the TTVF. The

Figure 49: Map of Western Nevada, showing the locations of the TTVF, the ACA in purple, McClennan Peak Basalts, and the volcanism in the Carson Sink., while the BVF is in the yellow box in the inset (Cousens et al., 2012).

source of magma for the post arc volcanism is asthenospheric upwelling from a slab window at the trailing edge of the subducting Juan de Fuca plate that drives lithospheric mantle melting.

Another nearby volcanic field of note is the Buffalo Valley Volcanic Field (BVF) that is north east of the Carson Sink near the city of Battle Mountain. Summarized in Cousens et al. (2012), the BVF is composed of 3.3 to 0.95 Ma lava flows and spatter cones nestled along the southern edge of Battle Mountain and the northeastern part of the Fish Creek Mountains.

Another nearby volcanic center is the McClellan Peak Basalt, east of Carson City, dated at 1.2 to 1.4 Ma (Cousens et al., 2012). The McClellan Peak olivine basalts flows issued from McClellan Peak itself as well as a cinder cone in the Carson Range (Thomson, 1959; Cousens et al., 2012). These basalts are vesicular and have olivine, plagioclase, and clinopyroxene phenocrysts.

2.2.1 Age of Upsal Hogback

Upsal Hogback's age is difficult to constrain since it is too young to date by radiogenic isotope techniques. Shevenell et al. (2005) dated a sample of a volcanic bomb using ^{40}Ar - ^{39}Ar at 0.60 +/- 0.09 Ma (total fusion age) but with no plateau or isochron, and is thus unreliable. Olmsted et al. (1984) have found that the deposits from Upsal Hogback "intertongue" with the Wyemaha Formation, and they conclude that the eruptions took place between 30,000 and 40,000 years ago. The volcano does lie above the Wono Ash

bed, which is dated at 25,000 years (Fultz et al., 1983). Tufa precipitated from Lake Lahontan waters on the edifice has been dated by ^{14}C at 11,100 $\pm$ 100 and 8,600 $\pm$ 200 years BP (Benson et al., 1992; Broecker and Kaufman, 1965). These ages give us an estimated age interval between 25,000 and 11,100 years old for the eruptions of Upsal Hogback. Comparing lake level intervals from Morrison (1964) and Rhodes et al. (2000) the age of Upsal Hogback could be further constrained between 15 and 11 ka.

2.3 Methods

2.3.1 Major and Trace Element Geochemistry

Eighteen bomb samples from Upsal Hogback (Figure 50) were cut and powdered. Weathered surfaces were cut off using rock saws and discarded, the remainder was broken down to -3mm with a Chipmunk crusher, and powdered to -200 mesh in a Cr-steel ring mill. Major elements geochemistry was analyzed by fused-disc x-ray fluorescence (XRF) spectrometry at the Ontario Geological Survey (OGS), Sudbury, Ontario. The samples were also analyzed for trace element geochemistry by acid digestion for inductively coupled plasma mass spectrometry (ICP-MS) at the OGS.

The eighteen bomb samples can be divided geographically into samples from the north complex and the south complex. The samples from the south complex are 12-UH-01, 12-UH-02, 12-UH-03, 12-UH-04, 12-UH-05, 12-UH-07, 12-UH-08, 12-UH-10, 12-UH-13, 12-UH-18, and 12-UH-22. The samples from the north complex are 12-UH-24, 12-UH-26, 12-UH-28, 12-UH-29, 12-UH-33, 12-UH-37 and 12-UH-43.

Figure 50: Bomb sample localities for geochemistry at Upsal Hogback. The photograph is from the USDA (2010).

2.3.2 Isotope Geochemistry

All radiogenic isotope analysis were prepared and analyzed at Carleton University. Isotopes of lead (Pb), strontium (Sr), and neodymium (Nd) were analyzed using a Thermo-Finigan Triton T1 thermal ionization mass spectrometer. Six samples of powdered bombs were chosen from either the north or the southern complex. The samples from the south complex are 12-UH-03, 12-UH-13, and 12-UH-32. The samples from the north complex are 12-UH-28, 12-UH-29, and 12-UH-37. Two samples, 12-UH-03 and 12-UH-28, come from the palagonitized upper edifice.

Two hundred mg of powdered bomb samples were dissolved in 2 to 3 mL of HF in Teflon screw cap beakers, and put on a hot plate for at least two days and up to a week until fully dissolved in the HF. An hour into the heating process, the vial was unscrewed in order to let accumulated gas escape. After the powder was dissolved, the cap was removed from the beaker and the solution dried down to a moist paste. 1 mL of 7N HNO₃ was added, and the solution was dried again to a moist paste. Then 2 mL of 6N HCl was added and the beaker capped overnight on the hotplate. This was then completely dried down, and 3 ml of 1N HBr was added to the dry residue. The beaker was capped again and left overnight, in preparation for Pb extraction chemistry.

For the first pass through Pb columns, polyethylene columns used in the extraction were rinsed with ultra-pure H₂O. Then 0.6 mL of AG1-X8 anion resin was added to the columns. The sides of the columns were washed down with ultra-pure H₂O in order for the resin to settle to the bottom. The resin was then washed twice with 2 mL

of 6N HCl, once with 0.5 mL of H₂O, and twice with 2 mL of 1N HBr. The sample was then added to the columns. Two washes with 2 mL of 1N HBr were done and collected in the 15 ml beakers for the Sr and Nd extractions. These were set on the hot plate to dry down. The columns were then washed with 0.5 mL of 1.5N HCl. A clean Teflon snap cap collection beaker for the Pb collection was placed under the columns to catch the next 5 mL of 6N HCl. The resin was then discarded, the columns rinsed, and stored.

For the second pass of for the Pb extraction, the columns were again rinsed with ultra-pure H₂O and 0.2 mL of the resin was added to each. The sides were rinsed with ultra-pure H₂O and the resin settled at the bottom. The resin were then rinsed twice with 2 mL of 6N HCl, once with 0.5 mL of H₂O, and then twice with 1 mL of 1N HBr. The samples were then added to the columns. The beakers that held the samples were cleaned with H₂O, 1 mL of 6N HCl was added and the beaker left on the hot plate for ten minutes. The HCl was discarded, and the beaker cleaned with H₂O again. Twice, 1 mL of 1N HBr was run through the resin. Then 0.2 mL of 1.5N HCl was run through the columns. The sample collection Teflon snap cap beakers were placed under the columns while 3 mL of 6N HCl was run through the resin to strip the Pb. These were then dried down on the hot plate, after which 0.5 mL of HNO₃ was added and dried down again. The samples were then ready for Pb mass spectrometry.

In lead mass spectrometry, samples were dissolved in 4 µl of H₃PO₄, half of that was loaded with 3 µl of silica gel onto a rhenium filament. The sample was dried down using 1.1 to 2.1 mA of current, loaded onto the sample wheel, and then run on the mass

spectrometer. The runs were corrected for fractionation using NIST SRM981 where the correction is +0.13%/amu, according to the procedure outlined in Cousens et al. (2008). The measured ratios for SRM981 averaged $^{206}\text{Pb}/^{204}\text{Pb} = 16.980 \pm 0.012$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.429 \pm 0.014$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.502 \pm 0.048$.

Following the Pb extraction, Sr extraction was the next step. The beakers that collected the Sr and Nd from the Pb extraction were dried down on the hot plate and then 1 mL of 1N HBr was added and the beakers left overnight on the hot plate. This solution was then dried down, and a drop of 7N HNO_3 was added. This caused effervescence and loss of Br gas, and once the sample was completely degassed 0.5 mL of 7N HNO_3 was added. The solution was again dried down, and 1.5 to 2 mL of 2.5N HCl was added. After dissolving overnight, the samples were centrifuged in case there was anything left undissolved. The used screw cap beakers were rinsed with ultra-pure H_2O and 1 mL of 6N HCl was added, the beakers were capped, then set on the hotplate. The solution was then pipetted into columns with Dowex 50-X8 Cation Resin. The sides of the columns were then washed with 1 mL of 2.5 N HCl. Afterwards, 18 mL of 2.5 N HCl was run through the columns and discarded. Another 6 mL was added to elute Sr, collected into snap cap beakers. These Sr beakers were set to dry on the hot plate and samples were ready for the mass spectrometry lab. In order to collect the REEs, 3.5 mL of 6N HCl was run through the columns. The screw cap beakers were emptied of HCl, and rinsed again with ultra-pure H_2O . Then 9 mL of 6N HCl was run through the columns and collected in the beakers, eluting the REE.

For the mass spectrometry, the dry residue collected from the Sr column procedure was dissolved in 4 μl of 0.3 N H_3PO_4 . Half of this was loaded onto a single tantalum filament and dried down using 1.1 to 2.1 mA of current. The filaments were then loaded onto the sample wheel and loaded onto the mass spectrometer for analysis. The procedure outlined in Cousens et al. (2008) stipulates that the isotope ratios are normalized to $^{86}\text{Sr}/^{87}\text{Sr} = 0.11940$ and that two standards are used. NIST SR987 has the $^{86}\text{Sr}/^{87}\text{Sr}$ ratio of 0.710251 ± 18 , and the other standard, Eimer and Amend SrCO_3 , has the ratio of 0.708037 ± 30 .

Nd extraction was the last process for the samples. Half a milliliter of 0.26N HCl was added to the screw cap beakers containing the bulk REE, and left at room temperature for thirty minutes. The Eichrom columns were uncapped and the acid drained. The samples were then pipetted into the columns. Half a milliliter of 0.26N HCl was added to the columns a total of 13 times as a washing stage. A snap cap beaker was then placed under the columns. To elute Nd, 4.5 mL of 0.26N HCl was run through the columns and collected. The Nd beakers were then placed on the hot plate to dry down.

These samples were then prepared for mass spectrometry by adding 4 μl of 0.3 N H_3PO_4 to the residue, and half of this was loaded onto a double rhenium filament. Between 1.1 and 2.1 mA of current was used to dry down the sample, and then loaded onto the wheel to be put in the mass spectrometer. The Carleton lab normalizes the Nd ratios to $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$. One of the standards used is from the U.S. Geological

survey (BCR-1), and has a $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.512668 ± 20 (n=4). The other, the La Jolla standard, had $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of 0.511877 ± 18 .

One tufa sample was also analyzed in order to estimate strontium values in Lake Lahontan waters. The method for dissolution was different for the carbonate sample. The tufa was analyzed twice with two different methods. One was to ascertain its Sr and Nd isotopic composition, and the second to calculate the amount of Sr.

A large piece of tufa was lightly crushed by an agate mortar and pestle. A small piece was weighed, and then immersed in acetic acid in order to dissolve just the carbonate fraction of the tufa. The acid solution was pipetted off the top to avoid particulate contamination. The solution was put into another Teflon beaker, dried down, and then redissolved in 2.5 M HCl (1.5 ml). The sample was then run through Sr and Nd columns through the same process as the bomb samples above, as well as the same mass spectrometer analysis.

A second sample of tufa was needed in order to calculate the concentration of Sr and Nd, so another piece of tufa was taken from the original tufa sample. This second tufa sample was weighed and then dissolved into acetic acid for a day. The solution was pipette off and centrifuged in order to eliminate any particulates. What was left in the beaker was dried down and weighed, the difference between the original weight and this weight being the weight of the dissolve tufa sample. The centrifuged solution was then transferred to another Teflon beaker, and spiked with 0.19528 g of Sr spike and 0.09771

g of Nd spike. These spikes are artificially enriched in one isotope allowing us to calculate the concentration of those elements in the original tufa sample. This sample was run through the columns and mass spectrometer the same way as the other tufa sample above, except the runs were not normalized.

2.3.3 Microprobe Analysis

Electron microprobe analysis was performed on polished thin sections using the Camebax MXB at Carleton University. It is equipped with 4 Wavelength Dispersive X-ray Spectrometry (WDS) analysers, Henderson automation system, Kevex Energy Dispersive X-ray Spectrometry (EDS), Macintosh Power PC computer, Aptec FP6300B spectrometry amplifier, HV power supply and a liquid nitrogen sensor (P. Jones, personal communication). The electron microprobe determines the major element oxides of a mineral by exciting the element using an electron beam, causing the element to jump atomic orbitals and release an x-ray. An EDS analyzer is used to convert the x-rays into electronic pulses to be analyzed to give a qualitative analysis of the concentration of the oxide in the mineral (Oxford Instruments Analytical, 1) in order to identify the type of mineral. Then the WDS is used to quantify the concentration of the oxide at a much higher resolution (Oxford Instruments Analytical, 2). The error on the analysis is 1-2% for major elements that are above 10 wt%, 3-10% for elements less than 10 wt% (P. Jones, personal communication). The operating conditions was an electron beam current of 20 nA with 20kV accelerating potential. Back scattered electron (BSE) images were taken using an Electron Optic Services system that uses a Lamont 4 element solid state BSE detector and BSE Quad Summing Amplifier. This system uses the 4Pi Analysis Inc.

digital imaging and the EDS while running NIH image and NIST desktop spectrum analyzer programs. Three bomb samples and four lapilli tuff samples (Figure 51) were analyzed on the microprobe. The focus of the microprobe analysis was to determine olivine and plagioclase phenocrysts compositions. The mineral analyses for the olivine and plagioclase phenocryst were then calculated into forsterite and anorthite content respectively according to the procedure outlined in Nesse (2000).

2.4 Results

2.4.1 Major Element Geochemistry

The major element geochemistry of all of the bomb samples is very similar. The two complexes have only subtle differences in the abundances of major elements. For example, the SiO_2 for the samples analyzed range from 46.65 to 47.82%. The north complex ranges from 46.65 to 47.05%, while the south complex ranges from 47.20 to 47.82% SiO_2 . All the samples plot as basalts on the TAS diagram, though the north complex has lower total alkalis (Figure 52). The basaltic bombs are alkalic, based on a plot Zr against P_2O_5 (Figure 53). The two complexes are distinguishable in this plot as the north complex has lower Zr and P_2O_5 , with the exception of 12-UH-03 from the south complex that has comparable P_2O_5 content but lower Zr than the other south complex samples.

The Upsal Hogback samples have a small range in Al_2O_3 from 15.30% to 16.72% (Figure 54). The north complex samples range from 15.30 to 15.97%, whereas the south complex ranges from 16.01 to 16.72%. Significant variations are seen in MgO content, as

Figure 51: Tuff sample localities at Upsal Hogback. The photograph is from the USDA (2010).

Figure 52: Discrimination diagram based on LeBas et al. (1986) showing that both the north and south complexes are basaltic.

Figure 53: Discrimination diagram for alkalic and tholeiitic basalts (Winchester and Floyd, 1976)

Figure 54: Al_2O_3 concentration is higher in south complex samples compared to the north complex.

The error represents a 1-sigma value.

the values range from 8.03 to 11.82% MgO (Figure 55). The north complex has higher values ranging from 10.61 to 11.82% MgO, and the south complex ranges from 8.03 to 9.65% MgO. There is even a slight variability in Fe_2O_3 , the samples range from 10.25 to 10.78% (Figure 56). The north complex has slightly higher Fe_2O_3 values (10.65 to 10.78%) than the south complex (10.25 to 10.51%). Thus, the south complex has lower Mg numbers (0.44 to 0.49) than the north complex (0.50 to 0.53). The Na_2O values of the samples are from 2.76 to 3.37% (Figure 57). The north complex samples have less Na_2O , and ranges from 2.76 to 2.98%. The south complex ranges from to 3.37% Na_2O . The CaO concentrations for the samples range from 9.30 to 10.50% (Figure 58). The north complex has lower CaO values that range from 9.30 to 9.91%. The south complex has values from 9.66 to 10.50%. The small differences continue for the amount of K_2O , where the north complex ranges from 0.89 to 1.01% and the south complex from 1.19 to 1.35% (Figure 59). The small differences are also seen in the TiO_2 contents, where the north complex ranges from 1.45 to 1.54% and the south complex was from 1.63 to 1.77% (Figure 60). The complexes differ in P_2O_5 contents (Figure 61), the north complex has values of P_2O_5 that range from 0.364 to 0.417%, and the south complex ranges from 0.457 to 0.495%. The complexes only have significant overlap in major element geochemistry more in MnO, where both range from 0.167 to 0.174%.

On Harker diagrams plotting major elements versus SiO_2 content, a distinction between the north and south complexes can be seen. With increasing SiO_2 , the samples from Upsal Hogback show a significant drop in MgO content (Figure 55), an increase in Al_2O_3 (Figure 54), and an increase in TiO_2 (Figure 60). Both complexes show a decrease

Figure 55: The south complex has less MgO than the north complex. The error represents the 1-sigma.

Figure 56: Fe₂O₃ concentrations versus SiO₂. The error represents the 1-sigma on the analyses.

Figure 57: Na₂O content is higher in the south complex compared to the north complex. The error is the 1-sigma of the analyses.

Figure 58: CaO is slightly higher in the south complex compared to the north complex. The error is the 1-sigma of the analyses.

Figure 59: The south complex is more enriched in K_2O than the north complex. The error is the 1-sigma of the analyses.

Figure 60: The south complex has higher TiO_2 content than the north complex. The error is the 1-sigma of the analyses.

Figure 61: P_2O_5 content is higher in the south complex over the north complex. The error represents the 1-sigma of the analyses.

in Fe_2O_3 with increasing SiO_2 (Figure 56). Overlap is also seen between the amount of Na_2O between the north and south complex (Figure 57), though it does increase with increase in SiO_2 . CaO content for the north complex increases slightly with increasing SiO_2 content, while the opposite occurs with the south complex, the CaO content decreases (Figure 58). There is some overlap between CaO and SiO_2 contents in both complexes. Both the north and south complexes has a small positive slope in K_2O content with increasing SiO_2 content (Figure 59). The P_2O_5 concentrations of the north and south complex remain steady with increasing SiO_2 concentrations (Figure 61).

When plotting the Mg number versus the $\text{CaO}/\text{Al}_2\text{O}_3$ ratio (Figure 62), it shows that a major crystallizing phase is olivine, as only the Mg number is being depleted, while the $\text{CaO}/\text{Al}_2\text{O}_3$ remains constant. This means that clinopyroxene is not a major crystallizing phase as there is no change in $\text{CaO}/\text{Al}_2\text{O}_3$. It is also possible that anorthite is crystallizing, as the ratio of $\text{CaO}/\text{Al}_2\text{O}_3$ would stay the same versus Mg number during crystallization of anorthite.

2.4.2 Trace Element Geochemistry

Trace element geochemistry shows the same trends observed in the major element geochemistry: the basalts from the north complex and the south complex have similar concentrations of trace elements, but have small differences between the two areas. Harker diagrams show that the south complex is more enriched in Ba, Sr, Rb and Zr than the north complex (Figure 63, Figure 64, Figure 65, and Figure 66). The south complex samples are less enriched in Cr and Ni, and only slightly less enriched in Sc than the

Figure 62: Mg# versus CaO/Al₂O₃ for Upsal Hogback samples.

Figure 63: The south complex is more enriched in Ba than the north complex. The error is the 1-sigma of the analyses.

Figure 64: Sr shows more variability but is more enriched overall in the south complex compared to the north complex. The error is the 1-sigma of the analyses.

Figure 65: Rb is more enriched in the south complex than the north complex. The error represents the 1-sigma of the analyses.

Figure 66: Zr is less enriched in the north complex compared to the south complex. The error is the 1-sigma of the analyses.

Figure 67: The south complex is less enriched in Cr than the north complex. The error is the 1-sigma of the analyses.

Figure 68: Ni is more enriched in the north complex compared to the south complex. The error is the 1-sigma of the analyses.

Figure 69: Sc is slightly less enriched in the south complex compared to the north complex. The error represents the 1-sigma of the analyses.

Figure 70: V concentration is the same for both the north and south complex. The error is the 1-sigma of the analyses.

north complex (Figure 67, Figure 68, and Figure 69). The north and south complexes have similar V values (Figure 70).

Compatible elements like Cr, Ni and Sc are more enriched in the north complex than the south. There is some overlap in concentration seen in Sc for the two complexes, but overall the south complex is less enriched. The lower amounts of Sc could reflect that some clinopyroxene is crystallizing since it partitions into the crystal structure. Sr is lower in the north complex than the south complex, though there are some anomalously large concentrations in some south complex samples. The higher strontium values would suggest that plagioclase was not crystallizing in during the magma evolution of the south complex and that Sr is behaving incompatibly. The compatible element V is relatively the same between the north and south complex.

The Large Ion Lithophile Elements (LILE) also display geochemical variations between the north and south complex. LILE like Cs, Rb, and Ba are more enriched in the south complex than the north complex. The range in Cs concentrations overlap between the two complexes, but the south has higher concentrations. High Field Strength Elements (HFSE) like Y, Th, Pb, Zr and are less enriched in the north complex than the south complex. The HFSE U concentrations are lower overall in the north complex, but a few anomalously high concentrations in samples from both complexes.

The Rare Earth Elements (REE), which behave as incompatible elements, are more enriched in the south complex than the north complex. The south shows a higher

concentration in REE like Nd, Eu, and Ho than the north complex. The south is more enriched in Light Rare Earth Elements (LREE) than Heavy Rare Earth Elements (HREE) compared to the north complex. There is a 30% difference in the highest concentrated LREE, La, concentration in the south complex compared to the lowest La concentration in the north complex. The percent difference in the HREE, Yb, is only 16% for the south complex compared to the north complex.

Sample 12-UH-03, differs from the rest of the samples in the south complex as well as the samples in the north complex. It has lower Ba, Ga, Mo, Nd, Rb, Sc, Sm, Tb, Y, and Zr than usual in the south complex. It has higher strontium than the other samples, perhaps due to tufa precipitating in small fractures in the bomb, causing contamination. It is also commonly has the smallest amount of trace elements of the south complex samples. This trend is not seen in the major element concentrations. 12-UH-10 also sometimes has lower than usual trace element concentrations for the south complex, especially seen in Nb, Mo, and La. It usually has higher concentrations than 12-UH-03.

A trace element normalized incompatible elements plot shows that the north complex and the south complex have very similar geochemical signatures, and that the south complex is more enriched in the incompatible elements (Figure 71). The REE patterns for both north and south complexes are very similar (Figure 72). Upsal Hogback basalts are enriched in LREE compared to HREE. The south complex is more enriched in

Figure 71: Normalized incompatible element plot of the north and south complex, normalized to primitive mantle (Sun and McDonough, 1989).

Figure 72: Normalized incompatible element plot focused on REE (Sun and McDonough, 1989).

LREE compared to the north complex. The concentrations of HREE are more enriched in the south complex compared to the north complex.

Some samples in the south complex show a slight negative Sr anomaly, while others show a positive Sr anomaly. The north complex does not have an anomaly in Sr. This range may reflect contamination by tufa, as it has a very high Sr content. There is a positive U anomaly in two samples, one from the northern complex (12-UH-08) and one from the southern complex (12-UH-28). This anomaly is most likely from uranium mobility during the weathering process. There is also a positive Pb anomaly present in both complexes, which also may be a weathering factor. They both also show a positive Cs anomaly, and a negative Th anomaly.

Sample 12-UH-43 has a different geochemical signature than the other bomb samples. Upon further inspection, the bomb sample is in fact a clast of Tertiary volcanic enveloped in lava from Upsal Hogback, leading to contamination of the bomb sample during crushing. This clast was a piece of wall rock picked up during the eruption. This analysis is not usable to characterize the geochemical signature of the magma from Upsal Hogback.

2.4.3 Isotope Geochemistry

All six samples show remarkably similar $^{144}\text{Nd}/^{143}\text{Nd}$ values, but a much larger spread in $^{87}\text{Sr}/^{86}\text{Sr}$. Overall, the $^{144}\text{Nd}/^{143}\text{Nd}$ ratios are between 0.51278 and 0.51284, and the average is 0.51280. The north complex is slightly more variable in $^{144}\text{Nd}/^{143}\text{Nd}$ than

the south complex, with values between 0.51279 and 0.51284, and the average is 0.51280. The south complex has a range from 0.51278 to 0.51280, with an average of 0.51279. The samples with from the palagonitized upper edifice have the ratios of 0.51279. The samples from the lower edifice have a range from 0.51278 to 0.51284, and the average is 0.51281.

The samples also show only a very small range in $^{206}\text{Pb}/^{204}\text{Pb}$ values from 18.89 to 18.93, where the average is 18.91. The south complex ranges from 18.89 to 18.90, and the average is 18.90. The north complex has slightly higher $^{206}\text{Pb}/^{204}\text{Pb}$ values from 18.90 to 18.93, with an average of 18.92. Two samples found in the upper edifice had the values of 18.88 and 18.93. The samples from the lower edifice ranged from 18.90 to 18.92, and the average is 18.91. The $^{207}\text{Pb}/^{204}\text{Pb}$ values for the six samples are also exhibit a very small range in values, from 15.59 to 15.61, and the average is 15.60. The $^{207}\text{Pb}/^{204}\text{Pb}$ values for the south complex are 15.59 to 15.61, and the average is 15.59. For the north complex they are 15.60 to 15.61, and the average is 15.60. The samples from the upper edifice have values of 15.59 and 15.61. The lower edifice has values from 15.59 to 15.60, and the average is 15.60.

There is more of a range seen in the $^{87}\text{Sr}/^{86}\text{Sr}$ values compared to the Nd and Pb. The $^{87}\text{Sr}/^{86}\text{Sr}$ values for the samples range from 0.7041 to 0.7050, and the average is 0.7045. The south complex has values from 0.7041 to 0.7050, and the average is 0.7045. The north complex has 0.7041 to 0.7049, and the average is 0.7046. The two samples

from the palagonitized upper edifice have values of 0.7050 and 0.7046. The lower unit samples have a range from 0.7041 to 0.7049, and the average is 0.7044.

2.4.4 Microprobe Analysis

2.4.4.1 Plagioclase

Overall, the plagioclase phenocrysts are calcium rich. Plagioclase phenocrysts have anorthite (An) contents between 50.6 and 90.7%, with an average of 76.9%. Microlites have An contents from 66.6 to 84.3%, with an average of 80.6%. The microprobe analyses did show that the phenocrysts were zoned, with a higher amount of sodium along their rims (Figure 73). The core of the normally zoned phenocrysts ranged from 81.91 to 90.75% An, with an average of 84.76% An. In the instances where the plagioclase showed more than just two zones under microprobe analysis, the zone between the core and rim was more sodic than the rim, and usually more sodic than the core (Figure 74). There are a few instances of reverse zoning, where the rims of the phenocrysts are less sodic than the core.

Samples from 12-UH-37 has two instances of reverse zoning, where the core is more sodium rich than the rim, with a large difference seen between them: the inner cores are 50.6-58.7% An, while the outside rims are 84.2-84.9% An. The reverse zoning is also seen in 12-UH-17, 12-UH-01, and 12-UH-34. In 12-UH-17, the An content of the core 78.1%, while the rim is 81.5%, exhibiting less of a range than 12-UH-37. 12-UH-01 the core is 57.6% An, while the rim is 66.9% An. Another phenocryst shows a larger range with the core being 59.5% An, the inside rim is 82.7%, and the outside rim is 82.7%. But

Figure 73: BSE photograph of zoned plagioclase phenocryst from Sample 12-UH-01.

Figure 74: BSE photograph of an alternating zoned plagioclase phenocryst next to zoned olivine phenocrysts.

another phenocryst from 12-UH-01 shows normal zoning, with the core exhibiting 90.74% An, inner zonation of 64.0 and 73.0%, and the rim is 80.0%. In one phenocryst in 12-UH-34 the An content in the core is 82.2%, and the rim is 83.0%. Another unusual phenocryst, shows an inner core with a very low An number of 65.5%, an inside rim with 83.0%, and an outside rim with 81.5% An. In addition to reverse zoned phenocrysts, 12-UH-34 also has a normally zoned phenocryst, displaying 84.7% An in the core, and 81.3% in the rim. The north complex has a slightly higher range in An contents than the south complex, but the south complex has one phenocryst that is much more calcium rich. The north complex has An contents from 50.6 to 84.9%, while the south complex has a range of 57.4 to 90.7% An (Figure 75). Dividing the samples into the upper part of the edifice and the lower part, the upper edifice has a range from 57.4 to 90.7% An. In the lower edifice, the An content ranges from 50.6 to 84.5% An (Figure 76). The ranges are similar, but the An content is slightly higher in the upper edifice. If the division is done to the samples on type, whether bomb or lapilli tuffs, the ranges are smaller for the lapilli samples. The bomb samples range from 50.6 to 90.8% An (Figure 77). The lapilli samples range from 61.6 to 84.7%.

Plagioclase microlites in the bomb samples are very similar to the plagioclase phenocrysts, with An contents between 66.6 and 84.3%. In the north complex, the microlites have An contents from 80.3 to 84.3% An. In the south complex the microlites have 66.6 to 83.1% An. One microlite in 12-UH-17, in the south complex, has lower An than the others, with only 66.6% An, and is 9.9% Or. Plagioclase found in the groundmass of sample 12-UH-39 is 33.6 to 48.5% An, and Or contents of 21.9 to 24.8%.

Figure 75: Mineral content in phenocrysts between the north and south complex of the Upsal Hogback edifice.

Figure 76: Mineral content of phenocryst between the upper and lower unit.

Figure 77: Mineral content of phenocrysts comparing bomb samples to tuff samples.

Dividing the samples into upper and lower edifice, the upper edifice has a range from 74.0 to 83.1% An. The lower edifice ranges from 66.6 to 84.3%. If the samples are divided among their type, bomb or lapilli, the bomb samples are from 74.0 to 84.2% An, and the lapilli samples range from 66.6 to 84.3% An.

2.4.4.2 Olivine

The olivine phenocrysts found in these samples are very magnesium rich, ranging from 76.6 to 88.4% forsterite (Fo), with an average of 84.7%. The high Fo content occurs in both north and south complexes, and in bomb and tuff samples. Almost all the phenocrysts are normally zoned, and have more iron in their rims. The cores of the normally zoned phenocrysts are between 85.6 and 88.4 % Fo, while their rims are between 80.4 and 86.7% Fo. There is one phenocryst in 12-UH-37 where there is more than one zone (Figure 78), the core is 88.3% Fo, an inside rim with 88.3% Fo which could represent growth rings, and an outside rim with 86.5% Fo. There is one phenocryst in sample 12-UH-39 that has reverse zoning, where the core (79.3% Fo) is more iron rich than the rim (83.4% Fo). Two phenocrysts in 12-UH-30 also show reverse zoning, though there are four other phenocrysts in the sample that show normal zoning. The reverse zoning shows that the cores are 76.6 and 81.6% Fo, while the rims are 83.5 and 85.6% Fo. The cores of the reverse zoned phenocrysts have lower Fo units than the rims of the normally zoned phenocrysts. 12-UH-17 has one very unusual phenocryst that appears to have a calcium rich mineral in the center. Around this core is a high magnesium olivine at 87.2% Fo, and a rim around that of 88.1% Fo.

Figure 78: BSE photograph of a zoned olivine phenocryst with a spinel inclusion from sample 12-UH-34.

The forsterite content of the olivine has a larger range in the north complex than the south complex. The south complex has a range from 81.9 to 88.3% Fo (Figure 75). The Fo content of the north complex is from 76.6 to 88.4%. If the samples are divided according to upper and lower edifice, the upper edifice has ranges 80.5 to 88.3% Fo (Figure 80). The lower edifice has ranges from 76.6 to 88.4% Fo. The ranges for the two units are very similar except for the outlier in the lower unit. Bomb samples have ranges from 80.4 to 88.3% Fo, and lapilli samples range from 76.6 to 88.4% Fo (Figure 77).

2.4.4.3 Spinel

Spinel is commonly found crystallized next to olivine phenocrysts or even within them (Figure 79). The spinel is very chromium rich, ranging from 10.85 to 13.49% Cr. The average amount is 11.92% Cr. Some of the spinel phenocrysts are zoned; two show a higher abundance of chromium in the outside rim than the interior zone, another shows the opposite, where the rim has less chromium. The zonation does not show a large difference in abundance of chromium, zoned phenocryst range from have very small ranges 12.43 to 12.38% Cr and 12.20 to 12.62% Cr, except for a larger difference in one phenocryst that has a core of 11.27 to a rim of 13.49% Cr. There are also trace amounts of titanium, nickel, and zinc in the spinel. The north complex has lower amounts of chromium, between 10.85 and 13.01% Cr (Figure 75). The south complex has chromium amounts between 11.00 and 13.49%. The upper edifice has values between 12.38 and 13.01% Cr, and the lower edifice between 10.85 to 13.49% Cr (Figure 80). Bomb samples range from 10.85 to 12.43% Cr. Spinel phenocrysts found in lapilli tuffs have chromium abundances between 11.00 and 13.49% Cr (Figure 77).

Figure 79: BSE photograph of a spinel phenocrysts next to an olivine phenocryst in sample 12-UH-17.

2.5 Discussion

2.5.1 Upsal Hogback Magma Evolution

The magma is slightly more fractionated in the bomb samples from the south complex compared to the bomb samples of the north complex. The north complex is more Mg rich than the south complex; as well the olivine phenocrysts in the samples are also more Mg rich in the north complex. The plagioclase phenocrysts are also more anorthitic overall in the north complex. The north complex also has a smaller abundance of SiO₂ than the south complex. The geochemistry implies a more primitive magma erupted to make the north complex while a more evolved magma was involved in the eruptions forming the south complex. This is also seen in the REE patterns, the south is more enriched in LREE and HREE than the north complex indicating a more evolved magma (Figure 72).

Both complexes show similar geochemical signatures in both major and trace element geochemistry, therefore their source of magma is similar. Comparing LREE, La/Sm, versus MREE, Tb/Yb, Upsal Hogback shows very little range in ratios (Figure 80). The south complex is more enriched in the MREE and LREE than the north complex, and between the two complexes we see a slight positive slope, which could indicate a small amount of garnet in the mantle source. Plotting Nb/La versus Cs/La, compares the enrichment of LILE to the REE (Figure 81). Upsal Hogback shows very little range in REE but a larger range in Cs/La, representing LILE. The two complexes overlap in enrichment, but the south complex is a little more enriched in LILE and REE than the north complex, which reflects the assertion that the south complex is more

Figure 80: The south complex is enriched in MREE and LREE compared to the north complex.

Figure 81: The south complex is more enriched in LILE and REE than the north complex.

enriched in incompatible elements. The trace element patterns for both north and south complexes do not show subduction signatures corresponding to negative Nb and Ta anomalies, thus they have an asthenospheric intraplate mantle source. The flat to slightly sloped REE patterns is evidence of a spinel peridotite or a very low percent garnet peridotite mantle source for the north and south complex, where melting occurred at a depth ~ 70 km.

As similar as the north complex and the south complex are geochemically, there still are small difference in geochemistry. It may be that the magma in the south complex spent more time in a magma chamber, allowing for more fractional crystallization to occur. A fractional crystallization model, allowing for the crystallization of olivine, plagioclase and clinopyroxene, was used to model the evolution of the major element geochemistry of the most primitive north complex magma to the most enriched south complex sample. A 20% fractional crystal fractionation with the proportions of 0.45 olivine, 0.35 plagioclase, and 0.20 clinopyroxene fits the evolution of north complex to the south complex. If the 20% fractionation is applied to the REEs of the south complex samples, the LREE overlap with the north complex while the HREE become even less enriched than the north complex (Figure 82). The difference in HREE could be from a small component of garnet in the mantle source for the south complex compared to the north complex. The garnet would keep the HREE from entering into the liquid phase as the source is melting. Another possibility is also a small difference in partial melting between the magma for the north and south complexes, though the discrepancies in HREE between the two is best explained by a difference in garnet in the source.

Figure 82: Normalized REE pattern (Sun and McDonough, 1989) after 20% fractional crystallization is removed from the south complex.

The major and trace geochemistry suggest that the south complex erupted after the north complex since the north complex is more primitive. The source would have a slight variation in garnet content, but major element geochemistry can be explained by fractional crystallization. Therefore, it is possible that the south complex had more time to evolve in a magma chamber than the north complex. Another possibility is that the opposite occurred, where the south complex erupted before the north complex, but there was a magma recharge of a more primitive but thermochemically similar magma that would have affected the geochemistry of the north complex and made it more primitive than the south complex. Possible evidence of this would be reverse zonation in phenocrysts.

Samples from Cousens et al. (2012) from Upsal Hogback exhibit the same trends seen in the north and south complex of the volcano. One sample, 06-LT-04 from the north complex, that shows some characteristics of the south complex as it has higher TiO_2 than is seen in the south complex. 06-LT-04 also has higher K_2O and P_2O_5 than the other northern samples. 06-LT-04 has SiO_2 contents that also overlap with the south complex. But the sample's other major element and trace element concentrations are similar to the north complex. The other samples from Cousens et al. (2012) from both the north and south complex have the same geochemical trends as the samples analyzed in this study.

The microprobe data for the chromium rich spinel in direct contact with olivine phenocrysts was used to calculate the magnesium number for the melt based on Allan et al. (1988). The spinel represents the crystallization at depth of the phenocryst, allowing

for a calculation of the Mg number for the melt at that time, assuming the phenocryst was in equilibrium with the melt. The rim of the olivine phenocryst is used to calculate the Mg number of the melt farther along the evolution of the magma. A Fe/Mg partition coefficient of 0.3 is used to correct for the difference of concentration of iron in the melt compared to the olivine. The spinel shows Mg numbers that range from 0.40 to 0.66, and the average is 0.57. The zoned spinel minerals show a higher Mg number in the core than the rim, in example one phenocryst having a 0.60 core, and a 0.45 rim. The cores show an earlier snapshot of the magma, and range from 0.59 to 0.65, while the rims of the olivine phenocrysts shows a range from 0.36 to 0.60, with an average of 0.47. This suggests an evolving magma through time. The samples from the south complex has rims of olivine that have higher Mg numbers than the north complex, which is contrary to what is seen in the bulk rock geochemistry. Conversely, the spinel cores from the south complex have lower Mg numbers than the north complex. This may reflect a greater amount of magma evolution compared to the north complex, which is reflected in the major and trace geochemistry. The Mg numbers of the melt calculated from the olivine rims range closer to the Mg numbers of the bulk rock bomb samples than the core of the spinel phenocrysts, which determines that the magma may have been close to eruption at the time of crystallization of the olivine rims.

The significant spread in $^{87}\text{Sr}/^{86}\text{Sr}$ values seen in the Upsal Hogback bomb samples could be from strontium exchange from reactions with brines from Lake Lahontan. It also could be due to sample contamination due to carbonate from the brines precipitating in vesicles and cracks of a bomb sample. This is observed in thin section, so

contamination is the most likely scenario. Contamination is likely since no significant spread in the other isotope values are observed. The tufa does have very high strontium concentration; our analyzed tufa sample has 2362 ppm Sr. The tufa sample also has an $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.7074. A two component mixing model was created using the tufa sample as one component, and the bomb sample with the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratio as the other (Figure 83). The diagram shows that the Sr would be highly affected by small amounts of tufa contamination, while the Nd would be relatively unaffected. The bomb samples follow this mixing curve, showing that Sr contamination has occurred. Both samples that have high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, with 12-UH-03 and 12-UH-28 having higher Sr contents for the south and north complex respectively, supporting this theory.

When the Upsal Hogback samples are plotted $^{87}\text{Sr}/^{86}\text{Sr}$ against $^{144}\text{Nd}/^{143}\text{Nd}$, the samples plot between the bulk silicate earth (BSE), prevalent mantle (PREMA) and high μ (HIMU) mantle reservoirs (Figure 84). The range in strontium values makes it harder to pinpoint the mantle reservoir with accuracy. Plotting $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{144}\text{Nd}/^{143}\text{Nd}$, the bomb samples are between BSE, HIMU, PREMA and the mid ocean ridge basalt (MORB) mantle reservoirs (Figure 85). Plotting $^{206}\text{Pb}/^{204}\text{Pb}$ against $^{207}\text{Pb}/^{204}\text{Pb}$, the samples are closest to enriched mantle two (EMII) (Figure 86). $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ shows a trend towards MORB for the samples, though the samples do plot near the PREMA and BSE reservoirs (Figure 87).

There is also oxygen isotope data for two Upsal Hogback samples from Cousens et al. (2012). The Upsal Hogback samples have a $\delta^{18}\text{O}$ value of +5.690‰ and +6.230‰,

Figure 83: Mixing curve between bomb samples from Upsal Hogback and tufa. The Sr error is smaller than the symbols, and the Nd error represents the 2-sigma of the analyses.

Figure 84: The samples from north and south complex have a large range in $^{87}\text{Sr}/^{86}\text{Sr}$ and less in $^{144}\text{Nd}/^{143}\text{Nd}$ (Zindler and Hart, 1986). The analytical uncertainty is smaller than the symbols.

Figure 85: Upsal Hogback is more constrained in $^{144}\text{Nd}/^{143}\text{Nd}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ values (Zindler and Hart, 1986). The analytical uncertainty is smaller than the icons.

Figure 86: Upsal Hogback shows a range in mantle components in a $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ plot (Zindler and Hart, 1986). The analytical uncertainty is smaller than the symbols.

Figure 87: Upsal Hogback plots near EMII in a $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ (Zindler and Hart, 1986). The analytical uncertainty is smaller than the symbols.

and both samples come from the south complex. The values at Upsal Hogback are typical for MORB, thus are not showing any enrichment due to fluids coming off of a subducting slab (Eiler, 2001; Eiler et al., 1998).

2.5.2 Comparisons with other volcanic centers

2.5.2.1 Comparisons with volcanism in the Carson Sink

Comparing samples of Soda Lakes (SLB) and Rattlesnake Hill from Cousens et al. (2012) and Zak (2013) leads to some interesting differences between the volcanism in the Carson Sink. Both SLB and Rattlesnake Hill have very similar REE patterns compared to Upsal Hogback (Figure 88). Samples from both volcanic centers from Zak (2013) and Cousens et al. (2012) are more enriched in all REE compared to the north and south complexes. Rattlesnake Hill is more enriched in REE than SLB. They exhibit enrichment in LREE compared to HREE and exhibit a flat to slightly sloped HREE pattern, like Upsal Hogback. This shows that there are similar mantle sources for all three volcanic centers in the Carson Sink area. The concentrations of HREE are the same for all the volcanic centers. They also show the same positive lead anomaly. All three have the same negative thorium anomaly and positive cesium anomaly and all three volcanic centers lack subduction signatures.

The SLB and Rattlesnake Hill samples have $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{144}\text{Nd}/^{143}\text{Nd}$ ratios similar to one another. The samples were analyzed in Cousens et al. (2012). One sample from SLB has $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.704496 ± 16 , $^{206}\text{Pb}/^{204}\text{Pb}$ values of 19.01 ± 0.012 , $^{207}\text{Pb}/^{204}\text{Pb}$ values of 15.62 ± 0.014 , and $^{144}\text{Nd}/^{143}\text{Nd}$ values of 0.512717 ± 8 . There are two

Figure 88: Normalized incompatible element plot for Rattlesnake Hill, SLB, and SLDC (Sun and McDonough, 1989).

samples from Rattlesnake Hill with $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.704527 ± 16 and 0.704471 ± 16 , $^{206}\text{Pb}/^{204}\text{Pb}$ values of 18.94 ± 0.012 and 18.96 ± 0.012 , $^{207}\text{Pb}/^{204}\text{Pb}$ of 15.61 ± 0.014 and 15.61 ± 0.014 , and $^{144}\text{Nd}/^{143}\text{Nd}$ values of 0.512727 ± 8 and 0.512726 ± 8 . Both volcanic centers have slightly less $^{144}\text{Nd}/^{143}\text{Nd}$ ratios than Upsal Hogback. Their $^{87}\text{Sr}/^{86}\text{Sr}$ values sit in the middle of the range seen in the samples from Upsal Hogback. The similar isotope values coupled with an intraplate incompatible trace element pattern show an asthenospheric mantle source, with $^{144}\text{Nd}/^{143}\text{Nd}$ values above 0.5127 and $^{87}\text{Sr}/^{86}\text{Sr}$ values below 0.7045 (Cousens et al., 2012). Upsal Hogback also shows these values and incompatible element geochemical signature and thus has a similar asthenospheric mantle source. The samples from the SLB and Rattlesnake Hill plot nearer to the BSE field than Upsal Hogback in the $^{144}\text{Nd}/^{143}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ plot (Figure 89). SLB and Rattlesnake Hill plot closer to EMII in the $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{144}\text{Nd}/^{143}\text{Nd}$ plot than Upsal Hogback (Figure 90). In the plot of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$, SLB and Rattlesnake Hill plot within the Upsal Hogback range (Figure 91). The SLB and Rattlesnake Hill also plot closer to the EMII field in the $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ plot, because they have higher $^{207}\text{Pb}/^{204}\text{Pb}$ than Upsal Hogback (Figure 92). Rattlesnake Hill has a $\delta^{18}\text{O}$ value of $+5.960\text{‰}$, and SLB has a $\delta^{18}\text{O}$ value of $+6.080\text{‰}$. The $\delta^{18}\text{O}$ for Rattlesnake Hill and SLB overlap with the $\delta^{18}\text{O}$ values from Upsal Hogback, which suggests a similar mantle source with no interaction with fluids from subduction. A lack of subduction signature also fits with the intraplate source that is suggested by the incompatible trace element geochemistry.

Figure 89: $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ plot for the volcanism in and neighboring the Carson Sink (Zindler and Hart, 1986).

Figure 90: $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ plot for the volcanism in the Carson Sink and neighboring it (Zindler and Hart, 1986).

Figure 91: $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ plot for the mantle components of the volcanism in and around the Carson Sink (Zindler and Hart, 1986).

Figure 92: Volcanism in and around Carson Sink plot near EMII in $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{206}\text{Pb}$ plot (Zindler and Hart, 1986).

Samples from two geothermal drill cores from Soda Lakes area show a subduction or crustal contamination signatures (Figure 88). These Soda Lake Drill Core (SLDC) samples came from depths greater than 671 meters (McLachlan and Faulds, 2012) and are dated at 5.11 Ma by Ar-Ar date by Chris Henry (McLachlan, personal communication). The SLDC have large negative Nb and Ta anomalies, and a large lead anomaly showing crustal contamination. The SLDC do show the same slightly sloped HREE signature, which may signify a spinel peridotite or low percent garnet peridotite mantle source. It is unlikely that the trachybasalts come from the same mantle source as the eruption at Soda Lakes maars, as the Soda Lake bomb samples from the surface all show the same intraplate geochemical signature. The SLDC sample's $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{144}\text{Nd}/^{143}\text{Nd}$ values place it firmly in the BSE field which differs from the Upsal Hogback, Rattlesnake Hill, and SLB samples, furthering this theory (Figure 89). The SLDC has slightly higher $^{206}\text{Pb}/^{204}\text{Pb}$ ratios than the volcanism in the Carson Sink, thus plots closer to EMII in $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{144}\text{Nd}/^{143}\text{Nd}$ plot (Figure 90). In the plot of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$, SLDC plots on the higher end of the Upsal Hogback range (Figure 91). The SLDC plots on the edge of the EMII field in the $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ plot since it has a higher $^{207}\text{Pb}/^{204}\text{Pb}$ ratio than Upsal Hogback (Figure 92).

Comparing LREE, La/Sm, versus MREE, Tb/Yb, SLB is more enriched in LREE and MREE than all of Upsal Hogback, but less enriched in LREE than Rattlesnake Hill (Figure 93). The 5.11 Ma SLDC samples have La/Sm ratios lower than the Holocene SLB but higher than Upsal Hogback basalts, with MREE enrichment as less than the SLB and higher than Upsal Hogback. In the plot comparing Nb/La versus Cs/La, SLB and

Figure 93: LREE versus MREE for the other volcanism in and near the Carson Sink.

Figure 94: LILE versus REE for the volcanism in and around the Carson Sink.

Rattlesnake Hill plot similarly to Upsal Hogback (Figure 94). SLB is more enriched in LILE than the north complex, while Rattlesnake Hill is less enriched in LILE. SLB does have one outlier sample that is very enriched in LILE. The SLDC show a much lower REE enrichment and a range in LILE.

2.5.2.2 Buffalo Valley Volcanic Field

Comparing the samples from the three volcanic centers in the Carson Sink to the alkalic and trachy basaltic volcanism in the Buffalo Valley Field (BVF) from Cousens et al. (2013), the BVF has slightly higher concentrations overall of SiO_2 and alkalis. The BVF has higher La/Sm ratios than Upsal Hogback as well as Tb/Yb, so it is more enriched in LREE and MREE than Upsal Hogback. The samples from the BVF show a slightly positive slope (Figure 93), which indicates a spinel peridotite mantle source or a small percent of garnet in the mantle source. The BVF samples have higher Nb/La ratios, but similar Cs/La ratios to Upsal Hogback, showing an enrichment in LILE (Figure 94).

The BVF and the volcanism in the Carson Sink have very similar geochemical signatures on a normalized incompatible element plot (Figure 95). The BVF samples are more enriched in REE than both the north and south complex. The BVF samples are even more enriched than Soda Lakes and Rattlesnake Hill. The only difference is that the BVF samples have a negative lead anomaly compared to the positive anomalies seen in some of the volcanism in the Carson Sink. BVF also has a very slight Ta anomaly compared to the other volcanic centers, where Nb and Ta have very similar enrichments. This Ta anomaly could be due to an analytical issue. The BVF samples also show the same slight

Figure 95: Normalized incompatible element plot of the BVF (Sun and McDonough, 1989).

slope in the HREE, which implies a similar mantle source between these volcanic centers.

The BVF samples have slightly lower $^{87}\text{Sr}/^{86}\text{Sr}$ than the range seen at Upsal Hogback, and lower than Soda Lakes and Rattlesnake Hill. All the BVF samples except one also have slightly higher $^{144}\text{Nd}/^{143}\text{Nd}$ than the other volcanic centers located in the Carson Sink (Figure 89). The BVF samples plot closer to HIMU and PREMA mantle reservoirs than the volcanic centers in the Carson Sink. The one exception is a BVF sample that has a lower $^{144}\text{Nd}/^{143}\text{Nd}$ than Upsal Hogback, Soda Lakes, and Rattlesnake Hill. The BVF also has lower $^{87}\text{Sr}/^{86}\text{Sr}$ values than Soda Lakes and Rattlesnake Hill, and overlaps with the lower range of Upsal Hogback. The BVF also has $\delta^{18}\text{O}$ values of +5.60‰ and +6.37‰. The $\delta^{18}\text{O}$ values for the BVF have a similar range to Upsal Hogback.

2.5.2.3 Miocene-Pliocene Ancestral Cascades Arc

Representative samples from the Ancestral Cascade arc from Cousens et al. (2008) Ancestral Cascade arc region was compared to the samples from Upsal Hogback in this study. The Ancestral Cascade arc has a wide range in both La/Sm and Tb/Yb ratios, above and below Upsal Hogback values (Figure 93). The Nb/La ratios for the Ancestral Cascade arc are very low while Cs/La ratios have a similar range to Upsal Hogback, so the Ancestral Cascade arc samples are less enriched in LILE than Upsal Hogback (Figure 94).

The Ancestral Cascade arc samples have a wide range in $^{144}\text{Nd}/^{143}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values, it has similar values of $^{144}\text{Nd}/^{143}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values as Upsal Hogback to considerably less of both $^{144}\text{Nd}/^{143}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than Upsal Hogback. The samples from the Ancestral Cascade arc plot near HIMU and PREMA and ranging past BSE in the $^{144}\text{Nd}/^{143}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ plot (Figure 89). The Ancestral Cascade arc has less range in $^{206}\text{Pb}/^{204}\text{Pb}$ values and it is slightly higher in $^{206}\text{Pb}/^{204}\text{Pb}$ compared to Upsal Hogback. The Ancestral Cascade arc ranges from close to MORB to close to EMII in the $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{144}\text{Nd}/^{143}\text{Nd}$ plot (Figure 90). In the plot of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$, the Ancestral Cascade arc ranges from MORB to past the BSE, the same trend as Upsal Hogback but with a larger range (Figure 91). There is also less range in $^{207}\text{Pb}/^{204}\text{Pb}$ values, and in a $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ plot, the Ancestral Cascade arc plots in the EMII field (Figure 92). The Ancestral Cascade arc also has a $\delta^{18}\text{O}$ value of 6.30‰, which is slightly higher than the $\delta^{18}\text{O}$ values of Upsal Hogback samples. The rest of the Ancestral Cascade arc has higher $\delta^{18}\text{O}$ values than the Ancestral Cascade arc basalt sample (Cousens et al., 2012), which indicates an enrichment of $\delta^{18}\text{O}$ values from fluids from a subducting slab (Eiler et al., 1998). It may be that the Ancestral Cascade arc basalt sample had a source that had less fluid interaction.

The Ancestral Cascade arc basalts are less enriched in REE compared to the BVF and the volcanism in the Carson Sink (Figure 96). Overall the Ancestral Cascade arc basalts are less enriched in HREE than the volcanic centers in the Carson Sink. The samples from the Ancestral Cascade arc have large negative Nb, though some samples show a larger Nb anomaly. The Ancestral Cascade arc samples also show positive Pb

Figure 96: Normalized incompatible element plot for the samples from the Ancestral Cascade arc (Sun and McDonough, 1989).

anomalies and a positive Nd anomaly. The Sawtooth Ridge sample shows a positive Sr anomaly and a negative Ta anomaly, though it is the only sample with a Ta analysis. A few samples also show a slight negative Zr anomaly not seen in the Carson Sink samples. Overall the Ancestral Cascade arc geochemical signature is more similar to the drilled SLDC samples from the Soda Lake area than to Upsal Hogback, especially the Sawtooth Ridge sample.

2.5.2.4 Tahoe-Truckee Volcanic Field

Samples from the TTVF from Cousens et al. (2011) were used to compare the volcanism in the Carson Sink to areas around it. The TTVF samples have higher La/Sm and Tb/Yb ratios than Upsal Hogback, showing that it is more enriched in LREE and MREE than Upsal Hogback (Figure 93). The Nb/La ratios for the TTVF are smaller than Upsal Hogback, while the Cs/La ratios are on the low end of the range seen at Upsal Hogback (Figure 94). This reflects that the TTVF is less enriched in LILE and REE than Upsal Hogback.

The samples from The TTVF are more similar in incompatible element geochemically to the Ancestral Cascades arc compared to the geochemical signatures of the volcanism in the Carson Sink (Figure 97). The TTVF samples are more enriched in incompatible elements than the Ancestral Cascade arc and the volcanic centers in the Carson Sink. The TTVF samples show higher positive Pb anomalies than the Ancestral Cascade arc, but less negative Nb and Ta anomalies. Some of the negative Nb and Ta anomalies observed in the TTVF samples overlap with the Ancestral Cascade arc

Figure 97: Normalized incompatible element plot of samples from the TTVF and McClellan Peak (Sun and McDonough, 1989).

samples, but most are more enriched in Nb and Ta than the arc. There are also high P anomalies in the TTVF samples. One TTVF sample shows a negative Zr anomaly similar to the Ancestral Cascade arc. Some TTVF samples show negative Cs and Rb anomalies. The TTVF is more enriched in LREE than the other volcanic centers, including Upsal Hogback, yet it is less enriched in HREE than the other volcanism except the Ancestral Cascade arc. The TTVF does show a higher slope in the HREE as the volcanism in the Carson Sink.

The samples from the TTVF plot in and around the BSE field on the $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{144}\text{Nd}/^{143}\text{Nd}$ mantle source plot, as it has higher $^{87}\text{Sr}/^{86}\text{Sr}$ values and lower $^{144}\text{Nd}/^{143}\text{Nd}$ values than Upsal Hogback (Figure 89). The $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of the TTVF are slightly higher than Upsal Hogback, and have a slightly larger variability in $^{206}\text{Pb}/^{204}\text{Pb}$ values. The TTVF samples plot a little bit closer than EM2 than the volcanic centers in the Carson Sink in the $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{144}\text{Nd}/^{143}\text{Nd}$ plot (Figure 90). $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ also has a large spread between MORB and past BSE that is a slightly larger in the TTVF samples than the spread seen at Upsal Hogback (Figure 91). There is also variability in TTVF samples' $^{207}\text{Pb}/^{204}\text{Pb}$ values where they are higher than Upsal Hogback, and in a $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ plot, it plots near the EMII field (Figure 92).

2.5.2.5 McClellan Peak

The sample from the basaltic McClellan Peak from Cousens et al. (2012) has incompatible element geochemistry that is not similar to Upsal Hogback. McClellan Peak has high ratios of La/Sm and Tb/Yb than Upsal Hogback (Figure 93); therefore it is more enriched in LREE and MREE than Upsal Hogback. McClellan Peak has a smaller value of Nb/La than Upsal Hogback, and is on the lower range of Upsal Hogback Cs/La ratios (Figure 94). Therefore McClellan Peak is less enriched in LILE and REE than Upsal Hogback. It is more enriched than Upsal Hogback in incompatible elements except for the HREE (Figure 97). Therefore it has a steeper slope in REE than Upsal Hogback. It has a positive Pb anomaly and a slight negative Th and Zr anomalies. McClellan Peak is similar to Upsal Hogback because it does not have subduction signatures but it is likely comes from a mantle source with higher garnet content.

The McClellan Peak sample plots near the BSE field on the $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{144}\text{Nd}/^{143}\text{Nd}$ mantle source plot (Figure 89), as it has higher $^{87}\text{Sr}/^{86}\text{Sr}$ values and lower $^{144}\text{Nd}/^{143}\text{Nd}$ values than Upsal Hogback. The $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of McClellan Peak is slightly higher than Upsal Hogback, and has a slightly higher $^{206}\text{Pb}/^{204}\text{Pb}$ value. The McClellan Peak plots a little bit closer than EM2 than Upsal Hogback $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{144}\text{Nd}/^{143}\text{Nd}$ plot (Figure 90). The McClellan Peak sample plots closer to BSE in the $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ plot than Upsal Hogback (Figure 91). The McClellan Peak $^{207}\text{Pb}/^{204}\text{Pb}$ values are slightly higher than Upsal Hogback, and in a $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ plot, it plots near the EMII field (Figure 92). McClellan Peak also has a $\delta^{18}\text{O}$ value of +7.010‰. This McClellan Peak high $\delta^{18}\text{O}$ value could reflect a metasomatized

source since higher $\delta^{18}\text{O}$ values indicate that the fluids passed through sediments from a subducting slab, enriching the fluids in $\delta^{18}\text{O}$ (Eiler et al., 1998). The $\delta^{18}\text{O}$ value indicates a very different source of magma compared to Upsal Hogback.

2.5.3 Source of Magma

It is clear that the sources of magma for the three volcanic centers in the Carson Sink are very similar, and may be the same source. The south and north complex of Upsal Hogback, Soda Lakes and Rattlesnake Hill are geochemically distinct but do have similar, parallel trace element geochemical signatures. The flat to slightly sloped HREE pattern shows that the source of magma is a spinel peridotite or low percent garnet peridotite mantle source, so the depth of melting is $\sim 70\text{km}$. The confluence of several regional tectonic trends of the Carson Sink area leads to lithospheric thinning in the Carson Sink, which explains why the asthenospheric melts can well up from such depth. The two largest contributing factors would be the lithospheric thinning of the Humboldt Lineament, and the extension in the Great Basin. The shearing due to the Walker Lane could also be a factor, perhaps weakening the crust in the area and creating pathways for magmas to get to the surface.

What is interesting is the similarity in mantle source to the BVF. The Walker Lane is not a tectonic factor in that region, so it may not be important in producing melting in the mantle. It may be that extension in the Great Basin and the thinning lithosphere in the Humboldt Lineament is a larger factor than the Walker Lane. This tectonic setting leads to melting in the asthenosphere that come from a spinel peridotite or

low percent garnet peridotite source that we are seeing in Upsal Hogback, Soda Lakes, Rattlesnake Hill, and the BVF.

It is clear that the sources of magma for the Ancestral Cascade arc and the TTVF are different than the source of magma for Upsal Hogback, Soda Lakes, Rattlesnake Hill and the BVF. The Ancestral Cascades arc and TTVF have much more of a subduction signature in its normalized incompatible element plot than the other according to Cousens et al (2012), compared to the intra plate signatures seen further east in the Great Basin. The subduction of the Farallon plate is what precipitated the volcanism in the Ancestral Cascade arc (Cousens et al., 2008).

2.6 Conclusions

In summary, the geochemical analysis of samples from Upsal Hogback leads to these conclusions:

1. The geochemistry of the north and south complex are very similar but each have distinct signatures. The north complex has a more primitive magma than the south complex so may have erupted first.
2. Upsal Hogback, Soda Lakes, and Rattlesnake Hill all have similar trace element signatures in the REE, showing that they come from a spinel peridotite or low percent garnet peridotite mantle source from the asthenosphere at around 70km depth.
3. The volcanic centers in the Carson Sink have similar geochemical signatures to the BFV, suggesting a similar source of magma. These volcanic centers do not have similar

geochemical signatures to the subduction signatures observed in Ancestral Cascades Arc and TTVF samples or McClellan Peak's geochemical signature.

4. The major factor allowing for asthenospheric melting is the thin lithosphere due to the Humboldt Lineament, shearing in the Walker Lane, and the extension in the Great Basin.

3 Chapter: Summary of Conclusions

Upsal Hogback is a tuff cone produced by phreatomagmatic volcanism that has had substantial post-eruption modification. The edifice can be divided into two complexes: the north complex with one vent and the south complex with three vents. The edifice is composed of two units; the lower unit that erupted under the water of Lake Lahontan, and the upper unit that is the part of the edifice that was built up above lake levels.

Lake Lahontan has had many post eruptive effects on the volcano. The wave action of the lake eroded much of the edifice, creating many slump blocks covered in tufa and wave cut terraces. These effects made the volcano look like it had the morphology of a tuff ring with low topographic relief compared to a tuff cone. Lake levels rose above the edifice at some point, and tufa was precipitated onto the edifice. Therefore, because the volcano erupted into shallow water but there was a high stand of the lake after the eruption, this narrows the age of the volcano to between 18 and 11 ka.

Geochemically, Upsal Hogback shows that the north and south complex are separate events since they have very similar geochemical signatures but they are distinct. The south complex is more enriched in REE than the north complex, and overall is a more evolved magma. Both complexes show an aesthenospheric intraplate mantle source. Their similar signature shows a spinel peridotite or low percent garnet peridotite mantle source.

Neighboring volcanic centers in the Carson Sink, Soda Lakes and Rattlesnake Hill, show similar geochemical signatures as Upsal Hogback but are more enriched in REE. The

Carson Sink has several tectonic factors influencing the geology in the area. The thinning of the lithosphere caused by the Humboldt Lineament and the thinning caused by shear in the Walker Lane as well as extension from the Great Basin leads to the melts in the mantle in the area. The difference in volcanic morphologies between these three volcanoes is caused by different water/magma ratios. Since Soda Lake is younger than Upsal Hogback and Lake Lahontan had desiccated by the time it erupted, only groundwater was involved in the eruption, creating a maar instead of a tuff cone. Rattlesnake Hill is the oldest, and predates Lake Lahontan, thus no water was involved in the eruption, creating a cinder cone.

The Buffalo Valley Volcanic Field also shows similar geochemical signatures to the volcanism in the Carson Sink, but is more enriched overall in REE. This may reflect that the field also lies in the Humboldt Lineament and the Great Basin, which are factors influencing the asthenospheric melts in the Carson Sink.

Other volcanic fields like the Tahoe-Truckee Volcanic Field and the Ancestral Cascade arc do not exhibit the same geochemical signatures as Upsal Hogback or other volcanism in the Carson Sink. This reflects the fact that these fields are produced from melts caused by the subduction of the Farallon plate (Cousens et al., 2011; Cousens et al., 2008), while the Carson Sink volcanism is from an intraplate source.

Upsal Hogback is in close proximity to the city of Fallon and its Naval Air Base, making another eruption a large risk to the population. Soda Lakes is a fairly young volcano and geothermal areas are active in the region, making another eruption a possibility. Since

Lake Lahontan is desiccated another eruption creating a tuff cone would be unlikely. If there is abundant groundwater available, in example near the farmland by Fallon, a tuff ring could be produced. If no groundwater is available, then a cinder cone similar to Rattlesnake Hill would be produced.

Appendices

Appendix A Physical Volcanology

A.1 Chapter 1 Abstracts

Upsal Hogback is a < 25 ka volcano located near the city of Fallon, Nevada, USA. The volcano includes a series of vents that can be divided into two complexes: the north complex (1 vent) and the south complex (1-3 vents). The vents are composed of indurated lapilli and ash tuff containing abundant olivine and plagioclase phyric basaltic bombs. This volcano erupted some time during the history of glacial Lake Lahontan, leading to a potential water-magma interaction. Upsal Hogback is a phreatomagmatic volcano that was emplaced as a tuff cone that has been significantly eroded to a morphology similar to a tuff ring. Evidence of tuff cone morphology is seen by its lower unpalagonitized units, and upper palagonitized units. Subaerial to shallow subaqueous features such as bomb sags and armored lapilli show that Lake Lahontan water levels must have been shallow. Large slump blocks such as the hogback indicate that there was a larger edifice that has been eroded by wave action from Lake Lahontan. Upsal Hogback has two neighboring volcanic centers: Soda Lakes (~3 ka maar) and Rattlesnake Hill (~1 Ma volcanic neck) (Zak, 2013; Shevenell et al., 2005). Their differing eruptive styles are due to their emplacement during different times in Lake Lahontan level history.

Abstract for Geological Association of Canada-Mineralogical Association of Canada Conference

Anderson, E., and Cousens, B., Quaternary volcanic centers and their relation to geothermal activity near Fallon, western Nevada, USA [*abstract*], Geological Association of Canada-Mineralogical Association of Canada Conference, 2014 May 21-23, Fredericton, New Brunswick, Canada, 2014

Quaternary volcanic centers and their relation to geothermal activity near Fallon, western Nevada, USA

Erika Anderson and Brian Cousens

Upsal Hogback is a <25 ka volcano situated near Fallon, Nevada and its Naval Air Base. It was formed by phreatomagmatic eruptions creating tuff cones composed primarily of coarse, indurated lapilli tuffs with abundant volcanic bombs. Both ash tuffs and cross bedding also occur rarely. The volcano consists of two complexes: the north complex comprising of one vent, and the south complex made of one to three vents. Given its proximity to Fallon, it is important to constrain its age. The relative age of the edifice indicates that it would have erupted during the history of glacial Lake Lahontan, leading to both effects on the volcano during its eruption and on its post-volcanic morphology. There is substantial evidence for a subaerial or shallow subaqueous emplacement, but only the upper part of the edifice is palagonitized. This indicates a tuff cone was produced, which has been since modified by erosional effects of Lake Lahontan to resemble a tuff ring. Olivine and plagioclase phyric bombs from Upsal Hogback were

analyzed, and show enrichment in LREE compared to HREE. Overall, the north complex is less enriched in REE compared to the south complex. Both complexes have flat HREE patterns, denoting a spinel peridotite or a low percent garnet peridotite mantle source. Two other volcanic centers neighbor Upsal Hogback: the younger Soda Lakes (maars) and the older Rattlesnake Hill (volcanic neck), and have similar REE signatures. The samples from both complexes are geochemically distinguishable in major and trace elements but have similar $^{143}\text{Nd}/^{144}\text{Nd}$ values. They differ in $^{87}\text{Sr}/^{86}\text{Sr}$ values, which could be from Sr contamination from Lake Lahontan brines. All three volcanoes are situated in the Humboldt Lineament, a zone of lithospheric thinning. These volcanoes also are located on the boundary between the Basin and Range, a zone of extension, and the Sierra Nevada, as well as on the edge of the Walker Lane, a zone of dextral shear. Geothermal potential exists in the area, including a producing geothermal plant at Soda Lakes along with several other plants in Churchill County. The source of magma for the volcanism is an asthenospheric intraplate mantle source, produced after pronounced lithospheric thinning during the late Pliocene and Quaternary, which likely also generates the geothermal activity.

A.2 Sample and measurement stations

Table 1: Location of structural measurements and location of samples.

Station	UTM Easting (NAD 1927 ZN11)	UTM Northing (NAD 1927 ZN11)	Elevat- ion (m)	Strike	Dip	Sample Number
20-1	345059	4387666	N/A			
20-2	345043	4387575	N/A			
20-3	344924	4387654	N/A			
20-4	344874	4387789	N/A			
20-5	344762	4387755	N/A			
20-6	344795	4387811	N/A			
20-7	345003	4387844	N/A			
20-8	345045	4387600	N/A	55	36	
20-9	345018	4387599	N/A	158	9	12-UH-01
20-10	344945	4387640	N/A	131	17	
20-10	344945	4387640	N/A	189	12	
20-11	344920	4387660	N/A	155	72	
20-12	344947	4387697	N/A	139	28	
20-13	344942	4387734	N/A	346	11	12-UH-02
20-14	344922	4387759	N/A	357	17	
20-14	344922	4387759	N/A	127	27	
20-15	344814	4387777	N/A	87	31	
20-16	344774	4387754	N/A	86	30	
20-17	344791	4387776	N/A	226	22	
20-18	344783	4387796	N/A	215	29	
20-19	344914	4387819	N/A	138	90	
20-20	344925	4387782	N/A	200	52	12-UH-03
21-1	344933	4387802	N/A	102	56	
21-2	344944	4387817	N/A	99	24	
21-2	344944	4387817	N/A	161	51	
21-2	344944	4387817	N/A	100	17	
21-2	344944	4387817	N/A	161	51	
21-2	344944	4387817	N/A	321	35	
21-2	344944	4387817	N/A	310	24	
21-2	344944	4387817	N/A	62	0	

Station	UTM Easting (NAD 1927 ZN11)	UTM Northing (NAD 1927 ZN11)	Elevat- ion (m)	Strike	Dip	Sample Number
21-3	344957	4387819	N/A	286	90	
21-4	344964	4387822	N/A	63	11	
21-5	344989	4387779	N/A	15	32	
21-6	344984	4387763	N/A	351	37	12-UH-04, 05
21-6	344984	4387763	N/A	337	81	12-UH-04, 05
21-7	345002	4387731	N/A	279	39	
21-7	345002	4387731	N/A	148	50	
21-8	345004	4387710	N/A	352	55	
21-8	345004	4387710	N/A	107	35	
21-9	344956	4387713	N/A	119	33	
21-10	344956	4387698	N/A	18	63	
21-11	344981	4387687	N/A	127	50	
21-12	344988	4387678	N/A	284	68	
21-13	345005	4387660	N/A	197	45	
21-14	344960	4387676	N/A	332	30	
21-15	344966	4387677	N/A	105	77	
21-15	344966	4387677	N/A	128	6	
21-15	344966	4387677	N/A	55	28	
21-15	344966	4387677	N/A	299	75	
21-16	345011	4387656	N/A	20	51	
21-17	345022	4387655	N/A	113	64	
21-17	345022	4387655	N/A	347	90	
21-1a	345109	4387542	N/A	170	5	12-UH-06
21-2a	345162	4387499	N/A	110	5	
21-3a	345193	4387422	N/A	50	10	
21-4a	345212	4387342	N/A	40	15	
21-5a	345205	4387242	N/A	20	5	
21-6a	345055	4387551	N/A	220	10	
21-7a	344973	4387697	N/A	190	15	
21-8a	344951	4387608	N/A	110	5	
21-9a	344920	4387635	N/A	220	20	
21-10a	344746	4387724	N/A	210	10	
21-11a	344682	4387778	N/A	100	5	

Station	UTM Easting (NAD 1927 ZN11)	UTM Northing (NAD 1927 ZN11)	Elevat- ion (m)	Strike	Dip	Sample Number
21-12a	344671	4387785	N/A	260	5	12-UH-07
21-13a	344620	4387788	N/A	280	5	
21-14a	344567	4387800	N/A	130	15	
21-15a	344473	4387813	N/A	230	5	
21-16a	344421	4387775	N/A	0	5	
21-17a	344299	4387686	N/A	230	5	
21-18a	344514	4387920	N/A	164	24	
22-1	345413	4387699	N/A	55	29	
22-2	345374	4387692	N/A	32	19	
22-3	345361	4387732	N/A	135	0	
22-4	345299	4387783	N/A	178	21	
22-5	345273	4387810	N/A		0	
22-6	345318	4387888	N/A	0	36	12-UH-08
22-7	345389	4388103	N/A	242	12	
22-7	345389	4388103	N/A	169	9	
22-8	345355	4388234	N/A		0	
22-9	345397	4388401	N/A		0	12-UH-09
22-10	345459	4388264	N/A	2	22	
22-11	345427	4388096	N/A	11	7	
22-12	345418	4388022	N/A	123	8	
22-13	345423	4387928	N/A	169	18	
22-14	345432	4387904	N/A	148	15	
22-15	345476	4387950	N/A	326	10	12-UH-10
22-16	345471	4387851	N/A	9	12	
22-17	345422	4387771	N/A	164	10	
22-18	345331	4387751	N/A	88	61	
22-19	345317	4387732	N/A	170	18	
22-20	345400	4387717	N/A	191	19	12-UH-11
22-21	345399	4387693	N/A	64	33	
22-22	345422	4387720	N/A	35	39	
22-23	345453	4387770	N/A	51	15	
22-24	345463	4387764	N/A	31	22	
22-25	345499	4387865	N/A	357	30	

Station	UTM Easting (NAD 1927 ZN11)	UTM Northing (NAD 1927 ZN11)	Elevat- ion (m)	Strike	Dip	Sample Number
22-26	345491	4387979	N/A	348	33	
22-1a	345309	4387260	N/A	80	3	12-UH-12
22-2a	345352	4387270	N/A	60	5	
22-3a	345431	4387324	N/A	80	5	12-UH-13
22-4a	345472	4387369	N/A	70	5	
22-5a	345500	4387329	N/A	240	5	12-UH-14, 15
22-6a	345532	4387705	N/A			
23-1	345009	4388293	1240	295	14	12-UH-16, 17
23-2	345099	4388549	1230		0	
23-3	345089	4388601	1235	107	24	
23-4	345059	4388639	1234	123	10	12-UH-18
23-4	345059	4388639	1234	156	4	12-UH-18
23-5	344969	4388638	1230	95	14	
23-6	344787	4388669	1227		0	
23-7	344807	4388564	1227	357	16	12-UH-19, 20
23-8	344635	4388340	1237	75	39	12-UH-21, 22
23-9	344563	4388251	1238		0	
23-10	344519	4388205	1235	247	10	
23-11	344455	4388190	1234	245	12	
23-12	344396	4388172	1232	127	4	
23-13	344396	4388172	1232	160	27	
23-14	344396	4388172	1232	55	41	
23-15	344396	4388172	1232	172	23	
23-16	344396	4388172	1232	181	15	
23-17	344396	4388172	1232	49	44	
23-18	344396	4388172	1232	138	26	
23-19	344396	4388172	1232	175	35	
23-20	344465	4388268	1233	262	16	
25-1	345342	4389466	1249	64	14	
25-2	345271	4389531	1253	149	19	
25-3	345224	4389616	1251	209	11	
25-4	345263	4389674	1258	329	21	
25-5	345278	4389735	1256	63	8	

Station	UTM Easting (NAD 1927 ZN11)	UTM Northing (NAD 1927 ZN11)	Elevat- ion (m)	Strike	Dip	Sample Number
25-6	345292	4389775	1262	132	6	
25-7	345247	4389817	1260	47	12	
25-8	345218	4389812	1257	145	42	
25-8	345218	4389812	1257	349	36	
25-8	345218	4389812	1257	119	6	
25-9	345221	4389909	1256	220	11	
25-10	345298	4389886	1254	342	9	
25-11	345308	4389803	1256		0	
25-12	345366	4389738	1255			
25-13	345495	4389419	1251	278	16	
25-14	345564	4389397	1249	86	12	
25-15	345580	4389426	1249	286	21	12-UH-28
25-16	346189	4389892	1256	30	12	
25-17	346165	4389827	1259	15	20	
25-18	346154	4389803	1259	355	31	
25-19	346126	4389660	1260	29	15	
25-20	346088	4389587	1256	187	17	
25-21	346149	4389617	1259	51	17	
25-1a	345166	4390187	1229			
25-2a	344970	4390079	1223			
25-3a	344888	4390140	1232	10	10	
25-4a	344839	4390179	1240	20	10	
25-5a	344819	4390253	1227	170	10	
25-6a	344806	4390415	1221	210	10	
25-7a	344758	4390301	1215	220	5	
25-8a	344745	4390175	1229	190	10	12-UH-23
25-9a	344710	4390093	1226	180	5	12-UH-24
25-10a	344731	4389971	N/A	40	5	
25-11a	344825	4389681	1228	190	10	12-UH-25
25-12a	344894	4389558	1233	160	5	
25-13a	344916	4389505	1223	150	10	12-UH-26
25-14a	344980	4389405	1229	160	10	
25-15a	345083	4389357	1228	120	15	

Station	UTM Easting (NAD 1927 ZN11)	UTM Northing (NAD 1927 ZN11)	Elevat- ion (m)	Strike	Dip	Sample Number
25-16a	345140	4389253	1227	170	10	
25-17a	345195	4389201	1214	100	5	12-UH-27
25-18a	345213	4389115	1259	150	5	
25-19a	346332	4389599	1229	40	3	
25-20a	346280	4389495	1233	40	5	
25-21a	346241	4389437	N/A		0	12-UH-29
26-1	346234	4389339	1225	62	16	12-UH-30, 31, 32, 33
26-1	346234	4389339	1225	41	10	12-UH-30, 31, 32, 33
26-2	346180	4389281	1229	57	14	
26-3	346217	4389751	1234			
26-4	346206	4389798	1257	338	31	
26-5	346155	4389797	N/A			12-UH-34
26-6	346002	4390238	1234	321	7	12-UH-35
26-7	345955	4390340	1244			12-UH-36, 37
27-1	344897	4387750	1253	131	27	
27-2	344917	4387765	1265			12-UH-38, 39
27-3	345119	4387552	1236			12-UH-40
27-4	345056	4389181		91	9	
28-1	345487	4389415	1252			12-UH-41
28-2	345701	4390757	1239	149	22	
28-3	345642	4390825	1231	133	13	
28-4	345604	4390884	1229	198	7	12-UH-42, 43
28-5	345674	4390919	1229	274	8	
28-6	345742	4390948	1224	220	9	12-UH-44
28-7	345899	4390845	1235	56	11	
28-8	346305	4390298	1248	35	20	
28-9	346323	4390259	1242	329	4	12-UH-45
28-10	346461	4390091	1228	27	5	
28-11	346323	4389591	1240	77	10	
10-1	344552	4386221	1209			13-UH-01
10-2	345308	4385626	1212			
10-3	345400	4384988	1214			13-UH-02
10-4	345761	4385194	1207			

Station	UTM Easting (NAD 1927 ZN11)	UTM Northing (NAD 1927 ZN11)	Elevat- ion (m)	Strike	Dip	Sample Number
10-5	344393	4387169	1224			13-UH-03
10-6	344152	4389782	1215			
10-7	343955	4389965	1205			
10-8	343888	4389992	1209			
10-9	343999	4389638	1214			
10-10	345391	4393921	1190			
10-11	345303	4393410	1195			
10-12	344494	4387758	1237			13-UH-04
10-13	344679	4387778	1232	241	29	13-UH-05
11-1	344919	4387760	1268			
11-2	344802	4387785	1250			
11-3	344970	4387818	1260			
11-4	345476	4387805	1258			
11-5	345396	4387701	1260			
11-6	344467	4388217	1240			
11-7	344562	4388382	1236	218	10	
11-8	344649	4388548	1230	173	8	
11-9	344663	4388616	1223	140	9	
12-1	346453	4390038	1239			
12-2	346324	4390257	1240			
12-3	346306	4389983	1250			
12-4	346157	4389799	1263			13-UH-06
12-5	346221	4389457	1248			
12-6	346234	4389330	1233			
12-7	345271	4389531	1257			
12-8	344972	4389493	1237			
12-9	345560	4383202	1207			13-UH-07

A.3 Petrography

Table 2: Thin section petrography of the Upsal Hogback bomb samples.

Samp- le	Phenocryst Mineral	Crystal Shape	Crystal size	Microlites	Matrix	Textures	Align- ment of microli- tes	Vesicles	Description
12- UH-01	Plagioclase: 20% Olivine: 10%	Plag: some anhedral, most euhedral Olivine: anhedral	Oliv: 0.5-3 mm Plag: 0.5-1 mm	Abundant, less in dark glass 15%	2 different glasses One darker, less microlite rich, some sections very vesicle rich, light glass more devitrified, microlite and vesicle rich	Some plagioclase shows zoned sieve textures, 2 nd zone is very dissolved. Some inner zones dissolved. Mixing texture for the glasses.	In small sections	Abundant Less in dark glass	Olivine is very fractured. Crystal aggregates of both minerals, individually.
12- UH-02	Plagioclase: 15% Olivine: 15%	Oliv: anhedral to subhedral Plag: subhedral to euhedral	Oliv: 1- 5mm Plag: 0.5 mm	Abundant 15%	Dark glass	Sieve texture in central and 2 nd zone of zoned plagioclase. The ones with sieved textures are anhedral, and embayed.	Roughly aligned	Some	Olivine very fractured. Some vesicles are calcite lined. Small clast of fine grained basalt, Small pieces of olivine and plagioclase and small microlites. Crystal aggregates of both minerals individually and together. Brown region of glass, probably weathering.
12- UH-03	Plagioclase: 15% Olivine: 10%	Plag: anhedral to euhedral Oliv: anhedral	Oliv: 0.5-5 mm Plag: 0.5-7 mm	Abundant 15%	2 different glasses, dark one is less abundant. The dark one has less vesicles and microlites. The lighter one looks more devitrified and has more microlites.	Sieve texture in central and 2 nd zone of zoned plagioclase. Some turn out euhedral, some anhedral.	Aligned	Abundant small round ones, and large elongated ones	Some devitrified zones. Vesicles are calcite lined. Olivine is fractured. Large crystal aggregate of olivine with plagioclase crystals stuck to the outside. An olivine crystal is surrounding a plagioclase crystal.

Sample	Phenocryst Mineral	Crystal Shape	Crystal size	Microclites	Matrix	Textures	Alignment of microclites	Vesicles	Description
12-UH-04	Plagioclase: 10% Olivine: 15%	Plag: subhedral to euhedral Oliv: anhedral to subhedral	Oliv: 0.5-1mm Plag: 0.5 mm	Abundant 10%, patches without them	All dark glass, but patches with rare microclites and vesicles. Dark patches of glass seen on thin section.	Sieve texture on zoned plagioclase, 2 nd and central zone. Olivine is embayed.	Slightly sometimes	Abundant, patches without them	Olivine is fractured. Small fine grained clast, with plagioclase and calcite (?). It has a lot of small vesicles, very rough edges. Vesicles are calcite lined. Crystal aggregates of plagioclase and olivine exist.
12-UH-05	Plagioclase: 10% Olivine: 10% Spinell: <1%	Plag: anhedral to euhedral Oliv: subhedral Spin: subhedral to euhedral	Plag: 0.5mm Oliv: 0.1-2mm Spin: 0.01mm	Abundant 10%	All dark glass, some darker patches can be seen on the thin section	Some sieve textures, central and 2 nd zone of zoned plagioclase. Embayed olivine.	Slightly sometimes, some radial patches	Abundant	Crystal aggregates of plagioclase and olivine, and individually. Spinel, that is enveloped by plagioclase, and the embayment in the middle shows plagioclase. It has a hexagonal cross section, brown, and isotropic. Calcite lined vesicles.
12-UH-07	Plagioclase: 10% Olivine: 5%	Plag: subhedral to euhedral Oliv: subhedral to anhedral	Plag: 0.5-4 mm Oliv: 0.1-0.5 mm	Abundant: 10%	Very fine grained glass, devitrified?	Sieve texture, 2 nd zone in a zoned plagioclase. Plagioclase texture: where the middle is a bunch of small round crystals	none	Abundant	Most olivines have been stripped out by polishing. Olivine is fractured. A mostly plagioclase crystal aggregate seen.
12-UH-08	Plagioclase: 5% Olivine: 15% Spinel: <1%	Plag: anhedral to euhedral Oliv: subhedral WM: subhedral to euhedral	Plag: 0.01 mm Oliv: 0.5-2 mm WM: 0.01 mm	Abundant: 10%	2 different glasses, one fine grained (devitrified) with some darker patches, another quite glassy and only small sections.	Sieve texture in central or 2 nd zone of zoned plagioclase.	Aligned	Abundant, some sections more vesicle rich than others	Crystal aggregates of plagioclase and olivine. Spinel occurs again, with cored centers. Spinel found with both other minerals. Olivine is fractured.
12-UH-10	Plagioclase: 2% Olivine: 10%	Plag: anhedral Oliv:	Plag: 0.01 mm Oliv: 0.05-2	Abundant 10%	2 different glasses, one is darker, one is lighter. The darker	Olivine has fine grained inclusion in it, with lower	none	Abundant, some patches	Crystal aggregates dominated by olivine. An area of finer grained glass

Samp- le	Phenocryst Mineral	Crystal Shape	Crystal size	Microlites	Matrix	Textures	Align- ment of microli- tes	Vesicles	Description
12- UH-10 cont.		subhedral to anhedral	mm		has less microlites. And sometimes less vesicles.	birefringence. Looks almost like a slightly bigger grained glass. Sieve texture in one plagioclase crystal		have far more vesicles or later.	occurs, might be a remnant of polishing.
12- UH-13	Plagioclase: 10% Olivine: 10%	Plag: anhedral to euhedral Oliv: anhedral to subhedral	Plag: 0.01-1 mm Oliv: 0.5-1 mm	Abundant: 20%	Fine grained glass (devitrified?).	Sieve texture in central or 2 nd or 3 rd outside zone of plagioclase crystals. Looks embayed.	none	Abundant	Almost all dissolved plagioclase, with a vesicle in the middle. Crystal aggregates of both minerals.
12- UH-18	Plagioclase: 5% Olivine: 15%	Plag: subhedral to anhedral Oliv: subhedral	Plag: 0.01 mm Oliv: 0.01-1 mm	Abundant: 10%	Fine grained glass (devitrified?), darker patches seen. The dark parts are even finer grained.	Sieve texture seen in some zoned plagioclase, 2 nd zone.	Aligned, very aligned in some sections	Abundant	Crystal aggregates of both minerals and individually. Olivine is fractured.
12- UH-22	Plagioclase: 5% Olivine: 10%	Plag: subhedral to euhedral Oliv: subhedral	Plag: 0.01-1 mm Oliv: 0.01-4 mm	Abundant: 10%	Fine grained glass (devitrified?)	Embayed plagioclase with overgrowth, sieve texture in central or 2 nd zone.	Aligned	Abundant	Crystal aggregates of both minerals. Calcite lined vesicle and fracture. The fracture shows weathering in the glass. Quartz xenocryst?
12- UH-24	Plagioclase: 10% Olivine: 10%	Plag: subhedral to euhedral Oliv: subhedral	Plag: 0.05-2 mm Oliv: 1 mm	Abundant 10%	Dark fine grained glass.	Plagioclase with sieve texture in 2 nd zone. Zoned plagioclase.	Some alignm- ent	Abundant	Olivine might have been plucked out by polishing. Crystal aggregates of both minerals individually. Calcite lined vesicles.
12- UH-26	Plagioclase: 10% Olivine: 20%	Plag: subhedral to euhedral Oliv: subhedral to euhedral	Plag: 0.5 mm Oliv: 1-5 mm	Abundant 10%	Dark fine grained glass.	Zoned plagioclase with sieve texture in second zone. Massive olivine that is embayed.	Minor alignm- ent.	Abundant	Radial crystal aggregates of plagioclase and olivine and individually. Some olivines look very plucked out.
12- UH-28	Plagioclase: 10% Olivine: 15%	Plag: subhedral to euhedral	Plag: 0.01- 0.5 mm Oliv: 0.5	Abundant 15%	Very fine grained glass, some patches are darker with less	Tiny circular crystals on an embayed	None	Abundant, some patches with	Patch with a large amount of smaller microlites, a couple of mm large. Is it a

Sample	Phenocryst Mineral	Crystal Shape	Crystal size	Microlites	Matrix	Textures	Alignment of microlites	Vesicles	Description
12-UH-28 cont.		Oliv: subhedral	mm		visible crystals. Some slightly darker patches seen on the thin section.	plagioclase. Almost look like penetrating twins.		less	clast or a part of the glass? Very radial aggregates of plagioclase with some olivine. Calcite in some vesicles.
12-UH-29	Plagioclase: 15% Olivine: 15%	Plag: anhedral to euhedral Oliv: subhedral	Plag: 0.5 -5 mm Oliv: 0.5-7 mm	Abundant 50%	Fine grained matrix, much more abundant than the rest	Sieve texture in middle zone. Some plagioclase very embayed..	Somewhat for the bigger ones	Some, well spaced	Crystal aggregates of individual minerals. Plucked out large olivine. Olivine very fractured.
12-UH-33	Plagioclase: 10% Olivine: 15% Xenocryst: trace	Plag: anhedral to euhedral Oliv: subhedral to euhedral Xen: subhedral	Plag: 0.1-0.5 mm Oliv: 0.1- 1 mm MM: 0.01 mm	Some 5%	Dark very fine grained glass. Some darker patches of glass.	Some plagioclase looks like penetrating twins. Sieve texture seen in subhedral plagioclase.	Aligned	Abundant, some patches with less.	Crystal aggregates of plagioclase and olivine. Calcite lines some vesicles. Olivine a little cloudy in some crystals. Mystery xenocryst is a pale brown in color, very fractured, high relief, subhedral, and has either very high birefringence colors or low. It may be pleochroic. It is probably a xenocryst.
12-UH-37	Plagioclase: 10% Olivine: 15% Spinel: trace Pyroxene: 20% Opaques: 5%	Plag: anhedral to euhedral Oliv: subhedral Spin: anhedral Pyroxene: subhedral to euhedral	Plag: 0.1 - 0.5 mm Oliv: 0.5-3mm MM: 0.1 mm	Abundant 40%	Groundmass not as fine grained as everything else. Pyroxene and olivine found in groundmass.	Zoned plagioclase with sieve texture in 2 nd zone.	none	Some	Large aggregate of crystals intergrown together, looks almost intrusive. Plagioclase and olivine in it, and mystery mineral. Plagioclase is very embayed. The spinel is very fractured, maybe with cleavage, Pale brown in plane polarized light, very low birefringence in crossed nichols. High relief, Most

Sample	Phenocryst Mineral	Crystal Shape	Crystal size	Microlites	Matrix	Textures	Alignment of microlites	Vesicles	Description
12-UH-37 cont.									likely a xenocryst. Though it looks intergrown with the groundmass, but this may be from the crystallization of the groundmass. Pyroxene in groundmass. Lots of square opaques in groundmass.
12-UH-43	Plagioclase: 30% Olivine: trace	Plag: subhedral to euhedral Oliv: anhedral	Plag: 0.5-2 mm Oliv: 0.01mm	Abundant: 20%	Dark glass. Lighter patches seen on thin section.	Some embayed plagioclase. Sieve texture found in the central parts of plagioclase crystals. Plagioclase has regrowth zones. Some different plagioclase morphologies.	Aligned	None	Obviously the tertiary volcanic part of the sample. Olivine more brown than usual, high birefringence, lots of fractures, high relief, looks dissolved. Brown patches seen in plucked crystals, may be altered olivine, might be more than we can see. Brown patches also seen in some groundmass, might be pyroxene or olivine. Crystal aggregates of plagioclase.
12-UH-06	Plagioclase: 5% Opaques: trace	Plag: anhedral to subhedral	Plag: 0.01-2 mm	Little 3%	Fine grained, bands of darker and lighter colors.	Some plagioclase is pretty dissolved.	Aligned offset from the flow banding.	none	Flow banded rhyolite. Some opaques with the plagioclase. Most plagioclase has twinning, but its possible there is some qtz.
12-UH-36	Plagioclase: 50% Quartz: 25% Biotite: 15% Amphibole: 5%	Plag: subhedral Qtz: anhedral Bio: euhedral Amph: anhedral	Plag: 1 mm Qtz: 0.01 mm Bio: 0.01mm Amph: 0.01	N/A	N/A	Intergrown crystals, plagioclase seems to have phenocrysts. Plagioclase is zoned and shows sieve texture.	N/A	N/A	Granite. Amphibole could be pyroxene. Calcite found in fractures. There might be a little orthoclase in there too.

Sample	Phenocryst Mineral	Crystal Shape	Crystal size	Microlites	Matrix	Textures	Alignment of microlites	Vesicles	Description
12-UH-36 cont.	Opaques: 5%		mm Opaques: 0.01 mm						
13-UH-01	Plag: 15% Oliv: 10%	Plag: euhedral Oliv: subhedral	Plag: 0.01 mm Oliv: 0.05 mm	Abundant: 30%	Dark fine grained groundmass, patches of darker.	Some branching cracks though a portion of the lapilli. Some intergrown crystals.	Aligned	Some	Interstitial calcite.
13-UH-02	Plag: 15% Olivine: 20%	Oliv: anhedral to subhedral Plag: anhedral to euhedral	Plag: 0.5 mm Oliv: 3 mm	Abundant: 25%	Dark glass.	Sieve texture in middle zone of zoned plagioclase.	Only aligned around vesicles	Abundant and large	Vesicles seem to have microlites within them, maybe from erosion. Microlites sometimes clumped together. Fractured olivine.
13-UH-07	Plag: 5% Pyro: 0.01%	Plag: subhedral Pyro: anhedral	Plag: 0.5 mm Pyro: 0.01 mm	Abundant: 30%	Some palagonitized glass found, could be a lapilli. Both dark and light glass found. The lighter is more microlite rich.	Dissolution textures in the middle of some plagioclase.	Sometimes aligned.	Abundant	A lot of calcite lining the vesicles. A lot of different patches of glass, some altered.

Table 3: Thin section petrography of lapilli and ash samples from Upsal Hogback.

Sample	Grain size	Lapilli Glass Description	Lapilli Shape	Phenocryst minerals	Crystal Shape	Vesicles	Microlites	Palagonite	Description
12-UH-09	0.5 cm	1. Dark glass 2. pale brown glass, some patches of darker glass 3. Dark brown, less glassy	1. angular 2. sub angular 3. subangular	1. plag and oliv 2. plag and oliv 3. plag and oliv	1. subhedral 2. subhedral 3. subhedral	1. Abundant 2. abundant 3. abundant	1. about 5% 2. aligned in some, abundant 3. abundant	Some palagonite rinds present	Calcite cement between the lapilli, brown fine grained material, might be palagonite. The calcite is nodular. Some fine grained fragments that are just phenocrysts, mostly olivine. Dark brown has some radial bunch of plagioclase. Wide variety of type of glass in lapilli. Palagonite rinds more pronounced on some lapilli.
12-UH-11	0.01-5mm	Mostly pale brown glass. Very minor dark glass.	Angular	Plag and oliv	Euhedral to anhedral.	Abundant. Few lapilli have no vesicles.	Abundant and aligned.	Brown stuff could be palagonite, then lots. Not sure if ash.	Lapilli with no vesicles have large plagioclase crystals. Some free olivine crystals. High relief blocky mineral. Large difference in size of lapilli.
12-UH-12	0.01-5mm	Mostly pale brown glass. Very minor dark glass.	Angular	Oliv and plag. Mystery Mineral	Euhedral to anhedral.	abundant	Abundant and aligned.	Brown stuff could be palagonite, then lots. Not sure if ash.	A lot of fine grained interstitial material. Olivine is a bigger phenocryst. Crystals found free floating. Spherulitic rings around some lapilli, most likely calcite. Dark glass lapilli are more plagioclase rich. Mystery mineral, probably pyroxene, pale green, low birefringence, mostly free floating, optically positive, maybe pleochroic, and inclined extinction. Lapilli on edge that has much more microlites, and another dark brown mineral, isotropic. Bright red pleochroic mineral, to pale brown like the glass, high relief, low birefringence, is it a piece of

Sample	Grain size	Lapilli Glass Description	Lapilli Shape	Phenocryst minerals	Crystal Shape	Vesicles	Microlites	Palagonite	Description
12-UH-12 cont.									biotite? Yellow mineral, yellow birefringence too, looks fine grained.
12-UH-14	0.01m m	Pale brown glass, some darker glass.	Angular	Oliv and plag	Anhedral	Some in bigger lapilli	Some	Found on one lapilli	Very fine grained, little large lapilli. Crystal are free floating, look embayed. Same yellowish mineral as above. Presence of interstitial calcite. Darker glass has more plagioclase. Some fine grained low birefringence clasts, probably are xenocrysts.
12-UH-15	0.01-1mm	Pale brown glass, some darker glass lapilli.	Angular	Oliv and plag	Euhedral to anhedral	Abundant	Abundant and sometimes aligned	Some concentrated around a few lapilli	Big olivine crystals. Fine grained clast, with a bit of green mineral in, it, probably a xenocryst.. Lapilli boundaries are less defined.
12-UH-16	0.01-1mm	Pale brown glass, some darker glass lapilli	Angular	Oliv and plag	Subhedral to anhedral	Abundant	Some	Brown stuff could be palagonite, then lots. Not sure if ash. Very Minor	Fairly fine grained, much more interstitial material than usual. A lot of free-floating crystals, mostly olivine. Presence of interstitial calcite. The dark glass lapilli vary in microlite richness, not much olivine, nor vesicles. Crystals are fairly fractured. Some lapilli have more of a groundmass. Lapilli have rinds around them, palagonite or armored? Yellow mineral from above, fragment from previous eruption of palagonite?
12-UH-17	0.5-5 mm	Pale brown glass	Angular	Oliv and plag	Euhedral to anhedral	Very Abundant	Abundant and aligned	Some	Abundance of large xenocrysts. One very dark glass lapilli, looks very embayed, probably a xenocryst, very crystal rich. Fair number of free-floating crystals. Some more vesicle free lapilli have more of a fine grained groundmass than a glass. Red xenocryst, maybe palagonite.

Sample	Grain size	Lapilli Glass Description	Lapilli Shape	Phenocryst minerals	Crystal Shape	Vesicles	Microlites	Palagonite	Description
12-UH-17 cont.									Other xenocrysts are grey or yellow and fine grained, look like granite.
12-UH-19	0.01-2 mm	Mostly pale brown glass, some darker glasses found	Angular	Oliv and plag	Anhedral	Abundant	Abundant	Dominant in some areas	Big dark glass lapilli has 2 different glasses, one slightly lighter, lighter glass has a groundmass. It is microlite rich, and has plagioclase and olivine phenocrysts. Calcite in vesicles. Some areas with smaller fragments. Oxides and mystery brown mineral. Lots of olivine over plagioclase.
12-UH-20	0.01m m	Pale brown glass, some darker glass	Angular	Oliv and plag.	Anhedral	Some	Some	Might be some, some in clasts	Most of it is very fine grained, though some larger fragments. Some rinds seen on armored lapilli. A yellow unknown mineral in as a clast. More olivine than plagioclase, one or two look embayed. Some areas have more area between the particles.
12-UH-21	0.01-1mm	Pale brown glass, some darker glass	Angular	Oliv and plag	Anhedral	Abundant	Abundant and sometimes aligned	Minor palagonite around some lapilli	More olivine than plagioclase. Mystery brown mineral present. Fine grained xenocrysts present. Dark glass lapilli very plagioclase and microlite rich, and has very large olivines. It is embayed. Yellow mineral present.
12-UH-23	0.01-0.5m m	Pale brown glass, some darker lapilli	Subangular	Oliv and plag	anhedral	Abundant	Some	Brown stuff could be palagonite, then lots. Not sure if ash.	Fairly fine grained, but some larger lapilli, normally of a darker glass. Dark glass is less vesicle rich. There are rinds around some of the lapilli. A lot more of the clear interstitial material, ash or epoxy? Areas with more pale brown glassy fine clasts. The clear stuff has more brown "maybe palagonite" material with it. Lots of free floating crystals of

Sample	Grain size	Lapilli Glass Description	Lapilli Shape	Phenocryst minerals	Crystal Shape	Vesicles	Microlites	Palagonite	Description
12-UH-23 cont.									olivine. Lapilli, that are dark brown and very plagioclase rich. Many fine grained xenocrysts.
12-UH-25	0.01-5mm	Pale brown glass, some darker lapilli	Angular	Oliv and plag	anhedral	Abundant	Some	Some	Some plagioclase crystals are intergrown. Vesicles are filled with calcite. Lots of interstitial calcite. Some free floating crystals, some are fairly large. Mystery blue mineral, high relief, high birefringence, near the epoxy, probably polishing grit. The mystery brown mineral also makes an appearance. Some phenocrysts inside a dark lapilli have halos of darker glass around them, mixing texture? One lapilli has elongated vesicles.
12-UH-27	0.1-1mm	Pale brown glass, with some darker glass lapilli	Angular	Oliv and plag	Euhedral to anhedral	Abundant	Abundant, aligned sometimes	Minor?	Less interstitial space, harder to define lapilli boundaries. Lapilli where a large phenocryst will dominate, primarily olivine. Dark brown mystery mineral is present. Some vesicles are filled with calcite. One dark lapilli has no vesicles, another has less but larger ones. Interstitial calcite is present. Some free floating olivine crystals. Green mineral, high relief, low birefringence, probably pyroxene. Some crystals are embayed. Yellow mystery mineral in a microlite rich xenocryst. Some lapilli have elongated vesicles.
12-UH-30	0.01-20mm	Majority is pale brown glass, but some very large darker	Angular	Oliv and plag	subhedral	Abundant	Abundant, sometimes aligned	Around edges of lapilli	Free floating crystals. Xenocrysts are present. Small piece of what looks like biotite. There are rinds around the lapilli, maybe palagonite. Microlites look

Sample	Grain size	Lapilli Glass Description	Lapilli Shape	Phenocryst minerals	Crystal Shape	Vesicles	Microlites	Palagonite	Description
12-UH-30 cont.		glass lapilli							aligned around the edges. A lot of cored phenocrysts. A very different amount of grainsize. Some olivines look cloudy, maybe slight alteration or weathering. Some phenocrysts are embayed.
12-UH-31	0.01-5mm	Pale brown glass, but there are some larger darker lapilli	Subangular	Oliv and plag	anhedral	Abundant	Abundant in some lapilli	Brown stuff could be palagonite, then lots. Not sure if ash.	Free floating crystals, mostly olivine. Some are embayed and quite large. Brown mineral appears inside the embayment of one of them, curls around, or is it just cored? Pleochroic mineral, high birefringence, parallel extinction, very pale brown to very pale green. Maybe some biotite, looks very weathered, in one lapilli that's very plagioclase rich, probably a xenocryst.
12-UH-32	0.01-0.5mm	Pale brown glass	Angular	Oliv, plag, spinel	Subhedral to anhedral	Abundant	Some	none	In some areas the lapilli boundaries are hard to distinguish. Spinel very similar to the one above, but it is a slightly paler brown, maybe because it's a larger crystal? Some of the darker brown also found, some of it cored. Some free floating crystals. Lots of interstitial dark stuff, polishing grit? A few darker brown glass lapilli.
12-UH-34	0.01-5mm	Primarily pale brown glass with a few darker glass lapilli	Angular	Oliv and plag	Euhedral to anhedral	Abundant	Some, sometimes aligned	Very abundant Rims around lapilli	Pleochroic pale green mineral, high relief, angular extinction, probably some pyroxene. Very similar crystals, pleochroic pale brown and pale green, and a lower birefringence. Free floating crystals, some are embayed. Large variety of amount of vesicles in the darker glass lapilli.

Sample	Grain size	Lapilli Glass Description	Lapilli Shape	Phenocryst minerals	Crystal Shape	Vesicles	Microlites	Palagonite	Description
12-UH-34 cont.									Some interstitial calcite. There are some large zoned plagioclase. Two lapilli with 2 different glasses, one black, another a dark brown groundmass. An area of one of them is a radial bunch of plagioclase crystals.
12-UH-35	0.01-3mm	Pale brown glass with a few lapilli with darker glass	Angular	Oliv and plag	Euhedral to anhedral	Abundant	some	none	Most of the pale brown glass is smaller than the darker glass lapilli. Sometimes the vesicles are elongated. Some of the olivine is cloudy from a little alteration. Lots of free floating crystals. One piece of biotite found. Lots of interstitial ash. A couple of fine grained xenocrysts.
12-UH-38	0.01-5mm	Pale brown glass with a lot of darker glass lapilli.	Angular	Plag and oliv	Euhedral to anhedral	abundant	abundant	A lot, it forms rinds around the lapilli and into the glass.	Large clast of tufa, has concentric circular structures made of carbonate. Some mineral crystals are also found, probably plag, oliv, and pyroxene. The palagonite makes the clasts look rounder. Brown isotropic mineral is found. A lot of blueish grey interstitial material, some of it looks like a blue high relief mineral, might be from polishing. Some of the dark glass lapilli are extremely plagioclase rich and have the yellow mystery mineral in it. Smaller fragments of glass are completely palagonitized. There is interstitial calcite. Vesicles are filled with calcite. Brown isotropic mystery mineral is also found. Darker glass lapilli seem more microlite rich than the paler glass. Some of the paler glass lapilli have the darker glass

Sample	Grain size	Lapilli Glass Description	Lapilli Shape	Phenocryst minerals	Crystal Shape	Vesicles	Microlites	Palagonite	Description
12-UH-38 cont.									patches in them.
12-UH-39	0.01-10mm	Pale brown glass with a few darker glass lapilli	Angular	Oliv and plag	Euhedral to anhedral	abundant	abundant	A lot, forms rinds around the lapilli	Even vesicles are lined with palagonite. The darker lapilli seem to be more plagioclase and microlite rich. Calcite occurs in the vesicles and interstitially. The large dark lapilli has more of a groundmass than a glass. Clast of what looks like carbonate and clear mineral with low birefringence and fine grained, it has a bright green mineral in it, similar to the yellow, high birefringence (yellow) and very fine grained.
12-UH-40	0.01-10mm	Mostly pale brown glass with some darker lapilli	subangular	Oliv and plag	Euhedral to anhedral	abundant	Abundant, sometimes aligned	none	Presence of interstitial calcite. Some of the dark brown mystery mineral. Clast of calcite with bulbous pattern, found near interstitial calcite. Pale brownish-green mineral, low birefringence, angular extinction, high relief, probably pyroxene. Calcite fills some vesicles. Two small pieces of biotite. Dark clasts vary in amount of vesicles. Fine grained xenocryst. Small speck of yellow mineral.
12-UH-41	0.01-10mm	Pale brown glass, a few darker glass lapilli	angular	Plag and oliv.	Euhedral to anhedral	abundant	some	A lot in one area associated with calcite	Rinds around the lapilli. Free floating crystals. Interstitial calcite. The phenocrysts look a bit clouded, might be alteration or the polishing. The darker glass lapilli are variable in vesicles and phenocryst abundances.
12-UH-42	0.01-5mm	Pale brown glass with a lot of darker	Subrounded to subangular	Oliv and plag, brown mystery mineral	Euhedral to anhedral	abundant	Abundant, sometimes aligned	none	The lapilli have rinds around them. The darker lapilli have far less vesicles and are more

Sample	Grain size	Lapilli Glass Description	Lapilli Shape	Phenocryst minerals	Crystal Shape	Vesicles	Microlites	Palagonite	Description
12-UH-42 cont.		glass lapilli							phenocryst rich with more euhedral crystals. There is a dark brown isotropic crystal.
12-UH-44	0.01-10mm	Pale brown glass, a few darker glass lapilli	Subrounded to subangular	Oliv and plag	Euhedral to anhedral	abundant	some	none	Mostly fine grained with a few larger lapilli in it. Pleochroic green mineral, pale green to bright green, high birefringence, and small.
12-UH-45	0.01-20mm	Pale brown lapilli with a lot of darker glass lapilli	Subrounded to angular	Oliv and plag, brown mystery mineral	Euhedral to anhedral	abundant	Abundant sometimes aligned	Very minor	Some lapilli have elongated vesicles. Brown mystery mineral appears. Some crystals have sieve textures and are embayed while others have perfect crystals structures. Small pale brown xenocryst, rounded and very fine grained. The large dark glass fragment is full of plagioclase crystals. Pleochroic green mineral, pale green to bright green, high birefringence, and small. Yellow mineral or xenocrysts, a bit orangish, with the fine grained under crossed polars.
13-UH-03	3mm	Pale brown and dark brown lapilli	subrounded	Oliv and plag	Euhedral to anhedral	abundant	Abundant	none	Interstitial calcite present, vesicles completely infilled. Calcite seems to have either infilled a void or was a clast in one of the lapilli. Free floating crystals in the calcite.
13-UH-04	5mm	Pale brown glass, a few dark lapilli	subangular	Oliv and plag	Subhedral to euhedral	abundant	Abundant, aligned	Some, interstitially around lapilli	Small chlorite or pyroxene crystal, green and pleochroic. Some interstitial calcite and in vesicles. Some lapilli have more microlites than others. Some minerals and glass of one lapilli look like they have a yellow stain. A lithic fragment is present that is fine grained.

Sample	Grain size	Lapilli Glass Description	Lapilli Shape	Phenocryst minerals	Crystal Shape	Vesicles	Microlites	Palagonite	Description
13-UH-05B	0.1m m	Mostly pale brown glass, with a few dark glass lapilli	Subangular to subrounded	Oliv and plag	anhedral	few	few	none	Mostly very fine grained, with a few larger lapilli and lithics. Yellow mystery mineral present too. Ashy rinds around lapilli. A biotite clast is also seen.
13-UH-05T	0.15m m	Mostly pale brown glass, with a some dark glass lapilli	Subangular to subrounded	Oliv and plag	Anhedral to euhedral	some	some	minor	Slight coral tinge on fractures of olivine crystal. One lapilli is half dark glass, and half dark brown glass. Crystal aggregates of plag and oliv are present. Some ashy rinds are found, thicker around crystals.
13-UH-06	0.1m m	Some pale brown glass and some dark glass	Subrounded to rounded	Oliv and plag	Anhedral to subhedral	some	some	Extremely palagonitized, both interstitially, clearly into lapilli, and in rinds	Interstitial dark material, could be dark ash? Not all lapilli are palagonitized. Lots of interstitial calcite, some almost behave like crystals. What looks like a small piece of tufa is found as a rounded clast. Bigger lapilli are more subangular.

Table 4: Petrography of lapilli and ash tuff slabs.

Samp-le	Grain Size	Grain Shape	Grading	Sorting	Bedding (top down)	Ash % Lapilli (lithic incl) %	Lithics	Lithic Abundance	Armoured/rinds	Palagonite	Description
12-UH-09	5mm	Rounded to subrounded	none	moderately	none	A:25% L: 60% C: 15%	Rhyolite fragments, one of dark red material (tertiary basalt?)	5%	Calcite rinds, and some palagonite rinds	Minor around a few lapilli, some looks around it, others look like its eating into it	One large rhyolite fragment, most other lithics are similar in size of lapilli. One large elongated lapilli but the rest are pretty rounded. Palagonite is found around a few lapilli. Calcite cements most of the lapilli together, there is some ash. This tuff could actually be reworked. 3 different lapilli seen, black, dark brown and light brown. Variable in vesicles, olivine phenocrysts seen.
12-UH-11	1. 2 mm 2. 0.01 and 3mm 3. 2mm 4. 0.01 and 3mm 5. 3mm 6. 0.01 and 5mm 7. 4mm	Subrounded to subangular	Only some in 4, reverse	1. moderate 2. poor 3. moderate 4. poor 5. poor 6. poor 7. poor	7 beds seen, alternates between coarse grained to very fine grained, 6 looks slightly cross bedded at the back of the slab	A:35% L: 65%	Small red fragment	0.1%	Prevalent in the coarser grained layers	None, except one palagonitized clast	White material appears on some of the surface, is it from the bigger saw blade water? Plagioclase and olivine seen as phenocrysts. Beds 2, 4, and 6 are more ash rich than the others. Only one palagonitized clast, is it a xenocryst? Fine grained layers are thinner, but similar in thickness to one another.
12-UH-12	1. 0.1 and 3mm 2. 0.01 and 5mm	Subrounded to subangular	Reverse graded on top bed, normally graded bottom	1. poor 2. poor	2 beds	A: 40% L: 60%	Some rhyolite fragments and a tertiary basalt	0.1%	Only palagonite seen	Some, on rinds around a few lapilli, not the full way around, mostly on	Plagioclase and olivine seen as loose crystals on top. Olivine seen as phenocryst mineral. Small patch of different glass seen in a lapilli. Large difference of grainsize seen in bottom bed.

Samp-le	Grain Size	Grain Shape	Grading	Sorting	Bedding (top down)	Ash % Lapilli (lithic incl) %	Lithics	Lithic Abundance	Armoured/rinds	Palagonite	Description
12-UH-12 cont.							fragment, small			the bottom of the lapilli	
12-UH-14	0.01m m	Subangular	none	Very well	There could be some slight bedding, but none really seen	A:97% L:3%	Small pale orange fragments, a few small orange ones	0.1%	none	None, maybe the small orange fragments?	Very ash rich. A few larger fragments up to 1mm are seen throughout but a very few. Plagioclase is a phenocryst phase.
12-UH-15	1.1-2mm 2.1-3mm 3.0.1m m	Subangular	none	1. poorly 2. poorly 3. well	3 beds, possibility of more	A:25% L:75%	Red tertiary basalt fragments or rhyolite	0.1%	Only palagonite	Some, along edges of bottom layer, and on top of lapilli	Plagioclase as phenocryst mineral and as free floating crystals. There could be more beds, but they are hard to distinguish. Palagonite only occurs on some parts of the outside of the lapilli.
12-UH-16	1.0.01 and 4mm 2. 1 mm 3. 0.1m m 4. 1-2mm 5.0.1m m 6.1-2mm	Subangular	In layer 1, reverse	1. poor 2. moderate 3. well 4. poor 5. well 6. poor	6 layers, 2 and 4 are very thin	A: 50% L:50%	Rhyolite, tertiary basalt	0.5%	Some thin ash rinds	Minor palagonite on bottom exposed lapilli	Fairly ash rich, with very small lapilli. The layer 1 is the thickest, the rest are similar in size. Not much palagonite.
12-UH-17	1-20mm	angular	none	poor	none	A:20% L:80%	Rhyolite, a few orange and yellow xenoliths,	1%	A bit seen on some lapilli. Only a few	Minor, Only a few rinds of palagonite	Olivine and plagioclase seen as phenocryst minerals. Mostly lapilli with some interstitial ash. Some rinds of ash on a couple of lapilli. A few unidentified lithics of different colors.

Samp-le	Grain Size	Grain Shape	Grading	Sorting	Bedding (top down)	Ash % Lapilli (lithic incl) %	Lithics	Lithic Abundance	Armoured/rinds	Palagonite	Description
12-UH-17 cont.							not sure what they are		lapilli with palagonite seen		
12-UH-19	5 mm	angular	none	poor	none	A:20% L:80%	Rhyolite	3%	A few seen around lapilli	Seen around a few lapilli, thicker in some areas, found in some interstitial ash	Olivine and plagioclase seen as phenocryst minerals. Long elongate plagioclase crystals seen.
12-UH-20	0.01-1mm	Subrounded	none	well	Possible, but sample quality makes it hard to distinguish	A:95% L:5%	Rhyolite, a few small specs of red, probably tertiary basalt	0.5%	none	none	Sample broke into 3 pieces, epoxied back together (not perfectly). Rhyolite fragment is larger than the average grainsize for the sample, looks flow banded.
12-UH-21	0.01-15mm	Subrounded to angular	none	poor	none	A:50% L:50%	Tertiary basalt	1%	One rind seen around large lapilli	Minor, seen around a couple of lapilli	Free floating olivine crystals. Plagioclase and olivine as phenocryst minerals. It is surprisingly ash rich. Not very much palagonite.
12-UH-23	0.01mm	Subangular	none	well	none	A:98% L:2%	A few light colored and red specks	0.01%	Perhaps in the clumps.	none	There seems to be balls of ash, or very pale glass lapilli. Are they accretionary lapilli or clumped together by moisture? Epoxy didn't penetrate a couple.
12-UH-25	1.0-10mm 2.1-3mm 3.0-1mm	Subangular	1 st layer is normally graded	1.moderate 2.moderate 3.poor	3 layers	A:45% L:55%	One small speck of red, tertiary basalt?	0.001 %	Maybe one	All over the bottom. Found a bit on top of third layer.	Lapilli of different shades, brown and dark grey, several lapilli even has both, the brown glass is on the outside. Surprisingly little lithics. Olivine and plagioclase as phenocryst minerals. Free floating

Samp-le	Grain Size	Grain Shape	Grading	Sorting	Bedding (top down)	Ash % Lapilli (lithic incl) %	Lithics	Lithic Abundance	Armoured/rinds	Palagonite	Description
12-UH-25 cont.											plagioclase crystals. 3 rd layer more ashy, 1 st layer has ash but is also graded.
12-UH-27	1mm	Subangular	none	moderate	None?	A:60% L:40%	Small pieces of red and white rock, tertiary basalt for the red?	0.1%	none	none	Might have some calcite precipitate, white coverings n some lapilli are present.
12-UH-30	1.2mm 2.0.01 - 20mm 3.0.01 -5mm 4.0.01 -5mm 5.0.01 -7mm	angular	None, maybe some in 1 st layer, reverse grading	1.well 2.poor 3.poor 4.poor 5.poor	At least 2 beds, maybe around 5	A:45% L:55%	Granite	0.5%	Seen around a few of the lapilli	Palagonite seen on big lapilli and interstitially	Free floating plagioclase crystals present. There are more sections that are lapilli rich. The large lapilli that is 3cm in size has 2 glasses, a dark brown one enveloping a dark grey one. Olivine and plagioclase are phenocryst minerals. Grading depends on where you put layer boundary. Nice olive crystal sticking out of one of the lapilli.
12-UH-31	1.0.01 -2mm 2.0.01 -5mm	angular	1.reverse graded	1.well 2.moderate	2 bedding sets, one is cross bedded. Maybe 4 or 5 layers in the cross bedded set.	A:70% L:30%	A few granite lithic fragments	0.5%	Seen on one lapilli	none	Cross bedding! One section looks like a rounded clump, hard to see. Some layers in cross bedded set are more ash rich. The cross bedding set might be overlain by a thin layer of ash, might be part of layer above. Dark grey and light grey glasses for lapilli.
12-UH-32	1.0.1-4mm 2.0.01 -1mm	Subangular	none	1.poor 2.moderate 3.poor	3 beds?	A:70% L:30%	Tan fragment looks like calcite or	1%	none	none	Brown and dark grey lapilli. Free floating plagioclase crystals. Surprisingly ash rich, though there are some hard to see lapilli.

Samp-le	Grain Size	Grain Shape	Grading	Sorting	Bedding (top down)	Ash % Lapilli (lithic incl) %	Lithics	Lithic Abundance	Armoured/rinds	Palagonite	Description
12-UH-32 cont.	3.0.01-5mm						qtz				
12-UH-34	0.01-30 mm	angular	none	poor	none	A: 55% L: 45%	none	0%	One seen on one lapilli	The whole thing looks fairly palagonitized except for the lapilli	Very large lapilli, looks mostly square, and made of dark glass. The rest of the lapilli are fairly small. Olivine and plagioclase seen as phenocrysts material. Free floating olivine and plagioclase crystals.
12-UH-35	0.01-5mm	Subangular to angular	none	poor	none	A:40% L:60%	Red and black vesicular clast, probably a tertiary basalt, rhyolite, and more tertiary basalt	2%	Only seen on 3 lapilli	none	Different types of glass: dark grey, and dark brown. More dark brown. Olivine and plagioclase seen as phenocryst phases.
12-UH-38	0.1-15mm	Subrounded to subangular	none	poor	none	A:25% L:75%	Carbonate (tufa?), tertiary basalt	3%	Some seen, could be palagonite	All throughout the interstitial material, eating into some of the lapilli	Lots of palagonite. The appearance of what could be tufa could mean this is a reworked sample. The exposed side shows a lot of what might be carbonate. The carbonate clasts have a pale yellow to neon yellow color and the main round clast has a halo. Its quite a jumble.
12-UH-39	0.01-20mm	Subangular to angular	none	poor	none	A:45% L:55%	White piece of rock (carbonate?), green piece, tertiary	0.5%	Palagonite rinds on most lapilli	All through the interstitial material and eating into some lapilli	Lots of palagonite. One large lapilli has a vesicle filled with palagonite. Primarily dark glass. Free floating plagioclase crystal. There are several different glasses, light grey, dark grey, brown. One lapilli looks light grey, with a dark grey rind on

Samp-le	Grain Size	Grain Shape	Grading	Sorting	Bedding (top down)	Ash % Lapilli (lithic incl) %	Lithics	Lithic Abundance	Armoured/rinds	Palagonite	Description
12-UH-39 cont.							basalt				it.
12-UH-40 12-UH-40 cont.	1. 0.5m 2. 0.5-10mm 3. 0.5m 4. 1-5mm 5. 0.5m 6. 0.5-3mm	Subrounded to subangular	none	1.moderate 2.poor 3.moderate 4.poor 5.moderate 6.poor	6 beds, not well defined	A:25% L:75%	Rhyolite, tertiary basalt	1%	Seen on one lapilli	none	Plagioclase and olivine seen as phenocrysts, some xenocrysts seen in the lapilli. Bedding is seen but it is not very distinctive. Wide range of glass: brown, dark grey, and lighter grey.
12-UH-41	1.0.1-20mm 2. 1-4mm 3. 0.5mm 4. 1mm	Angular to subangular	Beds can put together and make two normal graded beds	1. well 2. moderate 3.poor 4.poor	4 beds, not well defined	A:40% L:60%	Granite, tertiary basalt	0.5%	Seen on most lapilli, a lot are palagonitized	Palagonitized rinds appear around lapilli, seen on bottom of sample	Palagonite seen in rind around xenocryst, so there must have been an ash first. Clast with pale brown glass around a dark glass center with a palagonite rind. Large clast in the corner, very rounded, has a bit of palagonite around the edge, looks vesicular, has a dark center, light be pale brown glass around a dark glass. Olivine and plagioclase as phenocryst phases. First layer is mostly fine grained except for one large clast.
12-UH-42	1-2mm	Subangular	none	moderate	none	A:40% L:60%	rhyolite	0.1%	Some around lapilli, but not all	none	One big bomb fragment, with olivine as phenocrysts. Dark brown and dark grey glass as lapilli, even in the bomb. The rest is fairly the same size.
12-UH-4	1.0.1m	angular	6 th bed is graded	1.well 2.moderate	8 beds, alternate	A:70% L:30%	Tertiary basalt,	0.1%	Palagonite	A little on the bottom	The bedding is rippled. It is mostly seen in the first four layers. The

Samp-le	Grain Size	Grain Shape	Grading	Sorting	Bedding (top down)	Ash % Lapilli (lithic incl) %	Lithics	Lithic Abundance	Armoured/rinds	Palagonite	Description
12-UH-44 cont.	2.0.01 - 0.5m 3.0.5m 4.0.01-3mm 5.0.1m 6.0.01-0.1m 7.0.01mm 8.1-2mm		reversely.	3.well 4.poor 5.well 6.moderate 7.well 8.moderate	between light brown and darker brown.		granite		rinds on bottom layer,	layer around some clasts	light colored beds may be because they are more ash rich. 6 th layers has a lighter bottom edge to it, could be another bed.
12-UH-45	0.1-15mm	Subangular to angular	none	poor	none	A:40% L:60%	Basalt with amygdules or anhedral plag, rhyolite, granite	3%	Some palagonite rinds, and a lot of ash rinds	Some palagonite rinds around some lapilli, thicker on top	Plagioclase and olivine as phenocryst minerals. 2 different types of glass brown and dark grey, even one lapilli is split down the middle with both. The lithic even has a palagonite rind on top, must be ash.
13-UH-04	1.0.1-3mm 2.0.1-5mm 3.0.1-10mm	Subangular to angular	None, maybe some reverse grading in top layer	1.poor 2.poor 3.poor	3 possible beds	A: 30% L: 70%	Large rhyolite fragment	5%	Palagonitized and non-palagonitized rinds on some lapilli	Palagonite rinds, mostly on top of lapilli	Palagonite is in the corner of the rhyolite piece. The three beds have different proportions of large clasts, the second has more.
13-UH-05B	1.0.01-1mm 2.0.1m	Subangular	none	1.poor 2.moderate 3.moderate	4 beds	A:70% L:30%	Rhyolite, tertiary basalt	3%	none	none	Small piece, multiple layers. Surprising amount of lithics.

Samp-le	Grain Size	Grain Shape	Grading	Sorting	Bedding (top down)	Ash % Lapilli (lithic incl) %	Lithics	Lithic Abundance	Armoured/rinds	Palagonite	Description
	m 3.1-2mm 4.0.1-1mm			4.poor							
13-UH-05T	1.0.1mm 2.0.01 - 0.1mm 3.0.1mm 4.0.01mm 5.0.5mm 6.0 1mm 7.0.5mm 8.0.1mm 9.0.5mm	Subrounded	none	1.moderate 2.moderate 3.moderate 4.well 5.well 6.well 7.moderate 8.well 9.poor	Beds that are undulating, 9 possible	A:70% L:30%	Granite?	0.1%	none	none	Preliminary results as sample is not polished and falling apart. Some of it almost looks rippled, may just be saw marks. Beds seem to be similar, maybe a slight clast size change. Some lapilli may have calcite around them, might be product of epoxy.
13-UH-06	0.1-1mm	Subrounded to subangular	none	poor	none	A:95% L: 5%	White speck (granite?)	0.1%	Palagonite rounds around some lapilli	Palagonitized throughout	Pale brown and dark grey glass for lapilli. Free floating olivine crystals. Slightly more pale brown glass at the bottom.

A.4 Updated Map

Figure 98: Close up of geomorphological map of Upsal Hogback edifice.

Figure 99: Close up of the edifice with structural measurements.

Figure 100: Close up of geomorphological map of north complex of Upsal Hogback.

Figure 101: Close up of geomorphological map of the south complex of Upsal Hogback.

Figure 102: Structural measurements of the north complex.

Figure 103: Structural measurements of the south complex.

Figure 104: Close up of structural measurements around the hogback area.

Figure 105: Close up of west side of the south complex with structural measurements.

Figure 106: Close up of structural measurements of the east side of the south complex.

Appendix B Geochemistry

B.1 Chapter 2 Abstract

Upsal Hogback, a Quaternary tuff cone north of the city of Fallon, Nevada, is comprised of up to four vents composed of indurated lapilli and ash tuffs with olivine and plagioclase phyric basaltic bombs. These were sampled in order to characterize the geochemistry of the volcano. The geochemistry shows that the north and south complex of the volcano have similar geochemical signatures, but are distinguishable. The nearby volcanic centers of Soda Lakes (~3 ka maars), Rattlesnake Hill (~1 Ma volcanic neck), and Buffalo Valley Volcanic Field (1-3 Ma spatter cones and lavas) show geochemical signatures similar those of Upsal Hogback (Cousens et al., 2012; Shevenell et al., 2005). Their trace element geochemical signatures indicate a spinel peridotite or low percent garnet peridotite asthenospheric mantle source. The source of melt is the result lithospheric thinning beneath the Humboldt Lineament, extension in the Basin and Range, and shearing in the Walker Lane.

B.2 Sample Locations

Table 5: Location of sample stations.

Station	UTM Easting (NAD 1927)	UTM Northing (NAD 1827)	Sample Number
20-9	345018	4387599	12-UH-01
20-13	344942	4387734	12-UH-02
20-20	344925	4387782	12-UH-03
21-6	344984	4387763	12-UH-04, 05
21-6	344984	4387763	12-UH-04, 05
21-1a	345109	4387542	12-UH-06
21-12a	344671	4387785	12-UH-07
22-6	345318	4387888	12-UH-08
22-9	345397	4388401	12-UH-09
22-15	345476	4387950	12-UH-10
22-20	345400	4387717	12-UH-11
22-1a	345309	4387260	12-UH-12
22-3a	345431	4387324	12-UH-13
22-5a	345500	4387329	12-UH-14, 15
23-1	345009	4388293	12-UH-16, 17
23-4	345059	4388639	12-UH-18
23-4	345059	4388639	12-UH-18
23-7	344807	4388564	12-UH-19, 20
23-8	344635	4388340	12-UH-21, 22
25-15	345580	4389426	12-UH-28
25-8a	344745	4390175	12-UH-23
25-9a	344710	4390093	12-UH-24
25-11a	344825	4389681	12-UH-25
25-13a	344916	4389505	12-UH-26
25-17a	345195	4389201	12-UH-27
25-21a	346241	4389437	12-UH-29
26-1	346234	4389339	12-UH-30, 31, 32, 33
26-1	346234	4389339	12-UH-30, 31, 32, 33
26-5	346155	4389797	12-UH-34
26-6	346002	4390238	12-UH-35
26-7	345955	4390340	12-UH-36, 37

Station	UTM Easting (NAD 1927)	UTM Northing (NAD 1827)	Sample Number
27-2	344917	4387765	12-UH-38, 39
27-3	345119	4387552	12-UH-40
28-1	345487	4389415	12-UH-41
28-4	345604	4390884	12-UH-42, 43
28-6	345742	4390948	12-UH-44
28-9	346323	4390259	12-UH-45
10-1	344552	4386221	13-UH-01
10-3	345400	4384988	13-UH-02
10-5	344393	4387169	13-UH-03
10-12	344494	4387758	13-UH-04
10-13	344679	4387778	13-UH-05
12-4	346157	4389799	13-UH-06
12-9	345560	4383202	13-UH-07

B.3 Geochemistry

Table 6: Major element geochemistry analyzed by the OGS.

Sample	Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	LOI	MgO	MnO	Na ₂ O	P ₂ O ₅	SiO ₂	TiO ₂	Total
	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%
12-UH-01	16.36	9.685	10.37	1.34	-0.23	8.67	0.17	3.22	0.469	47.65	1.72	99.42
12-UH-02	16.2	9.984	10.34	1.31	0.27	9.04	0.171	3.06	0.463	47.21	1.68	99.73
12-UH-03	15.89	10.127	10.08	1.17	1.72	9.1	0.166	3.31	0.461	46.25	1.64	99.91
12-UH-04	16.19	10.444	10.2	1.27	0.87	8.92	0.169	3.14	0.464	47	1.67	100.34
12-UH-05	16.14	9.594	10.26	1.27	0.24	9.58	0.167	2.94	0.456	47.26	1.65	99.56
12-UH-07	16.37	9.759	10.31	1.32	0	8.92	0.169	3.29	0.468	47.86	1.68	100.15
12-UH-08	16.35	10.312	10.36	1.28	0.36	8.73	0.17	3.14	0.491	47.06	1.73	99.98
12-UH-10	15.97	9.681	10.36	1.3	-0.09	9.59	0.173	3.09	0.456	47.52	1.63	99.68
12-UH-13	16.69	10.173	10.29	1.35	-0.17	8.02	0.17	3.24	0.494	47.63	1.77	99.66
12-UH-18	16.06	9.667	10.47	1.25	-0.1	9.62	0.171	3.1	0.468	47.21	1.68	99.6
12-UH-22	16.15	9.992	10.53	1.28	0.08	9.55	0.174	3.09	0.477	47.3	1.67	100.29
12-UH-24	15.55	9.532	10.78	0.96	-0.37	11.56	0.174	2.85	0.399	47.03	1.48	99.95
12-UH-26	15.38	9.28	10.56	0.94	0.14	11.64	0.165	2.74	0.361	46.59	1.44	99.24
12-UH-28	15.08	9.715	10.5	0.88	0.67	11.65	0.17	2.76	0.405	45.99	1.44	99.26
12-UH-29	15.69	9.343	10.74	1.01	-0.42	11.2	0.17	2.99	0.418	47.16	1.51	99.81
12-UH-33	15.45	9.319	10.8	0.97	-0.47	11.82	0.171	2.84	0.389	46.94	1.46	99.69
12-UH-37	15.89	9.854	10.57	0.99	-0.04	10.55	0.168	2.92	0.412	46.59	1.53	99.43
12-UH-43	18.42	8.757	9.23	0.98	0.09	4.35	0.142	3.75	0.46	51.29	1.41	98.88

Table 7: Trace element concentrations for Upsal Hogback bomb samples.

Sample	Ba	Be	Bi	Cd	Ce	Co	Cr	Cs	Cu	Dy	Er
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
12-UH-01	452.6	1.63	0.052	0.14	51.65	42.8	316	1.04	54	5.08	2.88
12-UH-02	440.7	1.45	0.024	0.12	50.7	44	333	0.79	54	4.99	2.89
12-UH-03	427	1.48	0.096	0.13	49.1	42.5	288	0.26	57	4.8	2.74
12-UH-04	450.8	1.43	0.072	0.12	50.34	41.7	302	0.74	56	4.85	2.79
12-UH-05	436.9	1.52	0.061	0.11	49.62	44.8	305	0.88	59	4.87	2.81
12-UH-07	454.2	1.52	0.054	0.11	50.44	42.8	308	0.8	51	4.94	2.85
12-UH-08	438.9	1.48	0.072	0.13	50.7	41.6	296	0.45	55	5.01	2.94
12-UH-10	459.3	1.42	0.054	0.13	48.68	45.5	313	0.6	56	4.91	2.82
12-UH-13	463.8	1.58	0.046	0.12	53.53	40.2	274	0.35	53	5.3	2.98
12-UH-18	434.8	1.45	0.09	0.12	51.06	46.2	307	0.79	55	5.01	2.82
12-UH-22	438.8	1.47	0.032	0.12	49.71	45.7	310	0.45	53	5.03	2.89
12-UH-24	369.6	1.16	0.079	0.11	40.7	53.5	421	0.48	65	4.55	2.6

Sample	Ba	Be	Bi	Cd	Ce	Co	Cr	Cs	Cu	Dy	Er
12-UH-26	363.8	1.15	0.084	0.09	40.11	52.8	389	0.57	64	4.47	2.57
12-UH-28	393.8	1.13	0.062	0.18	41.5	54.9	406	0.42	68	4.5	2.61
12-UH-29	396.6	1.18	0.089	0.1	42.74	52.1	412	0.4	55	4.67	2.68
12-UH-33	373.4	1.18	0.092	0.1	41.77	52.5	412	0.43	67	4.75	2.75
12-UH-37	384.6	1.19	0.034	0.12	43.38	50	407	0.67	53	4.66	2.62
12-UH-43	720.7	1.24	0.066	0.18	44.18	25.6	90	1.42	43	4.84	2.71

Sample	Eu	Ga	Gd	Hf	Ho	La	Li	Lu	Mo	Nb	Nd
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
12-UH-01	1.71	16.93	5.3	3.92	0.99	24.56	10.7	0.41	2.7	33.24	27.48
12-UH-02	1.69	16.84	5.19	3.88	0.98	23.97	9.7	0.41	2.41	32.56	26.63
12-UH-03	1.65	15.99	5.05	3.53	0.95	23.14	9.7	0.39	1.17	31.22	25.59
12-UH-04	1.67	16.88	5.16	3.87	0.97	23.77	10.8	0.39	2.39	32.1	26.24
12-UH-05	1.68	16.74	5.16	3.78	0.96	23.53	12.9	0.39	2	32.47	26.19

Sample	Eu	Ga	Gd	Hf	Ho	La	Li	Lu	Mo	Nb	Nd
12-UH-07	1.7	16.77	5.29	3.86	0.98	24.37	11.4	0.4	2.74	32.4	26.31
12-UH-08	1.72	16.33	5.3	3.84	1.01	24	8.4	0.41	2.86	32.56	26.71
12-UH-10	1.67	16.35	5.17	3.62	0.97	23.01	10.1	0.39	1.89	29.83	26.53
12-UH-13	1.8	17.15	5.58	4.03	1.04	25.09	8.8	0.42	2.13	33.92	27.9
12-UH-18	1.69	16.58	5.23	3.83	0.98	23.87	8.8	0.41	2.39	32.33	26.73
12-UH-22	1.7	16.51	5.29	3.71	0.97	23.49	7.5	0.4	2.25	32.07	26.58
12-UH-24	1.55	15.54	4.72	3.05	0.89	18.99	7.7	0.37	1.83	24.06	22.54
12-UH-26	1.47	15.54	4.65	3.04	0.89	18.49	8.9	0.37	1.63	23.76	22.14
12-UH-28	1.52	15.38	4.67	3.07	0.9	19.51	8.6	0.37	2.58	24.41	23.11
12-UH-29	1.56	15.94	4.73	3.23	0.91	20.13	7.1	0.38	1.77	25.65	23.72
12-UH-33	1.54	15.45	4.88	3.19	0.96	19.41	6.8	0.39	1.8	23.71	23.09
12-UH-37	1.57	15.96	4.76	3.21	0.91	20.01	7	0.37	1.79	26.43	23.89
12-UH-43	1.75	20.73	5.41	3.56	0.93	20.19	23.6	0.37	1.64	10.9	25.89

Sample	Ni	Pb	Pr	Rb	Sb	Sc	Sm	Sn	Sr	Ta	Tb
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
12-UH-01	173	2.3	6.7	28.25	0.12	30	5.59	1.64	433	1.8	0.81
12-UH-02	184	2.2	6.6	25.38	0.08	29.2	5.48	1.69	484	1.9	0.793
12-UH-03	184	2.1	6.39	12.53	0.07	28.5	5.26	3	621	1.7	0.763
12-UH-04	171	2.3	6.53	26.13	0.15	29.3	5.38	2.1	550	1.8	0.784
12-UH-05	202	2.1	6.44	23.48	0.1	29.1	5.3	2.98	455	1.8	0.778
12-UH-07	183	2.4	6.59	27.79	0.11	29.3	5.54	1.99	444	1.8	0.797
12-UH-08	169	2	6.63	25.22	0.15	29.7	5.5	1.81	466	1.8	0.807
12-UH-10	219	2.7	6.34	25.07	0.12	29	5.41	1.8	437	1.6	0.778
12-UH-13	144	2.2	6.96	25.31	0.08	30.3	5.74	2.25	437	1.9	0.84
12-UH-18	218	2.3	6.57	26.45	0.14	30.3	5.48	1.74	435	1.8	0.796
12-UH-22	212	2.1	6.52	24.11	0.07	29.9	5.49	1.54	425	1.8	0.777
12-UH-24	311	1.9	5.41	19.94	0.08	30.7	4.68	1.39	385	1.3	0.72

Sample	Ni	Pb	Pr	Rb	Sb	Sc	Sm	Sn	Sr	Ta	Tb
12-UH-26	318	2	5.3	19.48	0.12	29.9	4.62	1.57	391	1.3	0.699
12-UH-28	326	2	5.53	17.43	0.11	29.1	4.76	1.35	446	1.4	0.718
12-UH-29	292	1.9	5.68	19.87	0.06	30.3	4.95	1.53	395	1.4	0.728
12-UH-33	317	1.9	5.52	18.69	0.11	29.7	4.85	2.01	379	1.4	0.747
12-UH-37	263	1.8	5.71	19.8	0.07	30.6	4.96	1.63	413	1.5	0.739
12-UH-43	40	6.8	6.08	25.08	0.11	24.1	5.8	1.36	704	0.6	0.776

Sample	Th	Ti	Tl	Tm	U	V	W	Y	Yb	Zn	Zr
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
12-UH-01	2.02	10204.18	0.05	0.414	0.69	213.97	0.56	27.62	2.672	78.96	178
12-UH-02	2.08	9893.55	0.05	0.409	0.72	208.1	<0.5	27.23	2.67	78.56	171
12-UH-03	1.88	9607.18	0.02	0.389	0.54	204.61	<0.5	25.99	2.573	75.65	142
12-UH-04	2.05	9831	0.04	0.403	0.75	207.47	0.53	26.85	2.608	77.97	171
12-UH-05	1.92	9823.46	0.02	0.403	0.62	207.5	<0.5	26.86	2.579	77.44	168

Sample	Th	Ti	Tl	Tm	U	V	W	Y	Yb	Zn	Zr
12-UH-07	2.01	9915.04	0.05	0.411	0.76	209.13	0.66	27.03	2.663	78.93	174
12-UH-08	1.96	10051.05	0.05	0.416	2.38	210.55	0.65	27.23	2.722	77.03	172
12-UH-10	2.01	9527.77	0.04	0.405	0.64	201.25	<0.5	26.13	2.601	78.68	160
12-UH-13	2.08	10336.86	0.04	0.432	0.68	220.31	1.14	28.49	2.784	77.67	177
12-UH-18	2.11	10055.51	0.05	0.416	0.7	209.3	0.63	27.21	2.663	79.97	172
12-UH-22	1.86	9829.2	0.05	0.408	0.7	205.85	0.59	26.84	2.66	78.65	166
12-UH-24	1.46	8832.24	0.04	0.366	0.5	207.56	<0.5	25.01	2.409	81.48	134
12-UH-26	1.6	8624.1	0.04	0.369	0.53	206.64	0.52	23.85	2.374	78.18	131
12-UH-28	1.48	8665.4	0.04	0.374	1.85	206.39	0.94	24.73	2.433	82.27	134
12-UH-29	1.49	9035.86	0.04	0.391	0.48	207.36	<0.5	25.55	2.501	79.34	141
12-UH-33	1.53	8596.93	0.04	0.395	0.52	218.49	0.77	24.97	2.541	77.11	135
12-UH-37	1.47	9226.53	0.04	0.384	0.47	215.31	0.61	25.17	2.471	78.54	138
12-UH-43	1.57	8732.3	0.08	0.378	0.63	242.99	<0.5	26.24	2.428	99.28	146

Table 8: Nd isotopes analyzed at Carleton University.

Sam- ple	^{144}Nd	StdErr(a bs)	$^{146}\text{Nd}/^{144}\text{Nd}$	StdErr(a bs)	$^{143}\text{Nd}/^{144}\text{Nd}$	StdErr(abs)	$^{145}\text{Nd}/^{144}\text{Nd}$	StdErr(abs)	$^{148}\text{Nd}/^{144}\text{Nd}$	StdErr(abs)	$^{150}\text{Nd}/^{144}\text{Nd}$	StdErr(abs)	$^{147}\text{Sm}/^{144}\text{Nd}$	StdErr(abs)
12- UH- 03	0.89497 275	0.00617 7541	0.71930 606	2.28E- 05	0.51279 282	4.21E- 06	0.34842 191	3.25E- 06	0.24161 741	3.11E- 06	0.23648 969	8.46E- 06	1.47E -05	3.02E- 06
12- UH- 13	1.24598 92	0.03187 2957	0.72032 489	0.00010 2066	0.51279 673	5.49E- 06	0.34842 007	4.07E- 06	0.24161 599	3.29E- 06	0.23648 296	6.15E- 06	2.27E -05	2.02E- 06
12- UH- 22	0.67491 207	0.00164 407	0.72093 331	0.00010 4575	0.51277 959	8.77E- 06	0.34842 229	4.13E- 06	0.24163 917	8.81E- 06	0.23649 061	1.07E- 05	1.44E -05	2.57E- 06
12- UH- 28	0.91248 034	0.02029 8983	0.71922 441	2.18E- 05	0.51278 809	4.30E- 06	0.34842 333	4.41E- 06	0.24160 0715	3.97E- 06	0.23647 507	8.71E- 06	1.12E -05	2.74E- 06
12- UH- 29	0.72416 078	0.01554 355	0.71983 116	1.91E- 05	0.51284 105	2.01E- 05	0.34846 025	9.74E- 06	0.27160 91	6.59E- 06	0.23646 302	1.06E- 05	2.42E -05	7.40E- 06
12- UH- 37	0.75618 39	0.00511 3042	0.71954 812	6.97E- 06	0.51280 519	5.77E- 06	0.34842 255	5.77E- 06	0.24164 693	2.91E- 06	0.23650 542	8.33E- 06	6.41E -06	4.04E- 06

Table 9: Corrected Pb isotope values.

Sample	$^{208}\text{Pb}/^{204}\text{Pb}$	2-sig	$^{207}\text{Pb}/^{204}\text{Pb}$	2-sig	$^{206}\text{Pb}/^{204}\text{Pb}$	2-sig
12-UH-03	38.49494102	0.017	15.5893977	0.007	18.88540659	0.001
12-UH-13	38.48186837	0.004	15.591406	0.001	18.89543442	0.001

12-UH-22	38.50198015	0.005	15.59542259	0.002	18.90445946	0.001
12-UH-28	38.57840489	0.0084	15.60948066	0.002	18.93354016	0.002
12-UH-29	38.5331534	0.003	15.60144748	0.001	18.91649285	0.001
12-UH-37	38.51605839	0.014	15.60044333	0.005	18.90746781	0.005

Table 10: Sr isotopes analyzed at Carleton University.

Sample	^{88}Sr	StdErr (abs)	$^{88}\text{Sr}/^{86}\text{Sr}$	StdErr(abs)	StdErr(abs)	$^{87}\text{Sr}/^{86}\text{Sr}$	StdErr (abs)	$^{84}\text{Sr}/^{86}\text{Sr}$	StdErr (abs)	$^{85}\text{Rb}/^{86}\text{Sr}$	StdErr (abs)
12-UH-03	5.220228	0.0265922 61	8.3055521	0.000893182	6.13E-06	0.70500297	6.62E-06	0.056485398	3.72E-06	5.02E-06	5.57E-06
12-UH-13	1.9633882	0.2251676 6	8.3494979	0.002458663	1.92E-05	0.7042733	4.51E-06	0.056482501	9.09E-06	0.00010863 1	3.86E-05
12-UH-22	3.65879	0.0031817 34	8.3226229	0.000210585	2.91E-05	0.70408552	2.28E-05	0.056448014	6.71E-06	6.06E-07	7.05E-06
12-UH-28	1.9572493	0.0548907 5	8.3783901	0.001738349	0.000112983	0.70456062	1.53E-05	0.05649091	1.34E-05	0.00177088 6	0.0002767 86
12-UH-29	20.792117	2.2434068	8.4130351	0.006600584	1.00E-05	0.704942	2.24E-06	0.056481148	3.24E-06	7.38E-05	1.52E-05
12-UH-37	2.1666933	0.0615298 89	8.3767139	0.000597178	8.56E-06	0.70414998	9.67E-05	0.05649618	8.34E-06	6.34E-06	9.66E-06

Table 11: Nd and Sr isotopes for the tufa sample from Upsal Hogback.

T u f a	^{144}Nd	StdErr (abs)	$^{146}\text{Nd}/^{144}\text{Nd}$	StdErr (abs)	$^{143}\text{Nd}/^{144}\text{Nd}$	StdErr (abs)	$^{145}\text{Nd}/^{144}\text{Nd}$	StdErr (abs)	$^{148}\text{Nd}/^{144}\text{Nd}$	StdErr (abs)	$^{150}\text{Nd}/^{144}\text{Nd}$	StdErr (abs)	$^{147}\text{Sm}/^{144}\text{Nd}$	StdErr (abs)
	0.7076 7372	0.00684 6305	0.720313 66	8.77E-05	0.512519 36	5.99E-06	0.348425 1	5.82E-06	0.241670 28	6.77E-06	0.236486 62	7.50E-06	1.69E-05	2.64E-06
	^{88}Sr	StdErr (abs)	$^{88}\text{Sr}/^{86}\text{Sr}$	StdErr (abs)	StdErr (abs)	$^{87}\text{Sr}/^{86}\text{Sr}$	StdErr (abs)	$^{84}\text{Sr}/^{86}\text{Sr}$	StdErr (abs)	$^{85}\text{Rb}/^{86}\text{Sr}$	StdErr (abs)			
	3.3620 866	0.03417 4346	8.395214 4	0.00323 5727	2.26E-05	0.70741 878	1.58E-05	0.05648 3372	8.38E-06	0.00037 1444	6.02E-05			

Table 12: Major element analytical uncertainty for samples sent to the OGS lab with three replicate analyses.

	Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	LOI	MgO	MnO	Na ₂ O	P ₂ O ₅	SiO ₂	TiO ₂	Total
Average	18.05	9.53	9.45	1.02	0.66	6.60	0.14	3.51	0.38	48.37	1.43	99.13
1-sigma	0.130	0.015	0.045	0.010	0.123	0.076	0.003	0.023	0.002	0.380	0.006	0.548

Table 13: Trace element analytical uncertainty for samples sent to the OGS lab with six replicate analyses.

Element	Ba	Be	Bi	Cd	Ce	Co	Cr	Cs	Cu	Dy	Er
Average	536.47	1.18	0.02	0.17	47.35	41.63	180.60	0.23	43.00	3.72	1.94
1-sigma	9.469	0.057	0.006	0.013	0.660	0.920	6.066	0.008	0.894	0.034	0.021
Element	Eu	Ga	Gd	Hf	Ho	La	Li	Lu	Mo	Nb	Nd
Average	1.58	19.03	4.43	3.41	0.70	21.94	7.58	0.24	1.49	10.67	25.26
1-sigma	0.018	0.416	0.040	0.068	0.012	0.317	0.417	0.000	0.035	0.205	0.448
Element	Ni	Pb	Pr	Rb	Sb	Sc	Sm	Sn	Sr	Ta	Tb
Average	117.50	4.87	6.13	12.80	0.09	20.28	5.00	1.53	896.00	0.60	0.63
1-sigma	1.049	0.082	0.088	0.249	0.005	0.504	0.037	0.080	7.321	0.000	0.009
Element	Th	Ti	Tl	Tm	U	V	W	Y	Yb	Zn	Zr
Average	1.94	8652.98	0.05	0.27	0.57	158.29	0.34	19.36	1.65	90.84	152.83
1-sigma	0.040	175.025	0.000	0.004	0.008	2.658	0.006	0.177	0.023	2.992	3.061

Table 14: Analytical uncertainty for isotopes analyzed at Carleton University. The Nd analytical uncertainties come from 115 replicate analyses. The Sr analytical uncertainties come from 79 replicate analyses. The Pb analytical uncertainties are from 56 replicate analyses.

Isotope	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{87}\text{Sr}/^{86}\text{Sr}$
Average	16.8809	15.4272	36.4987	0.511826	0.710246
2-sigma	0.0088	0.012	0.04	0.000014	0.000023

Table 15: Calculated Nd and Sr concentrations in the tufa sample.

Sample Name	Tufa
Nd	
Sample Wt. (g)	0.07274
Spike Wt. (g)	0.09771
$^{146}\text{Nd}/^{144}\text{Nd}$ measured	0.77306035
$^{148}\text{Nd}/^{144}\text{Nd}$ measured	7.7506364
$^{143}\text{Nd}/^{144}\text{Nd}$ measured	0.508184
Nd Alpha Factor	-0.000534442
Corrected $^{146}\text{Nd}/^{144}\text{Nd}$	0.772234038
Corrected $^{148}\text{Nd}/^{144}\text{Nd}$	7.734067333
Corrected $^{143}\text{Nd}/^{144}\text{Nd}$	0.508455595
Nd (ppm) calculated	1.082158
Error Magnification Factor	1.12
Sr	
Sample Wt.(g)	0.07274
Spike Wt (g)	0.19528
$^{84}\text{Sr}/^{86}\text{Sr}$ measured	0.077286844
$^{87}\text{Sr}/^{86}\text{Sr}$ measured	0.7074754
Sr (ppm) calculated	2362.123932
Error Magnification Factor	3.73

Table 16: Plagioclase phenocrysts and microlites electron microprobe analysis.

Samp- le	Position name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Co mm -ent
		Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	
12- UH-29	29-pheno3- 1core	49.77	31.58	0.00	0.00	0.43	0.00	0.00	0.00	0.00	14.81	2.97	0.16	0.00	0.00	0.00	99.73	
12- UH-29	29-pheno3- 2 int.	50.19	31.41	0.00	0.00	0.47	0.00	0.00	0.00	0.00	14.75	3.14	0.18	0.00	0.00	0.00	100.15	
12- UH-29	29-pheno3- 3-rim	49.63	31.64	0.00	0.00	0.54	0.00	0.00	0.00	0.00	14.99	2.95	0.15	0.00	0.00	0.00	99.89	
12- UH-29	29- microlite1- core	50.27	30.85	0.00	0.00	0.55	0.00	0.00	0.00	0.00	14.19	3.47	0.20	0.00	0.00	0.00	99.52	
12- UH-29	29- microlite2- core	49.59	31.48	0.00	0.00	0.49	0.00	0.00	0.00	0.00	14.96	3.01	0.16	0.00	0.00	0.00	99.67	
12- UH-29	29- microlite3- core	50.17	31.35	0.00	0.00	0.54	0.00	0.00	0.00	0.00	14.57	3.26	0.17	0.00	0.00	0.00	100.05	
12- UH-29	29-plag pheno-1	49.48	31.31	0.00	0.00	0.50	0.00	0.00	0.00	0.00	14.95	2.96	0.17	0.00	0.00	0.00	99.36	core ?
12- UH-29	29-plag pheno-2	50.04	31.60	0.00	0.00	0.50	0.00	0.00	0.00	0.00	14.80	3.16	0.17	0.00	0.00	0.00	100.28	rim?
12- UH-01	01-pheno1- 1	46.26	33.10	0.00	0.00	0.60	0.00	0.00	0.00	0.00	16.75	1.85	0.06	0.00	0.00	0.00	98.63	core
12- UH-01	01-pheno1- 2	56.41	27.34	0.00	0.00	0.48	0.00	0.00	0.00	0.00	10.09	5.83	0.66	0.00	0.00	0.00	100.79	2nd laye r core
12- UH-01	01-pheno1- 3	53.88	28.73	0.00	0.00	0.51	0.00	0.00	0.00	0.00	11.87	4.57	0.44	0.00	0.00	0.00	100.00	3rd laye r core
12- UH-01	01-pheno1- 4	51.76	30.30	0.00	0.00	0.54	0.00	0.00	0.00	0.00	13.68	3.58	0.31	0.00	0.00	0.00	100.18	rim
12- UH-01	01-pheno2- 1	58.80	26.53	0.00	0.00	0.15	0.00	0.00	0.00	0.00	8.52	6.44	0.81	0.00	0.00	0.00	101.26	core

Samp- le	Position name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Co mm -ent
12- UH-01	01-pheno2- 2	55.34	27.59	0.00	0.00	0.40	0.00	0.00	0.00	0.00	10.43	5.44	0.39	0.00	0.00	0.00	99.60	rim
12- UH-01	01-pheno2- 3	50.45	31.04	0.00	0.00	0.53	0.00	0.00	0.00	0.00	14.27	3.19	0.25	0.00	0.00	0.00	99.73	outs ide rim
12- UH-01	01-pheno3- 1	58.05	26.62	0.00	0.00	0.40	0.00	0.00	0.00	0.00	8.85	6.23	0.65	0.00	0.00	0.00	100.81	core
12- UH-01	01-pheno3- 2	51.08	31.07	0.00	0.00	0.42	0.00	0.00	0.00	0.00	14.60	3.23	0.22	0.00	0.00	0.00	100.63	rim
12- UH-01	01-pheno3- 3	50.32	31.03	0.00	0.00	0.57	0.00	0.00	0.00	0.00	14.45	3.18	0.24	0.00	0.00	0.00	99.79	outs ide rim
12- UH-01	01- microlite1	50.66	30.73	0.00	0.00	0.61	0.00	0.00	0.00	0.00	14.18	3.26	0.25	0.00	0.00	0.00	99.70	in dark er glas s
12- UH-01	01- microlite2	51.26	30.75	0.00	0.00	0.57	0.00	0.00	0.00	0.00	14.14	3.36	0.26	0.00	0.00	0.00	100.34	in dark er glas s
12- UH-01	01- microlite3	52.67	29.37	0.00	0.00	0.76	0.00	0.00	0.00	0.00	12.92	4.03	0.40	0.00	0.00	0.00	100.16	in light er glas s
12- UH-01	01- microlite4	53.59	29.08	0.00	0.00	0.77	0.00	0.00	0.00	0.00	12.27	4.43	0.51	0.00	0.00	0.00	100.65	in light er glas s
12- UH-37	37-pheno1- 1	57.89	26.65	0.00	0.00	0.24	0.00	0.00	0.00	0.00	8.62	6.32	0.56	0.00	0.00	0.00	100.27	core
12- UH-37	37-pheno1- 2	58.20	26.60	0.00	0.00	0.26	0.00	0.00	0.00	0.00	8.87	6.30	0.56	0.00	0.00	0.00	100.81	2nd laye r core

Samp- le	Position name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Co mm -ent
12- UH-37	37-pheno1- 3	52.72	29.84	0.00	0.00	0.46	0.00	0.00	0.00	0.00	12.38	4.17	0.31	0.00	0.00	0.00	99.88	rim
12- UH-37	37-pheno1- 4	50.13	31.83	0.00	0.00	0.41	0.00	0.00	0.00	0.00	14.96	2.84	0.16	0.00	0.00	0.00	100.34	outs ide rim
12- UH-37	37-pheno3- 1	60.29	25.50	0.00	0.00	0.15	0.00	0.00	0.00	0.00	7.10	7.44	0.33	0.00	0.00	0.00	100.81	core
12- UH-37	37-pheno3- 2	53.06	28.79	0.00	0.00	0.46	0.00	0.00	0.00	0.00	12.32	4.52	0.37	0.00	0.00	0.00	99.52	rim
12- UH-37	37-pheno3- 3	50.27	31.62	0.00	0.00	0.47	0.00	0.00	0.00	0.00	14.74	2.94	0.18	0.00	0.00	0.00	100.21	outs ide rim
12- UH-37	37- microlite1- 1	51.06	31.42	0.00	0.00	0.52	0.00	0.00	0.00	0.00	14.51	3.29	0.21	0.00	0.00	0.00	101.01	
12- UH-37	37- microlite2- 1	51.15	31.11	0.00	0.00	0.60	0.00	0.00	0.00	0.00	14.33	3.26	0.21	0.00	0.00	0.00	100.65	
12- UH-17	17- microlite1	51.30	30.33	0.00	0.00	0.68	0.00	0.00	0.00	0.00	14.17	3.27	0.24	0.00	0.00	0.00	99.98	in light glas s
12- UH-17	17- microlite2	58.92	23.84	0.00	0.00	2.59	0.00	0.00	0.00	0.00	8.26	3.21	2.06	0.00	0.00	0.00	98.90	in dark er glas s
12- UH-17	17- microlite3	55.38	28.09	0.00	0.00	1.11	0.00	0.00	0.00	0.00	11.76	4.02	0.38	0.00	0.00	0.00	100.73	in dark glas s?
12- UH-17	17-pheno3- 1	52.31	30.22	0.00	0.00	0.29	0.00	0.00	0.00	0.00	13.00	3.89	0.20	0.00	0.00	0.00	99.92	core
12- UH-17	17-pheno3- 2	51.62	30.99	0.00	0.00	0.43	0.00	0.00	0.00	0.00	14.00	3.38	0.21	0.00	0.00	0.00	100.64	rim
12- UH-17	17- microlite4	51.08	30.46	0.00	0.00	0.61	0.00	0.00	0.00	0.00	14.10	3.27	0.19	0.00	0.00	0.00	99.73	

Samp- le	Position name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Co mm -ent
12- UH-34	34- microlite1	50.96	30.35	0.00	0.00	0.64	0.00	0.00	0.00	0.00	14.05	3.16	0.18	0.00	0.00	0.00	99.33	
12- UH-34	34-pheno1- 1	51.48	30.96	0.00	0.00	0.48	0.00	0.00	0.00	0.00	14.05	3.26	0.16	0.00	0.00	0.00	100.39	core
12- UH-34	34-pheno1- 2	50.63	30.77	0.00	0.00	0.51	0.00	0.00	0.00	0.00	14.28	3.12	0.15	0.00	0.00	0.00	99.47	rim
12- UH-34	34-pheno2- 1	50.19	31.28	0.00	0.00	0.39	0.00	0.00	0.00	0.00	14.66	2.85	0.13	0.00	0.00	0.00	99.49	core
12- UH-34	34-pheno2- 2	51.35	30.36	0.00	0.00	0.56	0.00	0.00	0.00	0.00	13.72	3.36	0.19	0.00	0.00	0.00	99.54	rim
12- UH-34	34- microlite2	50.59	30.94	0.00	0.00	0.57	0.00	0.00	0.00	0.00	14.20	3.08	0.16	0.00	0.00	0.00	99.55	
12- UH-34	34- microlite3	50.81	29.16	0.00	0.00	1.15	0.00	0.00	0.00	0.00	13.78	3.31	0.17	0.00	0.00	0.00	98.38	sam e micr olite as abo ve
12- UH-34	34-pheno5- 1	56.52	27.42	0.00	0.00	0.32	0.00	0.10	0.00	0.00	9.78	5.49	0.32	0.00	0.00	0.00	99.93	core
12- UH-34	34-pheno5- 2	50.54	31.06	0.00	0.00	0.39	0.00	0.13	0.00	0.00	14.02	3.08	0.13	0.00	0.00	0.00	99.36	insi de rim
12- UH-34	34-pheno5- 3	51.84	30.85	0.00	0.00	0.51	0.00	0.17	0.00	0.00	13.49	3.30	0.13	0.00	0.00	0.00	100.30	rim
12- UH-39	39-pheno2- 1	51.51	30.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.38	3.31	0.24	0.00	0.00	0.00	100.03	core ?
12- UH-39	39-pheno2- 2	51.41	29.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.10	3.32	0.24	0.00	0.00	0.00	98.93	rim?
12- UH-39	39-pheno5- 4	50.91	30.11	0.00	0.00	0.56	0.00	0.00	0.00	0.00	14.16	3.30	0.24	0.00	0.00	0.00	99.28	micr olite
12- UH-39	39- groundmass 1-2	52.82	15.60	5.67	0.01	11.6 8	0.21	1.74	0.00	0.00	3.59	4.90	4.44	0.00	0.22	0.10	100.97	dark lapil li
12- UH-39	39- groundmass	52.13	15.09	3.66	0.02	13.5 7	0.24	1.36	0.00	0.00	5.38	3.63	4.07	0.00	0.23	0.13	99.51	X3 misl

Samp- le	Position name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Co mm -ent
	1-2																	abel ed
12- UH-39	39- pheno11-1	52.10	30.36	0.00	0.00	0.36	0.00	0.00	0.00	0.00	14.45	3.37	0.23	0.03	0.00	0.00	100.88	core
12- UH-39	39- pheno11-2	52.02	30.26	0.00	0.00	0.47	0.00	0.00	0.00	0.00	13.94	3.42	0.24	0.01	0.00	0.00	100.36	rim
12- UH-39	39- pheno11-4	51.99	29.75	0.00	0.00	0.48	0.00	0.00	0.00	0.00	14.18	3.32	0.22	0.02	0.00	0.00	99.96	micr olite
12- UH-30	30-pheno1- 3	58.12	26.12	0.03	0.00	0.39	0.00	0.00	0.00	0.00	9.15	5.92	0.57	0.00	0.00	0.00	100.29	core
12- UH-30	30-pheno1- 4	50.98	30.36	0.06	0.00	0.42	0.00	0.00	0.00	0.00	14.58	3.15	0.17	0.00	0.00	0.00	99.72	rim
12- UH-30	30-pheno1- 5	51.12	29.99	0.08	0.00	0.63	0.00	0.00	0.00	0.00	14.32	3.19	0.19	0.00	0.00	0.00	99.53	micr olite
12- UH-30	30-pheno5- 4	51.73	29.71	0.00	0.00	0.81	0.00	0.00	0.00	0.00	13.86	3.62	0.22	0.00	0.00	0.00	99.95	micr olite
12- UH-30	30-pheno2- 3	50.66	30.45	0.00	0.00	0.64	0.00	0.00	0.00	0.00	14.73	2.94	0.16	0.00	0.00	0.00	99.58	micr olite
12- UH-30	30- pheno16-6	51.22	29.63	0.00	0.00	0.71	0.00	0.00	0.00	0.00	14.44	3.12	0.20	0.00	0.00	0.00	99.32	micr olite
12- UH-17	17- microlite4	51.08	30/46	0.00	0.00	0.62	0.00	0.00	0.00	0.00	14.10	3.27	0.19	0.00	0.00	0.00	99.73	
12- UH-37	37-incl.-3	65.19	21.53	0.00	0.00	0.41	0.00	0.00	0.00	0.00	2.60	8.00	3.75	0.00	0.00	0.00	101.48	K- feld spar

Table 17: Olivine phenocrysts electron microprobe analysis.

Sample	Position Name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Comme- nts
		Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	
12-UH- 29	29- pheno1-1 core	40.23	0.08	0.03	0.05	11.17	0.15	48.04	0.32	0.00	0.30	0.00	0.00	0.00	0.00	0.00	100.36	
12-UH-	29-	39.06	0.06	0.03	0.03	16.61	0.25	43.82	0.19	0.00	0.30	0.00	0.00	0.00	0.00	0.00	100.36	

Sample	Position Name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Comments
29	pheno1-2rim																	
12-UH-29	29-pheno2-1core	40.44	0.07	0.02	0.05	12.01	0.18	47.25	0.31	0.00	0.29	0.00	0.00	0.00	0.00	0.00	100.61	
12-UH-29	29-pheno2-1rim	38.97	0.05	0.02	0.04	18.05	0.32	42.25	0.11	0.00	0.36	0.00	0.00	0.00	0.00	0.00	100.18	
12-UH-29	29-pheno4-1	40.11	0.08	0.01	0.05	11.47	0.14	47.65	0.00	0.00	0.29	0.00	0.00	0.00	0.00	0.00	99.79	core
12-UH-29	29-pheno4-2	39.99	0.06	0.01	0.05	13.36	0.16	46.39	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.00	100.29	rim
12-UH-29	01-pheno4-1	40.67	0.06	0.00	0.07	10.98	0.15	47.04	0.31	0.01	0.29	0.00	0.00	0.00	0.00	0.00	99.60	core
12-UH-01	01-pheno4-2	39.48	0.08	0.04	0.03	14.44	0.24	44.21	0.22	0.01	0.26	0.00	0.00	0.00	0.00	0.00	99.02	rim
12-UH-01	01-pheno5-1	40.75	0.04	0.01	0.04	11.93	0.19	46.59	0.30	0.00	0.26	0.00	0.00	0.00	0.00	0.00	100.11	core
12-UH-01	01-pheno5-2	39.73	0.03	0.02	0.01	16.71	0.26	43.07	0.16	0.00	0.28	0.00	0.00	0.00	0.00	0.00	100.27	rim
12-UH-01	01-pheno6-1	40.49	0.08	0.01	0.03	11.22	0.15	46.85	0.31	0.00	0.29	0.00	0.00	0.00	0.00	0.00	99.41	core
12-UH-01	01-pheno6-2	39.27	0.04	0.03	0.03	16.68	0.30	43.03	0.17	0.00	0.27	0.00	0.00	0.00	0.00	0.00	99.81	rim
12-UH-37	37-pheno2-1	40.71	0.10	0.00	0.07	11.11	0.17	46.63	0.32	0.00	0.30	0.00	0.00	0.00	0.00	0.00	99.40	core
12-UH-37	37-pheno2-2	40.09	0.06	0.02	0.03	13.16	0.20	45.53	0.23	0.00	0.28	0.00	0.00	0.00	0.00	0.00	99.60	rim
12-UH-37	37-pheno4-1	40.77	0.06	0.00	0.06	11.07	0.14	47.35	0.30	0.00	0.26	0.00	0.00	0.00	0.00	0.00	100.02	core
12-UH-37	37-pheno4-2	40.76	0.09	0.01	0.06	11.06	0.17	47.46	0.31	0.00	0.27	0.00	0.00	0.00	0.00	0.00	100.19	rim
12-UH-37	37-pheno4-3	40.71	0.04	0.02	0.04	12.67	0.20	46.19	0.27	0.00	0.26	0.00	0.00	0.00	0.00	0.00	100.41	outside rim
12-UH-17	17-pheno1-1	40.47	0.07	0.00	0.05	12.01	0.20	46.62	0.26	0.00	0.26	0.00	0.00	0.00	0.00	0.00	99.93	core
12-UH-17	17-pheno1-2	39.58	0.02	0.00	0.03	16.27	0.25	43.32	0.14	0.00	0.31	0.00	0.00	0.00	0.00	0.00	99.94	rim

Sample	Position Name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Comments
12-UH-17	17-pheno2-1	40.58	0.07	0.00	0.06	11.28	0.15	47.35	0.30	0.00	0.30	0.00	0.00	0.00	0.00	0.00	100.09	core
12-UH-17	17-pheno2-2	40.45	0.09	0.01	0.04	14.62	0.22	44.54	0.22	0.00	0.27	0.00	0.00	0.00	0.00	0.00	100.46	rim
12-UH-17	17-pheno4-1	40.65	0.07	0.00	0.05	11.17	0.17	47.10	0.33	0.00	0.27	0.00	0.00	0.00	0.00	0.00	99.81	core
12-UH-17	17-pheno4-2	40.12	0.09	0.00	0.02	13.57	0.19	45.02	0.23	0.00	0.27	0.00	0.01	0.00	0.00	0.00	99.53	rim
12-UH-17	17-pheno5-1	40.55	0.09	0.00	0.05	12.37	0.17	46.42	0.29	0.00	0.26	0.00	0.00	0.00	0.00	0.00	100.21	core
12-UH-17	17-pheno5-2	39.78	0.07	0.00	0.02	14.47	0.21	44.13	0.21	0.00	0.29	0.00	0.00	0.00	0.00	0.00	99.18	rim
12-UH-17	17-pheno7-1	48.64	17.80	1.72	0.03	8.30	0.15	5.29	0.03	0.00	10.84	2.53	1.14	0.00	0.00	0.00	96.48	core, amph?
12-UH-17	17-pheno7-2	40.08	0.08	0.01	0.03	11.83	0.22	46.07	0.28	0.00	0.28	0.00	0.00	0.00	0.00	0.00	98.87	rim
12-UH-17	17-pheno7-3	40.46	0.06	0.00	0.04	11.05	0.15	46.71	0.31	0.00	0.29	0.00	0.00	0.00	0.00	0.00	99.07	outside rim
12-UH-34	34-pheno3-1	40.45	0.08	0.01	0.06	12.15	0.18	46.97	0.29	0.00	0.27	0.00	0.00	0.00	0.00	0.00	100.45	core
12-UH-34	34-pheno3-2	39.90	0.07	0.02	0.05	17.11	0.32	42.85	0.17	0.00	0.33	0.00	0.00	0.00	0.00	0.00	100.81	rim
12-UH-34	34-pheno4	39.49	0.05	0.01	0.06	18.10	0.32	42.59	0.15	0.00	0.32	0.00	0.00	0.00	0.00	0.00	101.09	
12-UH-34	34-pheno6-1	40.42	0.07	0.02	0.07	11.20	0.18	48.09	0.34	0.00	0.29	0.00	0.00	0.00	0.00	0.00	100.67	core
12-UH-34	34-pheno6-2	40.42	0.07	0.03	0.04	16.50	0.28	43.98	0.20	0.00	0.31	0.00	0.00	0.00	0.00	0.00	101.82	rim
12-UH-39	39-pheno1-1	40.81	0.07	0.00	0.02	13.03	0.23	44.78	0.23	0.00	0.27	0.00	0.00	0.00	0.00	0.00	99.44	core
12-UH-39	39-pheno1-2	39.30	0.05	0.00	0.03	17.69	0.29	41.90	0.14	0.00	0.32	0.00	0.00	0.00	0.00	0.00	99.71	rim
12-UH-39	39-pheno5-1	40.67	0.06	0.00	0.03	11.20	0.16	46.75	0.31	0.00	0.27	0.00	0.00	0.00	0.00	0.00	99.45	core
12-UH-39	39-pheno5-2	39.78	0.06	0.00	0.02	14.75	0.27	44.43	0.22	0.00	0.26	0.00	0.00	0.00	0.00	0.00	99.79	rim
12-UH-39	39-pheno12-1	39.72	0.03	0.01	0.00	18.94	0.24	41.27	0.07	0.00	0.14	0.00	0.00	0.00	0.00	0.00	100.42	core

Sample	Position Name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Comments
12-UH-39	39-pheno12-2	40.07	0.05	0.01	0.03	15.20	0.25	43.39	0.20	0.00	0.25	0.00	0.00	0.00	0.00	0.00	99.44	rim
12-UH-30	30-pheno1-1	38.51	0.06	0.00	0.00	21.00	0.35	39.22	0.10	0.00	0.24	0.00	0.00	0.00	0.00	0.00	99.49	core
12-UH-30	30-pheno1-2	39.76	0.03	0.00	0.00	15.18	0.25	43.72	0.20	0.00	0.31	0.00	0.00	0.00	0.00	0.00	99.45	rim
12-UH-30	30-pheno3-1	39.39	0.07	0.00	0.00	16.74	0.21	42.11	0.19	0.00	0.15	0.00	0.00	0.00	0.00	0.00	98.86	core
12-UH-30	30-pheno3-2	40.11	0.05	0.00	0.06	13.17	0.18	45.26	0.24	0.00	0.30	0.00	0.00	0.00	0.00	0.00	99.36	rim
12-UH-30	30-pheno4-1	40.79	0.09	0.00	0.05	11.00	0.17	46.69	0.31	0.00	0.27	0.00	0.00	0.00	0.00	0.00	99.37	core
12-UH-30	30-pheno4-2	40.42	0.07	0.00	0.06	12.28	0.19	45.77	0.28	0.00	0.29	0.00	0.00	0.00	0.00	0.00	99.36	rim
12-UH-30	30-pheno5-1	40.42	0.09	0.00	0.04	10.87	0.13	46.98	0.32	0.00	0.31	0.00	0.00	0.00	0.00	0.00	99.16	core
12-UH-30	30-pheno5-2	40.34	0.08	0.00	0.04	12.69	0.17	46.27	0.26	0.00	0.26	0.00	0.00	0.00	0.00	0.00	100.10	rim
12-UH-30	30-pheno2-1	40.93	0.08	0.02	0.01	11.16	0.18	47.21	0.29	0.00	0.26	0.00	0.00	0.00	0.00	0.00	100.13	core
12-UH-30	30-pheno2-2	40.33	0.07	0.01	0.05	12.49	0.16	46.18	0.27	0.00	0.29	0.00	0.00	0.00	0.00	0.00	99.84	rim
12-UH-30	30-pheno16-1	41.04	0.00	0.00	0.06	11.10	0.15	46.98	0.30	0.00	0.29	0.00	0.00	0.00	0.00	0.00	99.92	core
12-UH-30	30-pheno16-2	39.41	0.00	0.00	0.03	14.58	0.21	44.08	0.23	0.00	0.27	0.00	0.00	0.00	0.00	0.00	98.81	rim

Table 18: Electron microprobe analysis of spinel phenocrysts.

Sample	Position name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Comment
		Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	
12-UH-01	01-pheno4-3	0.12	46.86	0.21	17.87	15.09	0.09	17.81	0.27	0.06	0.00	0.00	0.00	0.00	0.00	0.00	98.39	core
12-UH-01	01-pheno4-4	1.26	35.55	1.49	17.44	27.31	0.27	12.72	0.17	0.09	0.08	0.00	0.00	0.00	0.00	0.00	96.39	rim

Sample	Position name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Comment
12-UH-29	29-oxide2-1	0.16	49.17	0.19	16.09	14.27	0.11	19.12	0.00	0.05	0.01	0.00	0.00	0.00	0.00	0.00	99.18	
12-UH-29	29-oxide2-2	3.05	35.04	1.89	16.71	26.81	0.23	14.16	0.00	0.10	1.70	0.00	0.00	0.00	0.00	0.00	99.69	
12-UH-29	29-oxide3-1	0.18	50.35	0.19	15.76	13.01	0.12	19.71	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	99.39	
12-UH-17	17-spinel1	0.14	48.90	0.24	15.99	15.31	0.12	18.38	0.27	0.06	0.01	0.00	0.00	0.00	0.00	0.00	99.41	
12-UH-17	17-spinel2-1	0.12	47.96	0.18	16.02	14.41	0.12	18.11	0.28	0.06	0.01	0.00	0.00	0.00	0.00	0.00	97.28	core
12-UH-17	17-spinel2-2	2.37	33.29	1.75	19.35	27.92	0.26	12.20	0.17	0.11	0.72	0.00	0.00	0.00	0.00	0.00	98.14	rim
12-UH-34	34-spinel1	0.12	46.80	0.18	18.93	14.06	0.12	18.98	0.31	0.05	0.01	0.00	0.00	0.00	0.00	0.00	99.56	
12-UH-30	30-pheno4-3	0.13	48.27	0.18	15.88	13.09	0.08	18.96	0.29	0.07	0.02	0.00	0.00	0.00	0.00	0.00	96.98	
12-UH-30	30-pheno16-3	0.15	46.66	0.22	17.44	14.31	0.12	18.59	0.26	0.07	0.00	0.00	0.00	0.00	0.00	0.00	97.83	core
12-UH-30	30-pheno16-4	2.74	33.86	1.35	17.19	23.03	0.19	13.37	0.17	0.11	1.22	0.00	0.00	0.00	0.00	0.00	93.23	rim

Table 19: Pyroxene in groundmass and phenocryst analyzed by electron microprobe.

Sample	Position Name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total
		Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%
12-UH-29	29-groundmass-1	48.40	5.02	2.01	0.26	8.09	0.15	13.32	0.01	0.00	21.60	0.40	0.00	0.00	0.00	0.00	99.27
12-UH-29	29-groundmass-2	44.73	8.00	2.89	0.32	8.95	0.20	11.84	0.01	0.00	20.97	0.44	0.00	0.00	0.00	0.00	98.35
12-UH-29	29-groundmass-3	47.60	6.03	2.40	0.17	8.48	0.20	12.61	0.00	0.00	21.30	0.44	0.00	0.00	0.00	0.00	99.24
12-UH-17	17-pheno6	49.71	4.80	2.01	0.59	7.65	0.15	13.46	0.00	0.00	21.35	0.39	0.01	0.00	0.00	0.00	100.12

Sample	Position Name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total
		Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%
12-UH-39	39-groundmass1-1	44.51	8.25	4.16	0.04	11.72	0.24	9.02	0.00	0.00	20.04	0.76	0.22	0.00	0.00	0.01	98.96

Table 20: Glass electron microprobe analyses.

Sample	Position Name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Comments
		Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	
12-UH-17	17-glass1	48.82	15.95	2.16	0.03	9.91	0.24	5.78	0.00	0.00	10.19	3.82	1.53	0.00	0.10	0.04	98.56	light glass
12-UH-17	17-glass2	60.69	16.50	0.57	0.02	7.31	0.14	7.38	0.00	0.00	3.15	1.95	2.98	0.00	0.02	0.01	100.72	dark glass
12-UH-34	34-glass1	48.67	15.70	2.12	0.03	10.59	0.18	5.77	0.00	0.00	9.95	3.69	1.18	0.05	0.05	0.03	97.99	
12-UH-34	34-glass2	49.53	15.98	2.05	0.00	10.59	0.19	5.67	0.00	0.00	10.49	3.78	1.02	0.00	0.12	0.20	99.61	dark glass
12-UH-39	39-pheno5-3	49.18	15.34	2.34	0.02	10.06	0.19	5.16	0.04	0.00	9.87	3.69	1.81	0.00	0.13	0.04	97.87	
12-UH-39	39-pheno11-3	49.39	15.43	2.29	0.03	9.89	0.21	5.13	0.00	0.00	10.05	3.91	1.65	0.08	0.10	0.04	98.22	
12-UH-39	39-pheno12-3	49.55	15.28	2.27	0.01	9.90	0.23	5.22	0.00	0.00	10.08	3.80	1.65	0.00	0.10	0.04	98.13	
12-UH-30	30-pheno1-6	48.11	15.30	1.94	0.02	10.02	0.17	7.48	0.00	0.00	11.74	2.92	0.78	0.00	0.01	0.05	98.53	devitrified?
12-UH-30	30-pheno5-3	48.38	15.35	2.09	0.04	10.11	0.20	5.91	0.00	0.00	10.38	3.45	1.25	0.00	0.08	0.05	97.29	
12-UH-30	30-pheno16-5	48.90	15.46	2.17	0.02	10.02	0.21	5.67	0.00	0.00	10.23	3.60	1.31	0.00	0.11	0.05	97.76	
12-UH-39	39-groundmass1-2	52.82	15.60	5.67	0.01	11.68	0.21	1.74	0.00	0.00	3.59	4.90	4.44	0.00	0.22	0.10	100.97	dark lapilli
12-UH-39	39-groundm	52.13	15.09	3.66	0.02	13.57	0.24	1.36	0.00	0.00	5.38	3.63	4.07	0.00	0.23	0.13	99.51	dark lapilli

	ass1-2																	
--	--------	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Table 21: Other electron microprobe mineral analyses.

Sample	Position Name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Comment
		Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	
Amphibole																		
12-UH-37	37-incl.-1	53.65	10.12	0.94	0.03	9.53	0.29	10.83	0.00	0.00	14.20	1.82	0.52	0.00	0.02	0.00	101.94	
12-UH-30	30-pheno4-4	48.95	18.45	1.01	0.02	6.38	0.08	6.21	0.00	0.00	13.44	2.62	0.09	0.00	0.00	0.00	97.26	
12-UH-34	34-pheno6-3	50.13	19.35	1.19	0.01	6.37	0.14	5.81	0.06	0.00	13.77	1.95	0.78	0.00	0.00	0.02	99.59	
12-UH-17	17-pheno7-1	48.64	17.80	1.72	0.03	8.30	0.15	5.29	0.03	0.00	10.84	2.53	1.14	0.00	0.00	0.00	96.48	core
Titanomagnetite																		
12-UH-34	37-incl.-2	4.34	2.95	15.24	0.09	64.19	0.66	2.08	0.00	0.00	1.60	0.20	0.08	0.00	0.00	0.00	91.42	
12-UH-29	29--oxide1	0.20	1.72	24.73	0.03	67.43	0.81	2.57	0.03	0.11	0.34	0.00	0.00	0.00	0.00	0.00	97.98	
Alteration																		
12-UH-34	34-alteration1	46.91	12.99	2.07	0.01	9.93	0.11	7.48	0.00	0.00	6.29	0.39	1.39	0.02	0.13	0.00	87.73	
12-UH-34	34-alteration2	45.46	12.41	3.58	0.04	9.45	0.11	4.95	0.00	0.00	7.17	0.11	1.28	0.04	0.04	0.00	84.65	
12-UH-39	39-pheno8-4	58.56	20.08	0.40	0.00	1.92	0.00	0.44	0.00	0.00	1.13	4.28	5.58	0.00	0.00	0.08	92.46	
Silicate Lithics																		
12-UH-	34-pheno7	103.37	0.02	0.03	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	103.43	

Sample	Position Name	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	NiO	ZnO	CaO	Na ₂ O	K ₂ O	BaO	F	Cl	Total	Comment
		Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	
34																		
12-UH-39	39-pheno8-2	72.08	13.73	0.00	0.00	1.58	0.00	0.00	0.00	0.00	0.60	2.40	5.57	0.13	0.00	0.00	96.09	rhyolite fragment
12-UH-17	17-lithic1	68.20	19.43	0.00	0.00	0.50	0.00	0.00	0.00	0.00	1.92	7.17	4.13	0.21	0.00	0.00	101.57	
12-UH-39	39-pheno8-2repeat	73.13	14.03	0.37	0.01	0.96	0.04	0.13	0.00	0.00	0.58	2.33	5.68	0.15	0.05	0.09	97.54	
Carbonate																		
12-UH-39	39-pheno8-1	0.01	0.00	0.00	0.00	0.05	0.00	4.86	0.00	0.00	50.21	0.00	0.00	0.00	0.00	0.00	55.12	Probe not set up for carbonates

Table 22: Tufa microprobe analysis of sample 12-UH-38.

Position name	SiO ₂ (Wt%)	FeO (Wt%)	MnO (Wt%)	MgO (Wt%)	CaO (Wt%)	BaO (Wt%)	SrO (Wt%)	Total (Wt%)
38-tufa1-1	0.00	0.07	0.00	1.40	54.64	0.00	0.07	56.19
38-tufa1-2	0.00	0.01	0.36	1.19	53.91	0.00	0.13	55.60
38-tufa1-3	0.00	0.05	0.44	1.12	54.54	0.00	0.04	56.20
38-tufa2-1	0.00	0.00	0.06	1.06	54.99	0.00	0.02	56.14
38-tufa2-2	0.00	0.10	0.08	1.19	54.54	0.00	0.05	55.96
38-tufa2-3	0.00	0.02	0.02	1.18	55.16	0.00	0.00	56.37
38-tufa2-4	0.00	0.12	0.05	1.00	56.55	0.00	0.07	57.79
38-tufa2-5	0.00	0.09	0.15	0.94	55.13	0.00	0.06	56.37
38-tufa2-6	0.00	0.19	0.16	1.29	54.03	0.00	0.00	55.67
38-tufa3-1	0.00	0.06	0.61	0.83	54.66	0.00	0.10	56.24
38-tufa3-2	0.00	0.11	0.35	1.13	54.96	0.00	0.14	56.68
38-tufa3-3	0.00	0.06	0.27	1.24	55.23	0.00	0.20	56.99

Table 23: Anorthite content of plagioclase phenocrysts and microlites.

Sample	Position name	Albite (%)	Anorthite (%)	Orthoclase (%)
12-UH-29	29-pheno3-1core	15.27688105	84.17695892	0.546160035
12-UH-29	29-pheno3-2 int.	16.04100689	83.35528382	0.603709288
12-UH-29	29-pheno3-3-rim	15.0405484	84.46633014	0.493121452
12-UH-29	29-microlite1-core	17.98622134	81.34762164	0.666157027
12-UH-29	29-microlite2-core	15.31126883	84.16411451	0.524616661
12-UH-29	29-microlite3-core	16.72076867	82.7011334	0.57809793
12-UH-29	29-plag pheno-1	15.09314971	84.34864725	0.55820304
12-UH-29	29-plag pheno-2	16.09288349	83.32174288	0.585373634
12-UH-01	01-pheno1-1	9.046988113	90.74707573	0.205936154
12-UH-01	01-pheno1-2	33.48597417	64.03685314	2.477172694
12-UH-01	01-pheno1-3	25.42167171	72.96495325	1.613375039
12-UH-01	01-pheno1-4	18.94344679	79.98332451	1.073228694
12-UH-01	01-pheno2-1	39.29025728	57.44109977	3.26864295
12-UH-01	01-pheno2-2	31.58447983	66.92036816	1.495152011
12-UH-01	01-pheno2-3	16.66229039	82.46735807	0.870351548
12-UH-01	01-pheno3-1	37.8730591	59.51381047	2.61313043
12-UH-01	01-pheno3-2	16.56980288	82.69102574	0.739171138
12-UH-01	01-pheno3-3	16.47438677	82.70059009	0.825023139
12-UH-01	01-microlite1	17.07793561	82.05064297	0.871421416
12-UH-01	01-microlite2	17.55418496	81.56085471	0.884960337
12-UH-01	01-microlite3	21.70527444	76.8652561	1.429469458
12-UH-01	01-microlite4	24.18625707	73.98467403	1.829068896

Sample	Position name	Albite (%)	Anorthite (%)	Orthoclase (%)
12-UH-37	37-pheno1-1	38.97270006	58.7728511	2.254448839
12-UH-37	37-pheno1-2	38.25831376	59.50505807	2.236628167
12-UH-37	37-pheno1-3	23.11457398	75.7663433	1.119082724
12-UH-37	37-pheno1-4	14.58555979	84.8611094	0.553330808
12-UH-37	37-pheno3-1	47.99624866	50.58241593	1.421335414
12-UH-37	37-pheno3-2	24.58800477	74.075681	1.336314231
12-UH-37	37-pheno3-3	15.1815731	84.1957166	0.6227103
12-UH-37	37-microlite1-1	16.88883329	82.40241271	0.708754006
12-UH-37	37-microlite2-1	16.97286454	82.32249788	0.704637581
12-UH-17	17-microlite1	17.14926958	82.03254574	0.818184678
12-UH-17	17-microlite2	23.44671291	66.6469222	9.90636489
12-UH-17	17-microlite3	23.25335317	75.28248056	1.464166271
12-UH-17	17-pheno3-1	21.14563058	78.14757855	0.706790873
12-UH-17	17-pheno3-2	17.80972931	81.47265643	0.717614267
12-UH-17	17-microlite4	16.79680967	82.56245051	0.640739821
12-UH-34	34-microlite1	17.25644024	82.1814616	0.562098157
12-UH-34	34-pheno1-1	16.43803396	83.04049472	0.521471322
12-UH-34	34-pheno1-2	14.87819089	84.67030662	0.451502481
12-UH-34	34-pheno2-1	18.00362522	81.33740274	0.658972037
12-UH-34	34-pheno2-2	16.32087015	83.11264201	0.56648784
12-UH-34	34-microlite2	17.75162339	81.63236387	0.616012743
12-UH-34	34-microlite3	33.24502881	65.48216815	1.27280304
12-UH-34	34-pheno5-1	16.50535282	83.03168875	0.462958425
12-UH-34	34-pheno5-2	18.05041543	81.46871861	0.480865953
12-UH-34	34-pheno5-3	17.08115568	82.11221509	0.806629236
12-UH-39	39-pheno2-1	17.41669374	81.7555159	0.82779036
12-UH-39	39-pheno2-2	17.28570518	81.8932079	0.821086925
12-UH-39	39-pheno5-4	41.5822571	33.64415131	24.77359159
12-UH-39	39-pheno11-1	29.61399012	48.52575385	21.86025603
12-UH-39	39-pheno11-2	17.2668873	81.90732161	0.772954503
12-UH-39	39-pheno11-4	18.00483782	81.14604412	0.818480629
12-UH-30	30-pheno1-3	17.34089263	81.87564334	0.741344173
12-UH-30	30-pheno1-4	36.06795301	61.62714411	2.304902874
12-UH-30	30-pheno1-5	16.26273112	83.15648983	0.58077905
12-UH-30	30-pheno5-4	16.66325775	82.68269687	0.654045388
12-UH-30	30-pheno2-3	18.97509136	80.27305582	0.751852821
12-UH-30	30-pheno16-6	15.19168612	84.25051197	0.55780191
12-UH-17	17-microlite4	16.24247284	83.08917065	0.668356512
12-UH-37	37-incl.-3	60.00709322	21.51246371	18.48044307

Table 24: Forsterite content of olivine phenocrysts analyzed by electron microprobe.

Sample	Position Name	Forsterite (%)	Fayalite (%)	Tephroite (%)
12-UH-29	29-pheno1-1 core	88.31652206	11.52297094	0.160507
12-UH-29	29-pheno1-2rim	82.24659448	17.48904978	0.264355739
12-UH-29	29-pheno2-1core	87.35179319	12.46237649	0.185830325
12-UH-29	29-pheno2-1rim	80.38285693	19.26677957	0.350363498
12-UH-29	29-pheno4-1	87.97614239	11.88027502	0.143582589
12-UH-29	29-pheno4-2	85.94457154	13.89096072	0.164467741
12-UH-29	01-pheno4-1	88.27517345	11.56236471	0.162461841
12-UH-01	01-pheno4-2	84.29072817	15.44910808	0.260163756
12-UH-01	01-pheno5-1	87.25543672	12.53982384	0.204739443
12-UH-01	01-pheno5-2	81.89234024	17.82171443	0.28594533
12-UH-01	01-pheno6-1	88.0157525	11.82711754	0.157129956
12-UH-01	01-pheno6-2	81.87084395	17.80811505	0.321041001
12-UH-37	37-pheno2-1	88.0542517	11.76842552	0.17732278
12-UH-37	37-pheno2-2	85.86158193	13.92395535	0.214462723
12-UH-37	37-pheno4-1	88.2742411	11.57667194	0.14908696
12-UH-37	37-pheno4-2	88.27985902	11.54546959	0.174671394
12-UH-37	37-pheno4-3	86.47378546	13.31195994	0.214254595
12-UH-17	17-pheno1-1	87.18746641	12.60122725	0.211306339
12-UH-17	17-pheno1-2	82.36977645	17.35543276	0.27479079
12-UH-17	17-pheno2-1	88.0694835	11.77495356	0.155562944
12-UH-17	17-pheno2-2	84.24633987	15.51360333	0.240056805
12-UH-17	17-pheno4-1	88.1023644	11.71787708	0.179758519
12-UH-17	17-pheno4-2	85.35512935	14.44039035	0.204480303
12-UH-17	17-pheno5-1	86.83330536	12.9814337	0.185260945
12-UH-17	17-pheno5-2	84.27072282	15.49673014	0.232547038
12-UH-17	17-pheno7-1	52.70827722	46.43620863	0.855514144
12-UH-17	17-pheno7-2	87.20135056	12.56395099	0.234698444
12-UH-17	17-pheno7-3	88.1463902	11.6971827	0.156427106
12-UH-34	34-pheno3-1	87.16085413	12.65399511	0.185150762
12-UH-34	34-pheno3-2	81.42158395	18.23830982	0.340106232
12-UH-34	34-pheno4	80.46990596	19.18353302	0.346561017
12-UH-34	34-pheno6-1	88.27294588	11.53717211	0.189882006
12-UH-34	34-pheno6-2	82.36848989	17.33062865	0.300881458
12-UH-39	39-pheno1-1	85.75076689	14.00054905	0.248684053
12-UH-39	39-pheno1-2	80.59279984	19.08968795	0.31751221
12-UH-39	39-pheno5-1	88.00144165	11.82455211	0.174006233
12-UH-39	39-pheno5-2	84.05396924	15.65732762	0.288703138
12-UH-39	39-pheno12-1	79.31430619	20.42483778	0.26085603
12-UH-39	39-pheno12-2	83.35328189	16.37615358	0.270564531
12-UH-30	30-pheno1-1	76.60103783	23.01210009	0.386862086

Sample	Position Name	Forsterite (%)	Fayalite (%)	Tephroite (%)
12-UH-30	30-pheno1-2	83.4670144	16.2640457	0.268939899
12-UH-30	30-pheno3-1	81.57170855	18.19378822	0.234503235
12-UH-30	30-pheno3-2	85.79101362	14.01151147	0.197474916
12-UH-30	30-pheno4-1	88.15841449	11.6545863	0.186999207
12-UH-30	30-pheno4-2	86.73744921	13.05819903	0.204351755
12-UH-30	30-pheno5-1	88.38375194	11.47546958	0.140778475
12-UH-30	30-pheno5-2	86.50794394	13.30962806	0.182427998
12-UH-30	30-pheno2-1	88.12780785	11.68319121	0.189000938
12-UH-30	30-pheno2-2	86.67844808	13.14943874	0.17211318
12-UH-30	30-pheno16-1	88.15044528	11.6843491	0.165205626
12-UH-30	30-pheno16-2	84.15028659	15.61721919	0.232494224

Table 25: Fractionation model for north complex magma to south complex magma.

Oxide	North Complex	Olivine	Plag	Cpx		Proportions:	Bulk Solid	Residual Melt	Normalized Melt	South Complex
	wt%	wt%	wt%	wt%	Olivine:	0.45	wt%	wt%	wt%	wt%
SiO₂	47.48	40.15	52.27	46.99	Plagioclase:	0.35	45.76	47.91	47.83	48.68
TiO₂	1.49	0.01	0.16	2.69	Cpyroxene:	0.20	0.60	1.71	1.71	1.76
Al₂O₃	15.57	0.06	29.39	6.42			11.60	16.56	16.53	16.72
FeO	9.65	13.61	0.93	8.98	Total:	1.00	8.25	10.00	9.98	9.43
MgO	12.03	45.28	0.06	12.05	Frac Crys:	0.20	22.81	9.33	9.32	8.86
CaO	10.03	0.00	12.94	21.05			8.74	10.35	10.34	9.90
Na₂O	2.85	0.00	3.77	0.49			1.42	3.21	3.20	3.29
K₂O	0.91	0.00	0.43	0.05			0.16	1.10	1.09	1.37

Table 26: Mixing model between the bomb samples and the tufa sample.

$^{87}\text{Sr}/^{86}\text{Sr}$			
Bomb sample	% Tufa in Mix	Mix Conc	Mix Sr Isotopic Ratio
0.70408552	0	1000	0.70408552
Bomb sample Sr Concentration ppm	1	1013.621239	0.704163198
425	2	1027.242479	0.704238815
Tufa Ratio	3	1040.863718	0.704312454
0.70741878	4	1054.484957	0.70438419
Tufa Sr concentration ppm	5	1068.106197	0.704454096
2362.123932	10	1136.212393	0.704778487
	20	1272.424786	0.70532309
	50	1681.061966	0.706427365
	75	2021.592949	0.707006573
	100	2362.123932	0.70741878
$^{143}\text{Nd}/^{144}\text{Nd}$			
Bomb sample	% Tufa in Mix	Mix Conc	Mix Isotopic Ratio
0.51277959	0	26.58	0.51277959
Bomb sample Nd Concentration (ppm)	1	26.32502158	0.512779483
26.58	2	26.07004316	0.512779374
Tufa Ratio	3	25.81506474	0.512779263
0.51251936	4	25.56008632	0.512779149
Tufa Nd Concentration (ppm)	5	25.3051079	0.512779034
1.082158	10	24.0302158	0.512778418
	20	21.4804316	0.512776968
	50	13.831079	0.51276941
	75	7.4566185	0.512751265
	100	1.082158	0.51251936

References

- Allan, J. F. (1992). Cr-spinel as a petrogenetic indicator: deducing magma composition from spinels in highly altered basalts from the Japan Sea, ODP Leg 127 sites 794 and 797. In: Tamaki, K., Ingle, J., Suyehiro, K., Pisciotto, K., Allan, J., von Breymann, M. & et al. (eds.) Proceedings of the Ocean Drilling Program, Scientific Results. College Station, TX: Ocean Drilling Program, Vol. 127/128, 837-848.
- Benson, L., Currey, D., Lao, Y., and Hostetler, S., 1992, Lake-size variations in the Lahontan and Bonneville basins between 13,000 and 9000 14C yr B.P.: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 95, p. 19-32.
- Blewitt, G., Hammond, W.C., and Kreemer, C., 2009, Geodetic observation of contemporary deformation in the northern Walker Lane: 1. Semipermanent GPS strategy, in Oldow, J. S., and Cashman, P.H., ed., *Late Cenozoic Structure and Evolution of the Great Basin-Sierra Nevada Transition*, Boulder, The Geological Society of America, Inc., p. 1-15.
- Broecker, W.S., and Kaufman, A., 1965, Radiocarbon Chronology of Lake Lahontan and Lake Bonneville II, Great Basin: *GSA Bulletin*, v. 76, p. 537-566.
- Colgan, J. P. and Henry, C.D., 2009, Rapid middle Miocene collapse of the Mesozoic orogenic plateau in north-central Nevada: *International Geology Review*, v. 51, p. 920-961.
- Cousens, B., Henry, C.D., and Gupta, V., 2012, Distinct mantle sources for the Pliocene-Quaternary volcanism beneath Sierra Nevada and adjacent Great Basin, northern California and western Nevada, USA: *Geosphere*, v. 8, p. 562-580.

- Cousens, B. L., Henry, C.D., Harvey, B.J., Brownrigg, T., Prytulak, J., and Allan, J.F., 2011, Secular variations in magmatism during continental arc to post arc transition: Pliocene-Pleistocene volcanism in the Lake Tahoe/Truckee area, Northern Sierra Nevada, California: *Lithos*, v. 123, p. 225-242.
- Cousens, B., Prytulak, J., Henry, C., Alcazar, A., and Brownrigg, T., 2008, Geology, geochronology, and geochemistry of the Miocene-Pliocene Ancestral Cascades arc, northern Sierra Nevada, California and Nevada: The roles of the upper mantle, subducting slab and the Sierra Nevada lithosphere: *Geosphere*, v. 4, p. 1-25.
- Cousens, B., Wetmore, S., and Henry, C.D., 2013, The Pliocene-Quaternary Buffalo Valley volcanic field, Nevada: Post-extension, intraplate magmatism in the north-central Great Basin, USA: *Journal of Volcanology and Geothermal Research*, v. 268, p. 17-35.
- Faulds, J. E., Coolbaugh, M.F., Vice, G.S., and Edwards, M.L., 2006, Characterizing Structural Controls of Geothermal Fields in the Northwestern Great Basin: A Progress Report: *GRC Transactions*, v. 30, p. 69-76.
- Eiler, J. M., 2001, Oxygen Isotope Variations of Basaltic Lavas and Upper Mantle Rocks, *Review in Mineralogy and Geochemistry*, Washington, The Mineralogical Society of America, p. 319-364.
- Eiler, J. M. m. M., B., Valley, J.W., Grahams, C/M., and Stolper, E.M., 1998, Oxygen isotope evidence for slab-derived fluids in the sub-arc mantle: *Nature*, v. 393, p. 777-781.
- Faulds, J.E., and Henry, C.D., 2008, Tectonic influences on the spatial and temporal evolution of the Walker Lane: An incipient transform fault along the Pacific - North American plate boundary, *in* Spencer, J.E., and Titley, S.R., ed., *Ores and orogenesis*:

Circum-Pacific tectonics, geologic evolution, and ore deposits, Volume 22, Arizona Geological Society Digest, p. 437-470.

Fultz, L. A., Bell, E.J., and Trexler, D.T., 1983, Geochemistry, age and strontium isotope composition of late tertiary and quaternary basalts and andesites in western Nevada and their relation to geothermal potential, United States Department of Energy, p. 1-118.

LeBas, M. J., Le Maitre, R.W., Streckeisen, A., and Zanettin, B., 1986, A Chemical Classification of Volcanic Rocks Based on the Total Alkali-Silica Diagram: *Journal of Petrology*, v. 27, p. 745-750.

Louie, J. N., Thelen, W., Smith, S. B., Scott, J. B., Clark, M. K. and Pullammanappallil, S., 2004, The northern Walker Lane refraction experiment: Pn arrivals and the northern Sierra Nevada root. *Tectonophysics* 388, 253-269.

McLachlan, H. S. & Faulds, J. E. (2012). Some new constraints on the stratigraphic and structural setting of the Soda Lake Geothermal Field, Churchill County, Nevada. EOS, Transactions American Geophysical Union, Fall Meeting Supplement: San Francisco, V13A-2817.

Morrison, R. B., 1964, Lake Lahontan: Geology of Southern Carson Desert, Nevada: Geological Survey Professional Paper 401, p. 1-156.

Nesse, W. D., 2000, Introduction to Mineralogy: New York, Oxford University Press, p.1-442.

Olmsted, F. H., Welch, A.H., Vandenburg, A.S., and Ingebritsen, S.E., 1984, Geohydrology, aqueous geochemistry, and thermal regime of the Soda Lakes and Upsal Hogback geothermal systems, Churchill County, Nevada, Water Resources Investigation, p. 1-166.

Olmsted, F. H., Welch, A.H., Vandenburg, A.S., and Ingebritsen, S.E., 1984, Geohydrology, aqueous geochemistry, and thermal regime of the Soda Lakes and Upsal Hogback geothermal systems, Churchill County, Nevada, Water Resources Investigation, p. 1-166.

Ormerod, D. S., Hawkesworth, C. J., Rogers, N. W., Leeman, W. P., and Menzies, M. A. , 1988, Tectonic and magmatic transitions in the Western Great Basin, USA. *Nature* **333**, 349-353.

Oxford Instruments Analytical (1), Energy Dispersive X-ray Microanalysis Hardware, v. Technical Briefing, p. 1-16.

Oxford Instruments Analytical (2), Wavelength Dispersive X-ray Microanalysis, v. Technical Briefing, p. 1-11.

Pauly, B. D., P. Schiffman, R. A. Zierenberg, and D. A. Clague, 2011, Environmental and chemical controls on palagonitization: Geochemistry Geophysics Geosystems, v. 12, p. 1-26.

Rhode, D., Adams, K.D., and Elston, R.G., 2000, Geoarchaeology and Holocene landscape history of the Carson Desert, western Nevada, *in* Lageson, D. R., Peters, S.G., and Lahren, M.M., ed., Great Basin and Sierra Nevada, p. 45-74.

Shevenell, L., Coolbaugh, M., Faulds, J., Oppliger, G., Calvin, W., Blewitt, G., Kratt, C., Arehart, G., Sladek C., Lechler, P., Garside, L., and Zehner, R., 2005, Accomplishments at the Great Basin Center for Geothermal Energy, *in* Rhoden, H.N., Steineger, R.C., and Vikre, P.G., ed., Geological Society of Nevada Symposium 2005: Window to the World, Volume May 2005, p. 1131-1145.

- Stronck, N. A., and Schminke, H.U., 2002, Palagonite- a review: *International Journal of Earth Sciences*, v. 91, p. 680-697.
- Sun, S.-s. and McDonough, W.F., 1989, Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes, in Saunders, A. D. a. N., M.J., ed., *Magmatism in the Ocean Basins*, London, Geological Society Special Publication, p. 313-345.
- Thomson, G. A., 1959, *Geology of the Virginia City quadrangle, Nevada*, Contributions to Economic Geology 1956, Washington, United States Government Printing Office, p. 45-75.
- Unruh, J., Humphrey, J., and Barron, A., 2003, Transtensional model for the Sierra Nevada frontal fault system, eastern California: *Geology*, v. 31, p. 327-330.
- Walker, G. P. L. a. C., R., 1971, Characteristics of some basaltic pyroclastics: *Bulletin volcanologique*, v. 35, p. 303-317.
- Winchester, J. A., and Floyd, P.A., 1976, Geochemical magma type discrimination: application to altered and metamorphosed basic igneous rocks: *Earth and Planetary Science Letters*, v. 28, p. 459-469.
- Wohletz, K. H., and Sheridan, M.F., 1983, Hydrovolcanic explosions II. Evolution of basaltic tuff rings and tuff cones: *American Journal of Science*, v. 283, p. 385-413.
- White, J.D., 1991, The depositional record of small, monogenetic volcanoes within terrestrial basins, in Fisher, R.V., and Smith, G.A., ed., *Sedimentation in Volcanic Settings*, Volume 45: Tulsa, Society for Sedimentary Geology Special Publications, p. 155-171.
- Zak, J., 2013, *Volcanology and geochemistry of the Soda Lakes maar volcanoes*, Fallon

Nevada, p. 1-45.

Zindler, A. a. H., S., 1986, Chemical Geodynamics: Annual Review of Earth and Planetary Sciences, v. 14, p. 493-571.

.