Cooling Before Super-Eruption: No Role for Rejuvenation in the Cottonwood Wash Tuff Magma Body, Southern Great Basin Ignimbrite Province, Utah and Nevada

Keryn Tobler Ross
Brigham Young University - Provo

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Cooling Before Super-Eruption: No Role for Rejuvenation in the
Cottonwood Wash Tuff Magma Body, Southern Great
Basin Ignimbrite Province, Utah and Nevada

Keryn Tobler Ross

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

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Department of Geological Sciences
Brigham Young University
December 2015

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ABSTRACT

Cooling Before Super-Eruption: No Role for Rejuvenation in the Cottonwood Wash Tuff Magma Body, Southern Great Basin Ignimbrite Province, Utah and Nevada

Keryn Tobler Ross
Department of Geological Sciences, BYU
Master of Science

The model of rejuvenation of a near-solidus crystal mush to produce large volumes of crystal-rich magma is tested here by analyzing the mineralogical, chemical, modal, and physical characteristics of the 31.1 Ma super-eruptive (2000 km$^3$) Cottonwood Wash Tuff. It is the oldest in a series of three so-called “monotonous intermediate” ignimbrites from the Indian Peak-Caliente volcanic field in southern Utah and Nevada. A crystal-rich (~50% Pl > Qz ≈ Hbl ≈ Bt > Mag ≈ Ilm > Cpx + Zrn + Ap+ Po) dacite (62 – 69 wt% SiO$_2$), the Cottonwood Wash Tuff is similar in age, volume, mineralogy, crystallinity, and elemental composition to the 28.0 Ma, ~5000 km$^3$ Fish Canyon Tuff (~45% Pl + Kfs + Qz + Hbl + Bt + Ttn + Mag + Ilm + Ap + Zrn + Po, 66 – 68 wt% SiO$_2$), used as the basis of the rejuvenation model, which suggests that magma chambers remain in a near-solidus state until a late heating event melts the magma enough to allow eruption. The Cottonwood Wash magma chamber was compositionally varied, as shown by the composition of mineral and juvenile clast compositions. Most of the whole-rock compositional variations are likely due to the variation of mineral proportions induced by shear in the magma chamber. A volumetrically minor component with evolved mineral compositions, is represented by “evolved” juvenile clasts. Mineral compositions and experimental phase relationships show the pre-eruption magma crystallized at 800°C, 2.3 kb under water-undersaturated but oxidized conditions (delta QFM = 2.1). The majority of plagioclase and amphibole grains exhibit small-scale oscillatory zonation; where systematic compositional zonation exists, normal and reverse zonation are equally present. Cathodoluminescence of quartz reveals typically normally zoned phenocrysts with late resorption, considered to be the result of eruptive decompression. Many of the characteristics used to identify the warming of a near-solidus mush for the Fish Canyon Tuff are not present in the Cottonwood Wash Tuff [i.e., reversely zoned hornblende or plagioclase, partially remelted mineral aggregates, evidence of fluid saturation, resorption textures not related to decompression, rapakivi mantles, and hybrid andesite inclusions]. The Cottonwood Wash Tuff magma system did not undergo rejuvenation from a near-solidus state. Instead, the magma was apparently cooling and crystallizing just prior to eruption.

Keywords: Cottonwood Wash Tuff, rejuvenation, monotonous intermediate, ignimbrite
ACKNOWLEDGEMENTS

I would like to express my appreciation for all those who assisted me in the completion of this work. I am especially grateful for the brilliant help of Dr. Eric Christiansen, who has been willing to spend countless hours offering explanations, guidance, direction and support. I am also grateful for the insight, explanations, and comments of my committee, Dr. Mike Dorais and Dr. Bart Kowallis, with special thanks to Dr. Dorais for his cheerful help with the electron microprobe, both past and present. Dr. Myron Best, who first began to unravel the mysteries of the Indian Peak – Caliente volcanic field in the southern Great Basin, has been an invaluable resource, guide, and teacher in this work. All of the professors and office staff in the Department of Geological Sciences, both current and emeritus, have helped and encouraged me throughout my education. Thank you all.

Special gratitude goes to my field assistants, without whom I would have not survived in the deserts of Nevada and Utah: Michael D. Tobler, my late father; Telima Smith, my sister, Tony Tobler, my uncle, and Emily Lamas, my dear friend. Thank you for taking time out of your summers to help (and rescue!) me.

This work would have never reached completion without the support of my patient family. I’d like to thank LaDonna Tobler, my mother, for keeping an eye on my family during my absences, and my children, Ezra, Mercy, Gideon, Heber, and Miriam Ross, for their patience, love, and prayers.

Last, but certainly not least, I am grateful for the encouragement, love, enthusiasm, and patience of my husband, Bradley Ross. It was his idea that I should return to school to finish what I started fifteen years ago. This work would not have been possible without his constant support and sacrifices.
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INTRODUCTION

The extensively studied Fish Canyon Tuff is the basis for recent models for the origin of crystal-rich dacites. Bachmann et al. (2002), Bachmann & Bergantz (2006), and Huber et al. (2010) suggest that the Fish Canyon Tuff magma existed as a near-solidus crystal mush for much of its residence in the upper crust, and melted to around 45% phenocrysts due to heating (also called defrosting or “rejuvenation”) just prior to eruption. This late heating has been attributed to the injection of volatiles from underplated mafic magmas, called “gas sparging” by Bachmann & Bergantz (2006). This model is supported by a population of reversely zoned amphibole and plagioclase, resorbed quartz, and resorption textures in quartz and feldspar in the Fish Canyon Tuff and other eruptive products from the La Garita Caldera (Bachmann et al., 2002). Trace element modeling using zircons from the Fish Canyon magma is also proposed to show the reheating of a near-solidus magma chamber just prior to eruption (Wotzlaw et al., 2013, Bachmann et al., 2005). This hypothesis has been applied to other crystal-rich ignimbrites, both large and small (Molloy et al., 2008; Girard & Stix, 2009; Cooper & Kent, 2014). However, work done on the Wah Wah Springs Tuff, a large super-eruptive monotonous ignimbrite (5400 km³) in the Great Basin, by Woolf (2008) found no evidence of rejuvenation as seen by Bachmann et al. (2002) in the Fish Canyon Tuff.

In this paper, we compare the Cottonwood Wash Tuff to the Fish Canyon Tuff to determine if rejuvenation of a near-solidus magma body can be universally applied to crystal-rich ignimbrites. Both the Cottonwood Wash Tuff and the Fish Canyon Tuff are Oligocene age crystal-rich dacites with similar major and trace element compositions, mineral assemblages, and pre-eruptive pressures (Table 1), although the Fish Canyon Tuff seems to be cooler (760°C) and drier (3.5 H₂O wt%) (Newman & Lowenstern, 2002) than the Cottonwood Wash Tuff (800°C)
Fig. 1. (a) Distribution and thickness (in meters) of the Cottonwood Wash Tuff ignimbrite. The presumed location of the caldera is shown by a black dashed line. Stratigraphic sections and sample locations are indicated. Younger calderas and source areas are indicated by blue dashed lines. (b) Index map of western United States, showing the location of the Indian Peak - Caliente volcanic field, southern Great Basin, Nevada and Utah. Also indicated are the locations of Cottonwood Wash Tuff distal ash layers and the Fish Canyon Tuff (La Garita caldera).
and 4.7 H2O wt%). However, these differences should not obscure evidence if the Cottonwood Wash Tuff experienced pre-eruption rejuvenation similar to that proposed for the Fish Canyon Tuff.

SOUTHERN GREAT BASIN IGNIMBRITE PROVINCE

The crystal rich dacitic Cottonwood Wash Tuff is one of more than 250 recognized ignimbrites emplaced in the Great Basin province of the western United States (Best et al., 2013b) during the Cenozoic southward sweep of magmatism known as the “ignimbrite flare-up” (Noble, 1972; Coney, 1978) (Fig.1). More than 70,000 km³ of explosive volcanic products were erupted between 36-18 Ma, covering an area of 100,000 km². At least thirty of these explosive units—including the Cottonwood Wash Tuff, with a volume of approximately 2000 km³ (Best et al., 2013a)—were the products of super-eruptions of more than 1000 km³ (Miller and Wark, 2008).

Tectonic Setting

Previous to the ignimbrite flare-up, the crust of western North America—late Precambrian crystalline basement rocks, miogeoclinal Paleozoic sedimentary rocks (Dickinson, 2006), and Mesozoic sedimentary rocks (Miller & Gans, 1989; Best et al., 1993)—was modified by Cordilleran orogenic belt development. These mountain building events, caused by flat-slab subduction of the Farallon plate off the coast of western North America during the late Paleozoic through the Mesozoic (Severinghaus & Atwater, 1990), thickened the crust in the region to as much as 70 km (DeCelles, 2004; Dickinson, 2006). The extreme crustal thickening likely created a high-elevation plateau similar to the Andean Altiplano in west-central South America today (Best et al., 2009).

The transition from flat-slab to steep-angle subduction is thought to have triggered massive silicic volcanism in western North America (Rowley and Dixon, 2001). During flat-slab
**Table 1:** Comparison of characteristics of the Cottonwood Wash Tuff (Utah and Nevada) and the Fish Canyon Tuff (Colorado).

<table>
<thead>
<tr>
<th></th>
<th>Cottonwood Wash Tuff</th>
<th>Fish Canyon Tuff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Type</td>
<td>High K dacite</td>
<td>High K trachydacite</td>
</tr>
<tr>
<td></td>
<td>Magnesian</td>
<td>Magnesian</td>
</tr>
<tr>
<td></td>
<td>Calcic to calc-alkalic</td>
<td>Calcic to calc-alkalic</td>
</tr>
<tr>
<td>Volume (km³)</td>
<td>2000</td>
<td>5000</td>
</tr>
<tr>
<td>Age (Ma)</td>
<td>31.13</td>
<td>28.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2, 4</td>
</tr>
<tr>
<td>Whole rock SiO₂ wt%</td>
<td>62 - 69</td>
<td>65 - 71</td>
</tr>
<tr>
<td>Glass SiO₂ wt%</td>
<td>76.5 - 78</td>
<td>76.5 - 78</td>
</tr>
<tr>
<td>Crystallinity</td>
<td>50% (30-65%)</td>
<td>45%</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>pl + qz + hbl + bt + mag + ilm + cpx + ap + zrn + po</td>
<td>pl + kfs + qz + hbl + bt + ttn + mag + ilm + ap + zrn + po</td>
</tr>
<tr>
<td></td>
<td>An 49 - An 70 (cores)</td>
<td>Some calcic cores to An85</td>
</tr>
<tr>
<td>Amphibole composition (Al₂O₃ wt%)</td>
<td>6.5 - 10.2</td>
<td>7.5 - 8.5 (rims)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 - 6 (cores)</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>798</td>
<td>760</td>
</tr>
<tr>
<td>Pressure (kb)</td>
<td>2.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Water wt%</td>
<td>4.7</td>
<td>3.5</td>
</tr>
<tr>
<td>fO₂(QFM)</td>
<td>2.1</td>
<td>1.9 - 3.0</td>
</tr>
</tbody>
</table>

References: 1 - Best et al., 2013; 2 - Lipman & Bachmann, 2015; 3 - Peter Lipman, personal communication; 4 - Coble, 2013; 5 - Bachmann et al., 2013; 6 - Carrichi & Blundy, 2015; 7 - Newman & Lowenstern, 2002
subduction, magmatism was suppressed (Lipman, 1992) as the crust thickened and warmed. Slab roll back began around 51 Ma (Best & Christiansen, 1991), and the exposure of the asthenosphere to fluids from the dehydrating plate generated massive amounts of basaltic magma, which in turn precipitated the silicic ignimbrite flare-up. Between 36 – 18 Ma, voluminous caldera-forming silicic ignimbrites with some lava flows erupted in the southern Basin and Range. Closely following the ignimbrite flare-up, extensional faulting collapsed the high plateau, separating and dividing the outflow sheets. Some calderas are exposed in block-faulted mountain ranges while others are obscured, likely buried in the intervening valleys (Best et al., 2013a).

INDIAN PEAK – CALIENTE VOLCANIC FIELD

The Indian Peak – Caliente volcanic field of the southern Great Basin, straddles the border between Utah and Nevada (Fig.1). The volcanic field has more than 50 ignimbrite units, with 9 exposed calderas (Best et al., 2013b). At least nine of the ignimbrites have dense rock volumes greater than 1000 km$^3$ (Best et al., 2013b), placing them in the super-eruptive category of Miller & Wark (2008).

The Cottonwood Wash Tuff, emplaced at 31.13 Ma (Best et al., 2013b), is the oldest of the super-eruptive ignimbrites in the field. The Wah Wah Springs Tuff (30.06 Ma), the Lund Tuff (29.20 Ma), and the Cottonwood Wash Tuff represent the eruption of more than 12 300 km$^3$ of crystal-rich, monotonous intermediate dacite from overlapping calderas in 2 million years (Fig. 1; Best et al., 2013b).

Monotonous intermediates

The Cottonwood Wash Tuff, along with three other large volume ignimbrites of the southern Great Basin, are considered “monotonous intermediates,” so named by Hildreth (1981) because
of their intermediate silica and lack of pronounced modal and chemical zoning common in smaller ignimbrites (Table 2) (Best et al., 2013b; Best et al., 2013c). A possible fourth monotonous intermediate, the Harmony Hills Tuff from the Caliente caldera complex, is currently being studied (J. Kaiser, pers. com.). Besides these southern Great Basin ignimbrites, other monotonous ignimbrites are in the Fish Canyon Tuff of southwestern Colorado (e.g., Whitney & Stormer, 1985; Bachmann et al., 2002, Fig. 1), and the La Pacana and Cerro Galan ignimbrites of the Andes (e.g., Lindsay et al., 2001; Folkes et al., 2011).

**ANALYTICAL TECHNIQUES**

Samples were collected from throughout the outflow sheet, although the southwestern section is underrepresented. In five locations, samples representing the exposed stratigraphic section were collected (Figs. 1 & 2). Juvenile clasts (pumiceous and dense cognate inclusions) were collected from six sites: four sites (two near the center of the outflow sheet, two on the edges) from near the base of the outflow sheet, and two sites near the top of the outflow sheet, with one proximal and one distal. See appendices A & B for exact locations and descriptions of each sample.

Modal abundances were collected by petrographic microscope using 1500 points per thin section. Dense rock equivalence (DRE) calculations were done by determining the density of the samples (Table 3). Because the standard method of determining density by measuring water displacement is ineffective with porous rock (especially the vesiculated pumice clasts), density was measured using mercury displacement. Pure mercury is too viscous to fill the pore spaces of the rocks, but fluid enough to allow measurable displacement. Mercury has the added benefit of sheeting completely off the sample, allowing the rock to be used in other analytical procedures. Nearly all juvenile clasts (n=15) and a representative number of tuff samples (n=9) were
Table 2. Representative whole rock analyses of the Cottonwood Wash Tuff ignimbrite and juvenile clasts.

<table>
<thead>
<tr>
<th></th>
<th>GOUGEWL-1</th>
<th>HAM-1V</th>
<th>HFW-21V</th>
<th>KNOLL-1-9</th>
<th>KNOLL-1-40</th>
<th>MWASH-1-10</th>
<th>MWASH-1-40</th>
<th>SHNG-4-34</th>
<th>SHNG-4-78</th>
<th>SILVRWL-3-0</th>
<th>WARM-3-25</th>
<th>WARM-3-70</th>
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<tr>
<td>SiO₂</td>
<td>62.14</td>
<td>66.39</td>
<td>65.58</td>
<td>64.23</td>
<td>64.50</td>
<td>67.36</td>
<td>67.38</td>
<td>63.28</td>
<td>65.34</td>
<td>61.82</td>
<td>65.73</td>
<td>63.67</td>
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<tr>
<td>TiO₂</td>
<td>0.74</td>
<td>0.54</td>
<td>0.61</td>
<td>0.63</td>
<td>0.65</td>
<td>0.53</td>
<td>0.54</td>
<td>0.64</td>
<td>0.66</td>
<td>0.79</td>
<td>0.64</td>
<td>0.66</td>
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<tr>
<td>Al₂O₃</td>
<td>16.99</td>
<td>15.60</td>
<td>15.77</td>
<td>15.90</td>
<td>15.60</td>
<td>15.29</td>
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<td>15.80</td>
<td>15.82</td>
<td>15.46</td>
<td>15.95</td>
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<tr>
<td>Fe₂O₃</td>
<td>6.09</td>
<td>4.65</td>
<td>4.99</td>
<td>5.38</td>
<td>5.48</td>
<td>4.44</td>
<td>4.44</td>
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<td>MnO</td>
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<td>0.07</td>
<td>0.07</td>
<td>0.06</td>
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<td>0.10</td>
<td>0.10</td>
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<td>MgO</td>
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<td>1.57</td>
<td>1.63</td>
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<td>CaO</td>
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<td>4.81</td>
<td>5.17</td>
<td>5.18</td>
<td>3.90</td>
<td>3.80</td>
<td>5.70</td>
<td>3.99</td>
<td>5.79</td>
<td>4.52</td>
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<td>Na₂O</td>
<td>2.48</td>
<td>3.11</td>
<td>3.29</td>
<td>2.84</td>
<td>2.85</td>
<td>2.96</td>
<td>2.87</td>
<td>2.53</td>
<td>2.70</td>
<td>2.96</td>
<td>3.08</td>
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<tr>
<td>K₂O</td>
<td>2.30</td>
<td>3.30</td>
<td>2.70</td>
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<td>3.83</td>
<td>3.89</td>
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<td>3.51</td>
<td>3.27</td>
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<tr>
<td>P₂O₅</td>
<td>0.16</td>
<td>0.10</td>
<td>0.14</td>
<td>0.14</td>
<td>0.15</td>
<td>0.11</td>
<td>0.11</td>
<td>0.13</td>
<td>0.15</td>
<td>0.17</td>
<td>0.15</td>
<td>0.18</td>
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Anal Total 98.93 99.16 98.56 98.70 98.12 98.26 98.54 97.69 99.41 98.32 99.39 98.26

LOI 3.97 1.79 2.30 2.44 1.58 0.78 0.83 0.57 2.57 0.85 2.11 2.91

Sc 14 10 13 12 14 14 13 15 18 17 14 14
V 105 93 93 95 76 74 96 85 122 100 101
Cr 17 17 16 17 8 10 13 14 20 25 20 19
Ni 11 7 9 11 6 8 5 10 11 6 9 10
Cu 19 13 14 16 8 11 17 19 17 15 18
Zn 64 59 55 54 52 52 52 56 56 57 54 56
Ga 20 17 18 17 17 17 17 18 19 17 18 18
Rb 126 152 149 134 144 142 145 157 102 126 122
Sr 452 394 396 396 348 351 389 357 387 435 412 435
Y 25 20 23 23 17 20 19 21 21 25 23 23
Zr 191 170 176 179 166 153 153 181 173 184 172 179
Nb 9 8 8 5 5 8 7 7 4 7 7 8
Ba 573 725 732 615 657 785 779 750 714 656 574 710
La 41 46 43 50 42 37 43 23 47 47 44 40
Ce 86 82 78 84 78 66 76 84 88 87 82 84
Nd 37 35 37 39 35 31 33 38 37 41 37 38
Sm 5 8 8 8 7 8 7 3 8 7 7 7
Pb 22 22 24 24 17 22 22 22 22 19 21 21
Th 25 23 26 28 25 25 24 25 30 23 23 22
U 4 4 4 5 5 4 4 4 3 4 4 4

Oxide values (in weight %) have been recalculated to 100% on a volatile-free basis. LOI = loss on ignition. Trace elements are given in ppm.
Samples from vertical sections are listed from bottom to top in order of stratigraphic height in meters. Suffix (V) in sample name indicates a vitrophyre. * Sample has adjusted calcium totals, see text for details ** Sample has depleted alkalis, see text for details
Table 2. (cont.) Representative whole rock analyses of the Cottonwood Wash Tuff ignibrite and juvenile clasts.

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Fig. 2. Five stratigraphic sections of Cottonwood Wash Tuff. Section name indicates topographic quadrangle where section is located; see Fig. 1. Samples are indicated at corresponding stratigraphic height. Where present, the vitrophyre is indicated by gray shading.
Table 3. Representative modal analyses and measured or estimated densities of the Cottonwood Wash Tuff ignimbrite and juvenile clasts.

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<th>% Phenocryst</th>
<th>Plagioclase</th>
<th>Quartz</th>
<th>Biotite</th>
<th>Hornblende</th>
<th>Pyroxene</th>
<th>Fe-Ti Oxides</th>
<th>Xenocryst Sanidine</th>
<th>Rock Density</th>
<th>Adj. % Phenocryst</th>
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All modes based on 1500 point counts. Modes are normalized to 100% phenocrysts dense rock equivalence. Percentages of phenocrysts were calculated using densities. (see text for details). Estimated densities indicated by a star (*).
measured this way. In dense rock equivalence calculations, when a sample was not directly measured as described, the density of a comparably welded measured sample was then used.

Geochemical analyses were performed on tuff (50 samples) and juvenile clasts (18 samples) (Table 2). While most of the tuff and juvenile clast samples were fresh, several samples, especially those of two of the eastern sample localities, Warm Point, Bullgrass, and Toms Knoll, had significant calcite in the pore spaces of the vesiculated pumice and non-welded tuff samples, due to submergence under the pluvial lakes of the Pleistocene Epoch. These samples (8 tuff, 6 juvenile clasts) were crushed, bathed briefly in a weak (10%) hydrochloric acid solution, and allowed to dry in a 100°C oven overnight. After analysis, the results from these samples were compared to fresh samples. Thirteen samples still had anomalous CaO in relation to Al₂O₃ and SiO₂. The CaO concentrations in these samples were adjusted so that the CaO/Al₂O₃ ratio fit within the trend defined by the fresh samples. The modified analyses are marked with a single star in Table 2.

Each juvenile clast sample represents a separate, unique clast; multiple juvenile clast fragments were not used to create one sample. Major and trace element concentrations were determined by X-ray fluorescence spectrometry (Siemens SRS 303 at Brigham Young University) on glass discs and pressed powder pellets.

Mineral compositions were determined on a Cameca SX50 electron microprobe at Brigham Young University. An accelerating voltage of 15 kV was used, and beam currents were generally between 10 – 20 nA. Quartz cathodoluminescence images were obtained using an FEI XL30 ESEM scanning electron microscope with a Gatan MiniCL detector at Brigham Young University. Quartz grains were imaged using a spot size of 6, a tilt of 12 -15°, a scan time of 116 ms/line, and an accelerating voltage of 15 kV.
PHYSICAL CHARACTERISTICS OF THE COTTONWOOD WASH TUFF

No caldera or caldera fill have been found for the Cottonwood Wash Tuff. The caldera was possibly engulfed by later caldera formation, either the Indian Peak Caldera (formed by eruption of the Wah Wah Springs Tuff) or the White Rock Caldera (formed by eruption of the Lund Tuff), or both. The most likely place for the Cottonwood Wash Tuff caldera, based on outcrop thicknesses and Bouguer gravity studies, is in the Wilson Creek Range and the White Rock Mountains (Fig.1) (Best et al., 2013b).

There is no evidence of precursory eruptions of an evolved rhyolitic cap; the Lamerdorf Tuff, a crystal-poor rhyolite erupted ~0.8 Ma prior to the Cottonwood Wash Tuff, is chemically distinct and unlikely to be related (Best et al., 2013b). In almost all places, the Cottonwood Wash Tuff rests unconformably on Paleozoic and Mesozoic sedimentary rocks or on earlier Paleogene volcanic rocks (Hintze & Kowallis, 2009). Corrected for approximately 50% extension, the outflow sheet covers an area of 12 000 km² (Fig. 1). The thickness of the Cottonwood Wash Tuff is somewhat irregular throughout the outflow sheet, in some areas varying more than 140 m in less than 20 km, with a maximum thickness of 280 m in the Fairview Range (Fig. 1) (Best et al., 1998). As later ignimbrites show less variation in thickness, a progressive smoothing of the terrain has been suggested, with the first regional ignimbrite (the Cottonwood Wash Tuff) being deposited on irregular terrain, and filling in paleovalleys and canyons (Best et al., 2009). The irregularity of section thickness hinders accurate calculation of total volume, and the figure of 1000 km³ for the outflow portion of the Cottonwood Wash Tuff used by Best et al. (2013b) should be considered a conservative estimate. The absence of a source caldera makes volume estimates less accurate. However, given that the intracaldera volume and outflow volume of some ignimbrites are approximately equal (Lipman, 1997), the total eruptive volume of the
Cottonwood Wash Tuff is estimated at 2000 km$^3$. (For a complete discussion of volume estimations in the Indian Peak – Caliente volcanic field, see “Dimensions of Ignimbrites” in Best et al. (2013b).) A caldera diameter of 30 km and a magma chamber thickness of about three km is estimated for the Cottonwood Wash Tuff, based on calculations using the volume of the outflow sheet; comparisons with the similarly sized Wah Wah Springs and Lund Tuffs from the Indian Peak caldera complex (Best et al. (2013b) were also used.

A survey of five stratigraphic sections (four complete and one partial) indicates the Cottonwood Wash Tuff ranges from densely welded with a prominent near-basal vitrophyre in some sections to nearly non-welded in others (Fig.2). The poorly to non-welded sections are primarily found on the eastern margin of the outflow sheet (Knoll Hill and Warm Point sections), with the exception of the centrally located Gouge Eye Well section, which ranges from poorly to densely welded in just a few meters. No major partings indicative of significant cooling breaks are present in the ignimbrite.

Poorly bedded pyroclastic surge deposits are found beneath the tuff in three locations: Knoll Hill (KNOLL), Gouge Eye Well (GOUGEWL), and Warm Point (WARM) (Figs. 2, 3; Ross et al., 2002; Best et al., 2013b). Varying in thickness from 1.1 m (KNOLL) to 0.21 m (GOUGEWL), these surge deposits are in planar contact with the tuff with no visible scours or troughs. The surge layers range between two end-members: a coarse, phenocryst-rich (45 – 75% dense rock equivalent (DRE)) andesite, with biotite grains sorted by shape in the layers; and a finer, phenocryst-poor (14 – 30% DRE) rhyolite, dominated by tiny (~0.5 mm) pumice and glass fragments (Fig. 4d). In three sections, the surge deposits are underlain by a local conglomerate. We suspect the surges formed at the front of the pyroclastic flow when it encountered surface
Fig. 3. Basal contact of the Cottonwood Wash Tuff on the flank of Toms Knoll, Knoll Hill Quadrangle, Utah. Light colored pumice clasts are clearly visible in the massive tuff. Note the ~1 meter, crudely bedded surge deposit. Hammer lies at the contact between the main ash-flow tuff and the surge. Below the surge is a local fluvial conglomerate. See Knoll Hill Section, Fig. 2.
Fig. 4. Photomicrographs of the four types of Cottonwood Wash Tuff lithofacies. (a) Vitrophyric tuff, sample HFW-22V. (b) Loosely welded tuff, sample WARM-3-87. Bubble wall shards and fractured phenocrysts (phenoclasts) are visible. (c) Pumiceous juvenile clast, sample ATL-1-70-1P-3. (d) Non-vesiculated juvenile clast, sample KNOLL-1-38-1P-3. (e) Microdacitic juvenile clast with glassy groundmass sample GOUGEWL-1-5Pb-md. (f) Crudely bedded surge, sample WARM-5-1.
water. Perhaps small, localized steam explosions created conditions that mechanically separated and sorted glass and phenocrysts.

As is common with monotonous ignimbrites (Hildreth, 1981), the Cottonwood Wash Tuff lacks precursory plinian deposits. However, ash layers correlated both by age and phenocryst composition to the Cottonwood Wash Tuff have been found on the eastern slope of the Uinta Mountains (Diamond Mountain Plateau in the Bishop Conglomerate, ~500 km away from the presumed caldera) (Kowallis et al., 2005), in the base of Chimney Rock, Nebraska (Upper ash of the Whitney Member of the Brule Formation, ~1000 km away) (Blaylock, 1998), and near the town of Mercury, Nevada (Barnes et al., 1982; Slate et al., 1999). These ash beds likely formed from co-ignimbrite plumes, which can carry fine particles hundreds and even thousands of kilometers from the source vents (Blaylock, 1998; Kowallis et al., 2005). The tops of dense pyroclastic flows can generate these dilute, buoyant clouds of small ash-sized particles—usually considered to be dominantly glass, but small crystals or fragments of crystals are present as well—through the heating of entrained air within the pyroclastic flow (Carey & Bursik, 2000).

Determining the volume of such distal ash fall is problematic. The combination of uncertainty in the original distribution of the ash and in posteruption erosion and reworking (Izett et al., 1988) make calculating volumes difficult. A reasonable distribution, given that the location of the most distal ash fall bed identified as Cottonwood Wash Tuff is in Nebraska, about 1000 km away from the source caldera, allows that ash could have been carried over an area 2000 km in diameter. Assuming that the ash layer was between 1 – 10 cm thick, then between 31 – 310 km³ of material could have been carried away in the co-ignimbrite ash clouds. Corrected to a dense rock equivalent, the fallout tuff would represent 20 to 200 km³ of magma. Similarly,
Scarpati et al. (2014) suggest about 240 km$^3$ of magma for the distal ash of the Cottonwood Wash Tuff. These estimates are at best a minimum, as the farthest extent and/or thickness of the ash fall could have been greater. Ash from the younger and smaller Bishop Tuff in California has been found more than 1800 km away from the source (Izett et al., 1988).

**Phenocrysts**

One of the distinguishing characteristics of the Cottonwood Wash Tuff is the presence of large books of biotite, some as large as 8 mm across, and doubly terminated quartz crystals as large as 5 mm. No other ignimbrite in the Indian Peak – Caliente volcanic field has similarly sized biotite grains. Plagioclase crystals, some as large as 9 mm, are visible in the tuff as well. Although more abundant modally, the smaller sized hornblendes are easily overlooked in the field. Other phenocrysts include magnetite, ilmenite, clinopyroxene, and rare orthopyroxene and pyrrhotite.

**Juvenile Clasts**

Several types of juvenile clasts are found in the Cottonwood Wash Tuff. Vesiculated pumice fragments and non-vesiculated dense cognate inclusions (collectively called “juvenile clasts” in this paper) are rare but can be found at all stratigraphic levels in the outflow sheet (Fig. 4c-e). Some from the eastern half of the outflow sheet are as much as 30 cm across but most are less than 10 cm across.

Juvenile clasts with uniformly sized (between 0.75 and 0.25 mm) small phenocrysts in a glassy rhyolitic matrix (with local spherulites) (Fig. 4c) are found in all parts of the outflow sheet. These fine-grained clasts are referred to as “microdacite inclusions” in this paper. In most samples, these inclusions are small (< 2 mm). Typically, a thin rind of devitrified glass coats the inclusion. Rare larger microdacite inclusions (> 4 mm) found in juvenile fragments in the centrally located Gouge Eye Well section, while not large enough to analyze whole rock
composition by X-ray fluorescence spectrometry, are of a sufficient size to make thin sections and analyze the phenocryst compositions. Phenocrysts of biotite, feldspar, amphibole, and oxides, while included with all other phases (except quartz) present, are nearly compositionally identical to the main tuff assemblage, with some small variations. Interestingly, there is little to no quartz in these microdacite fragments.

**Lithic fragments**

Lithic fragments, typically no more than 3 mm across, are sparse in the Cottonwood Wash Tuff outflow sheet. Andesitic lava fragments with feldspar microlites, small euhedral hornblendes, in a commonly microlitic but rarely glassy matrix, are found in most areas sampled (absent in Gouge Eye Well section, as well as Hamlin Valley and Bullgrass samples). Baked carbonates and small sandstone or quartzite fragments are unique to the Warm Point section at the eastern margin of the outflow sheet.

**WHOLE-ROCK COMPOSITION**

The Cottonwood Wash Tuff samples (Table 2), both tuff and juvenile clasts, are dacites in the total alkali-silica classification diagram (Fig. 5a). Two whole rock samples of tuff (GOUGEWL-1-1 and SILVRWL-3-0), both collected from the base of the stratigraphic sections, plot in the andesite field. The GOUGEWL-1-1 sample also has depleted alkalis, indicating post-eruptive alteration. It is included here because the phenocryst compositions do not appear to be perturbed. The Cottonwood Wash Tuff is high-K (Ewart, 1979), metaluminous, magnesian (calc-alkaline in some classifications) and calc-alkalic to calcic according to the Frost et al. (2001) classification (Fig. 5b). The whole-rock compositions fall in the volcanic arc-granite field on the Rb-Y-Nb tectonic discrimination diagrams of Pearce et al. (1984) (not shown). Normalized trace elements patterns (Fig. 6) (McDonough & Sun, 1995) show negative Nb and Ti anomalies characteristic of
Fig. 5. Chemical variation diagrams for the Cottonwood Wash Tuff ignimbrite, juvenile clasts, and glass (electron microprobe) are represented by blue circles. Fish Canyon Tuff is represented by a gray field (Peter Lipman, personal communication). (a) Total alkalis-silica by classification (LeMaitre, 1989). (b) Modified alkali-lime index-silica (Frost et al., 2001). N = number of individual samples.
Fig. 6. Mantle-normalized multi-element diagrams for the Cottonwood Wash Tuff ignimbrite, juvenile clasts, and Fish Canyon Tuff (Fish Canyon from Peter Lipman, personal communication). Concentrations normalized to primitive mantle composition of McDonough & Sun (1995). Note the lack of systematic differences between sample types.
continental arc magmas, or of magma derived from preexisting continental crust. The negative 
Ba, Sr, and P anomalies seen on the trace element patterns may be accounted for in the 
fractionation of biotite, plagioclase, and apatite respectively.

**Chemical trends**

For most major elements the Cottonwood Wash Tuff defines linear arrays with K₂O and SiO₂ 
decreasing with increasing TiO₂, while MgO, Fe₂O₃, CaO, and P₂O₅ increase along with TiO₂ 
(Fig. 7). Although enriched in Al₂O₃, P₂O₅, and Na₂O compared to the Cottonwood Wash Tuff, 
the Fish Canyon Tuff samples follow the same trends, and have comparable concentrations of 
TiO₂. Trace elements that positively correlate with TiO₂ are considered to be compatible 
elements and include Sc, V, Cr, Ni, Cu, Zn, Ga, Sr, and Zr (Fig. 8). Incompatible trace elements 
that negatively correlate with TiO₂ include Rb, La, U, Th, and Pb. Compatible element 
abundances vary widely, with Cr showing the largest variation. Incompatible element 
enrichments are smaller, with Pb showing the best correlation with TiO₂ and increasing by 2.5 
times. In general, the juvenile clasts and the tuff lie between the composition of the glass and the 
bulk composition of the phenocrysts calculated from their compositions and modal proportions 
(Fig. 9).

The silica content of the tuff (61.8 – 69 wt% SiO₂) and juvenile clasts (63.4 – 69.8 wt% 
SiO₂) has considerable overlap, and both span the dacite field in the total alkalis-silica 
classification diagram (Fig 5a, Table 2). The more silicic end of the range is dominated by 
juvenile clasts, and the less silicic end is dominated by tuff samples. However, juvenile clasts are 
found throughout the range of tuff compositions, including the more mafic compositions. 
Varying amounts of glass removal by co-ignimbrite ash elutriation may account for the most 
mafic tuff samples. But the range of compositions in the juvenile clasts, presumably unmodified
Fig. 7. Major element concentrations plotted against TiO$_2$ for the Cottonwood Wash Tuff. The average of the Upper Whitney Ash, a probable distal ash from the Cottonwood Wash Tuff (Blaylock, 1998), is represented by a cross. Fish Canyon Tuff are represented by a gray field (Peter Lipman, personal communication). Although the Fish Canyon Tuff is enriched in Al$_2$O$_3$, P$_2$O$_5$, and Na$_2$O compared to the Cottonwood Wash Tuff, the major element trends are similar. (P$_2$O$_5$ was not analysed in glass matrices.)
Fig. 8. Trace element concentrations plotted against TiO$_2$ (wt%) for the Cottonwood Wash Tuff and Fish Canyon Tuff (gray field) (Peter Lipman, personal communication). Rb, Th, Pb behave incompatibly. Sc, Cr, Zr, Ni, and V are compatible.
Fig. 9. TiO$_2$ (wt%) vs percent crystallinity. The whole rock compositions of the Cottonwood Wash Tuff ignimbrite and juvenile clasts lie on a line between the composition of the glass (0.11 TiO$_2$ wt%) and the bulk composition of the phenocryst phases (1.1 - 1.47 TiO$_2$ wt%). Based on the whole rock composition, the samples have calculated crystallinities (~40 - 67 %) comparable to the measured (by point count) crystallinities (~37 - 55 %).
by glass removal, indicates that most of the compositional range is a primary feature of the magma. The Cottonwood Wash Tuff may be a monotonous intermediate, but the magma had considerable variation.

The seventeen juvenile clasts span nearly the entire SiO₂ range (Fig. 5a), ranging from the most mafic (63 wt% SiO₂) to silicic (nearly 70 wt% SiO₂). Although the compositions of the juvenile clasts lie on a continuum, for convenience, the seven most silicic clasts (>68.00 SiO₂ wt% and <0.57 TiO₂ wt%) will be referred to as “evolved” juvenile clasts, and the ten others as “less-evolved” juvenile clasts. No attempt was made to classify any tuff samples into “evolved” and “less evolved” as the tuff samples define a continuum between the most mafic and most silicic juvenile clasts.

Modest differences between the phenocryst compositions in the less evolved and more evolved clasts are noted in the discussions below. However, these differences are not large enough to account for the compositional variation between the most evolved and least evolved juvenile clasts. The chemical trends (Fig. 7) suggest the more evolved juvenile clasts have fewer phenocrysts and more glass (i.e., lower Fe₂O₃, CaO, Al₂O₃, and MgO, and higher K₂O).

**MODAL ABUNDANCES**

The Cottonwood Wash Tuff magma was a crystal-rich (46 ± 6 % phenocrysts in the evolved juvenile clasts, 51 ± 8 % phenocrysts in the less-evolved juvenile clasts, and 49 ± 5 % phenocrysts in the tuff samples) dacite consisting of plagioclase > biotite ≈ hornblende ≈ quartz > magnetite ≈ ilmenite > clinopyroxene, with rare orthopyroxene and accessory apatite, zircon, and pyrrhotite. In fresh glassy samples, the matrix is a microlite-free vitroclastic matrix of high-silica (76.6 – 78.1 wt% SiO₂) rhyolite glass (Table 3, Fig. 10). Altered samples have a matrix of clays, microlites, and spherulites. In a minority of samples the pore spaces are filled with calcite
Fig. 10. Modal proportions of phenocrysts in the Cottonwood Wash Tuff ignimbrite and juvenile clasts, with dense rock equivalent (DRE) total phenocrysts.
crystals. The full mineral assemblage is present in both juvenile clasts and tuff. Similar to other monotonous intermediates (Maughan et al., 2002; Whitney & Stormer, 1985; Bachmann et al., 2002), no major crystalline phase appears or disappears vertically or laterally through the Cottonwood Wash Tuff.

Rare euhedral to subhedral sanidine grains, some with alteration, were found in less than 20% of samples modally analyzed; its presence was not systematic in the deposit. One K-feldspar grain had a composition of Or$_{80}$, too high to be in equilibrium with the other phenocrysts; most sanidine in dacitic volcanic rocks has Or$_{60-70}$, (e.g., Christiansen et al., 2015; Bachmann et al., 2002). The K-feldspar found in the Cottonwood Wash Tuff is likely xenocrystic, and is not considered further here.

If co-ignimbrite winnowing of glass occurred, the tuff samples would be expected to have higher percentages of phenocrysts when compared to the juvenile clasts. Using t-tests, it appears that there is no statistical difference between the phenocryst proportions is the juvenile clasts and tuffs, bolstering the idea that ash elutriation, at most, played a minor role in the emplacement of the tuff. Between 31 – 310 km$^3$ of ash-sized particles may have been removed from during co-ignimbrite elutriation, as discussed above. Even if the higher number is used (~15% of the outflow ignimbrite volume), this difference may not be noticeable in the highly variable phenocryst point counts.

When comparing the evolved juvenile clasts to the less evolved juvenile clasts, individual phenocryst proportions and dense rock equivalence (DRE) crystallinities are subequal (average total phenocrysts 46 ± 6% and 47 ± 10% DRE respectively). Although the juvenile clasts’ chemical trends suggest the evolved clasts should have a higher percentage of glass as compared to the less evolved clasts, this difference is not discernable in the modal proportions.
Individual phenocryst proportions vary significantly in the Cottonwood Wash Tuff (Fig. 10, Table 3). This variability is common in the ignimbrites of the Indian Peak – Caliente volcanic field (Maughan et al., 2002; Woolf, 2008; Best et al, 2013b). It is unclear how much of the variation accurately reflects the conditions in the magma chamber prior to eruption. The coarse grain size of some phases, relative scarcity of phenocrysts in the vesiculated pumice fragments, and the small countable area of a thin section make highly accurate modal counting difficult. As with the whole rock composition of the most mafic samples, ash removal during eruption may be responsible for some of the variation in the tuff phenocryst proportions. However, the juvenile clasts would not have experienced this elutriation, and modal abundances in the juvenile clasts show essentially the same variability as in the tuffs. The variation of phenocryst proportions in the juvenile clasts may be attributable to convective processes in the magma chamber, while the effect of eruptive glass winnowing on the phenocryst proportions seems to be negligible.

PHENOCRYST TEXTURES AND COMPOSITION

Plagioclase

Plagioclase is the dominant crystal phase in the Cottonwood Wash Tuff, ranging from ~44 – 70% (evolved juvenile clasts), ~54 – 69% (less evolved juvenile clasts), and 48 – 66% (tuff samples) of the phenocrysts in the tuff and juvenile clasts (Fig. 10). The plagioclase crystals are typically <2 mm long, but can range to as much as 5 mm (in the tuff) and 9 mm (in the juvenile clasts). While the majority of the plagioclase grains are broken (phenoclastic, e.g. Best & Christiansen, 1997); most plagioclase phenocrysts have at least one euhedral face visible. Often the crystals are glomerophyric with other plagioclase grains. All major phases, including rare quartz, appear as inclusions in the plagioclase grains of all samples, demonstrating that all of the
phases co-crystallized. Glassy melt inclusions in plagioclase are present in all samples, but not common.

Plagioclase phenocryst textures in the Cottonwood Wash Tuff can be divided into three main categories. “Clean” (few to no inclusions, no distinct cores, or sieve textures), “sieved” (full of small holes or melt inclusions), and “resorbed core” (with an optically or textually distinct center). In a survey of 29 Cottonwood Wash Tuff juvenile clasts and tuff samples, more than half (~60%) of the plagioclase phenocrysts were “clean”, and roughly equal amounts (~20% each) of plagioclase grains were “sieved” and “resorbed core.” Interestingly, half of the plagioclase grains in the microdacitic inclusion are heavily included, and only a small proportion (~20%) were “clean” and 30% were “sieved”. There are no obvious differences between the plagioclase textural types in the juvenile clasts and tuff samples. A similar survey of five Fish Canyon Tuff samples from Wolf Creek Pass, Colorado, revealed similar percentages (~60 % “clean”, 14% “sieved”, and 26% “resorbed core”).

Resorption is evident in the embayed outlines and rounded edges of many grains. Splotchy, optically distinct, or inclusion-rich resorbed cores are present in plagioclase in many samples. Grains with inclusion-rich growth zones, often with non-included euhedral mantles, exist in most samples, although in a minority of crystals.

Analyses of 99 plagioclase grains from juvenile clasts and tuff samples reveal compositionally restricted rims of An$_{49±5}$ (evolved juvenile clast An$_{45±3}$, less evolved juvenile clasts An$_{51±3}$, microdacite inclusion An$_{51±9}$, tuff An$_{50±6}$) (Fig. 11, Table 4). More than 40% of the grains (42 of 99 grains) have cores more calcic than their rims (normally zoned) and 27% (27 grains) have cores less calcic than their rims (reversely zoned). The remainder of the grains analyzed (30% or 30 grains) had little to no variation between cores and rims. The most calcic
Fig. 11. Anorthite plagioclase content in Cottonwood Wash Tuff ignimbrite and juvenile clasts. HAM-1V has the greatest range of the tuff samples; while the evolved juvenile clast ATL-1-70-1P-3 and the microdacite clast have the greatest range of the juvenile clasts. The less evolved juvenile clasts typically have no analyses less than An\textsubscript{45}. The line shows the average An composition of plagioclase from the Cottonwood Wash Tuff (An\textsubscript{51}); the blue band is one standard deviation from the mean. The gray band represents the typical range of the plagioclase in the Fish Canyon Tuff (Bachmann et al., 2002).
## Table 4. Representative electron microprobe analyses of plagioclase from the Cottonwood Wash Tuff

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Grain Site</th>
<th>wt%</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>BaO</th>
<th>Na₂O</th>
<th>K₂O</th>
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<tr>
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<td>9.15</td>
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<td>5.57</td>
<td>0.63</td>
<td>100.10</td>
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<tr>
<td></td>
<td>r</td>
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<td>26.63</td>
<td>0.30</td>
<td>8.51</td>
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<td>ATL-1-70-1P-3</td>
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<td>11.52</td>
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</table>

Note: Site designations are c (core), m (middle), r (rim) & e (edge). Sites were only designated as cores or rims if it was clear the actual core or rim of a crystal was sampled. If the grain did not appear intact and it was unclear where in the larger crystal it originated, the site was designated as the edge or middle.
compositions are all cores, and reach over An\textsubscript{75} in two samples of tuff. Rare core analyses higher than An\textsubscript{80} may be antecrystic remnants of the magma’s andesitic parent. The most sodic compositions are all rims, and some plagioclase grains have a rim as low as An\textsubscript{41}. Overall, core compositions are more calcic than the rims and average An\textsubscript{54±9} (evolved juvenile clasts An\textsubscript{53±8}, less evolved juvenile clasts An\textsubscript{50±4}, microdacite inclusion An\textsubscript{56±12}, tuff An\textsubscript{56±12}.). Two juvenile clasts (ATL-1-70-1P-3, evolved, and GOUGEWL-1-5Pb-md, microdacite) have a larger range of An compositions than the other juvenile clasts, which are all in the “less evolved” category. The plagioclase in less evolved juvenile clasts typically have no analyses less than An\textsubscript{45}. The tuff sample HAM-1V has the greatest range in An compositions (An\textsubscript{86} – An\textsubscript{42}).

Sixteen grains from four samples were chosen for detailed analysis, using <40 micron steps on core-to-rim traverses similar to those constructed by Bachmann et al. (2002) and Bachmann & Dungan (2002) (Fig. 12). Half of the grains (50%, 8 of 16 grains) are normally zoned with small scale oscillations. Five of the grains (of 16) show only small scale oscillatory zonation with calcium spikes, without a distinct normal or reverse trend. Reversely zoned trends in An are only found in 3 of the 16 grains with detailed analyses (Appendix C). Plagioclase from juvenile clasts and tuff samples have similar zoning patterns: small scale oscillations with calcium spikes, where larger compositional variation occurs, normal zonation is more likely in both tuff and juvenile clasts. Plagioclase from the microdacite inclusion have greater changes in An content, and lack small scale oscillatory zonation. However, the rim An content typically trends to An\textsubscript{50-45}, as with the other types of sample (Fig. 12a).

Narrow calcic spikes of >An\textsubscript{7} to An\textsubscript{20} above the normal oscillations of ~An\textsubscript{5}, are found in most plagioclase grains in all samples with detailed transects except the microdacite. They are similar to those described in Bachmann et al. (2002) and tied by those authors to thermal
Fig. 12. Core-to-rim electron microprobe traverses across representative plagioclase phenocrysts from the Cottonwood Wash Tuff. Lines on the grains show traverse paths. The majority of grains show only small scale oscillatory zonation with calcic spikes, comparable to similar spikes noted in plagioclase the Fish Canyon Tuff (Bachmann et al., 2002). (a) Euhedral plagioclase phenocryst from the microdacite juvenile clast. There is almost no change in An content except for two abrupt calcic spikes. (b) Euhedral, oscillatory zoned plagioclase inclusion in biotite from a less evolved juvenile clast shows little compositional variation.
Fig. 12 (cont.) Core-to-rim electron microprobe traverses across representative plagioclase phenocrysts from the Cottonwood Wash Tuff. (c) Euhedral plagioclase mantle on a corroded core in a phenoclast from an evolved juvenile clast. The mantle is oscillatory with a normal trend in the outermost zones. (d) Euhedral plagioclase grain from a less evolved juvenile clast. Oscillatory zoning with one abrupt calcic spike is recorded adjacent to a minor dissolution surface. An content increases with final step. The spike in this grain is unusually calcic (An$_{65}$).
perturbations. These excursions into high An compositions are generally, but not exclusively, found next to internal dissolution surfaces in the plagioclase in Fig. 12c and 12d. An influx of a hotter, more mafic magma may have allowed brief crystallization of a more calcic plagioclase layer before returning to the dominant sodic plagioclase.

Quartz
Doubly terminated large quartz crystals are one of the distinguishing field characteristics of the Cottonwood Wash Tuff. When examined in thin section, the quartz grains are typically deeply embayed and/or broken. Both euhedrally terminated phenocrysts and grains with resorbed or rounded edges are common. This contrasts with the Fish Canyon Tuff quartz crystals, rarely have euhedral terminations (Bachmann et al., 2002). Melt inclusions are ubiquitous in the quartz grains, although most are devitrified and/or broken. In many crystals, fractures often intersect or radiate out from melt inclusions (Fig 13a, d, & f). Large grains of more than 5 mm (in the juvenile clasts) and 4 mm (in the tuff) are not uncommon, but typically the quartz grains are between 1 – 2 mm. Apatite and zircon are the most common inclusions, although all other major phases except clinopyroxene appear as inclusions in the quartz. As mentioned above, the microdacite inclusion lacks quartz phenocrysts.

Quartz crystallized at higher temperatures (Wark & Watson, 2006) or lower pressures (Thomas et al., 2010) have greater concentrations of titanium and/or aluminum, which causes increased fluorescence in quartz under cathodoluminescence (CL) imaging (Wark & Spear, 2005). If pressure remains constant during crystallization, darker shades indicate cooling temperatures, whereas if the temperature was constant, darker shades would indicate higher pressures.
Fig. 13. Cathodoluminescence images of representative quartz crystals from the Cottonwood Wash Tuff. (a) A broken grain from a less evolved juvenile clast, normally zoned with a dark rim and some oscillations. This grain represents the most common type of quartz in the Cottonwood Wash Tuff. (b) A rounded, subhedral grain from an evolved juvenile clast. The core is complexly zoned with light and dark swirls, embayments, and melt inclusions, and the rim is dark. (c) A quartz crystal from an evolved juvenile clast with a complexly healed core and a slightly brighter rim. (d) A quartz grain from an evolved juvenile clast. The dark rounded (likely xenocrystic) core is reversely zoned and truncated. The brighter mantle is normally zoned. (e) An unzoned, resorbed phenocryst from a surge deposit. (f) A shallowly embayed quartz grain from an evolved juvenile clast. An unzoned mantle surrounds the likely xenocrystic core. (g-h) Quartz grains with multiple crystallization and resorption events recorded by refilled embayments, marked by arrows.
Using cathodoluminescence, zoning in quartz grains in four samples (three juvenile clasts and one tuff) was imaged (Fig. 13). Almost 60% of the grains imaged had rims darker than the zone adjacent to the rim, indicating decreasing titanium (Fig. 13a, b; Wark & Spear, 2005). Twenty percent had brighter rims (Fig. 13c, d), and 20% were unzoned (Fig. 13e, f). Severely broken phenocrysts, where a core or rim could not be determined, were excluded. Ten percent of the phenocrysts analyzed had complex cores of swirled or broken light and dark parts, often healed together with brighter patches of quartz (Fig. 13b, c). Quartz grains from the evolved juvenile clast (ATL-1-70-1P-3) are similar in nature to other quartz grains analyzed.

CL images were used to determine the nature of the last growth or resorption event, using cross-cutting relationships. If an embayment truncated zoning, or if the edges of the grain were rounded, this was considered “resorption”. Growth was determined if sharp crystal edges were present without embayment or truncations. Because of the high degree of broken crystals in the tuff samples, the last growth event was difficult to determine for many grains. At least half of the analyzed quartz grains in the tuff were not categorized because of the phenoclastic nature of the crystals. Of the categorized grains (n=33), almost 80% had resorbed rims (Fig. 13e). Less than 20% lack embayment and have sharp crystal faces indicating growth as the last phase before eruption (Fig. 13a).

Dark rounded cores, several with reverse zoning truncated by the resorption, were found in 11 of the 60 phenocrysts analyzed (Figure 13d, f). Each sample had at least one, and three samples had three grains with dark cores each. These cores were disregarded in the determination of the general thermal history, as we believe they are xenocrystic. The magma would have passed through or resided within several quartz-rich formations of Mesozoic,
Paleozoic, and Precambrian-age (Hintze et al., 1988; Grant et al., 1998; Hintze & Kowallis, 2009) would have provided reasonable sources for these xenocrystic quartz cores.

Zoning in many of the quartz grains has recorded a complex history, many showing multiple crystallization events separated by resorption events. One grain shows a distinct embayment into darker quartz which was then refilled with lighter quartz (Fig. 13g). Another grain (Fig. 13h) formed a dark core, which was then embayed. Recrystallization then occurred with high-Ti quartz, which underwent resorption as well. A euhedral mantle of slightly darker quartz was then recrystallized, and finally resorbed and deeply embayed.

**Amphibole**

Amphibole in the Cottonwood Wash Tuff occurs as euhedral phenocrysts and broken phenocrysts, ranging from 3 mm to <0.75 mm, that are typically poikilitic with all major and accessory phases. Many amphibole grains are glomerophyric with pyroxene, biotite, quartz, plagioclase, oxides, and other amphiboles. Rare amphibole mantles on clinopyroxene grains are present in most samples. In contrast with the Fish Canyon Tuff amphiboles (Fig. 14a), which display oscillatory compositional zoning visible in thin section (Bachmann & Dungan, 2002), amphiboles in the Cottonwood Wash Tuff are typically unzoned (Fig. 14b). Unusually, the amphibole of the microdacite inclusion show an abundance of optically zoned grains, although the composition of the grains is indistinguishable from the other samples (Table 5, Fig. 15).

Analyses of 135 amphibole grains from juvenile clasts (n=64), tuff samples (n=57), and the microdacite inclusion (n=14) overlap nearly perfectly in all major oxides (Fig. 15), indicating that no one rock type preferentially sampled chemically different parts of the magma chamber. More than 70% of the amphiboles analyzed are magnesio-hornblende or magnesio-ferri-hornblende; the remainder are a mix of magnesio-hastingsite, pargasite, and Ti-rich pargasite.
Fig. 14. Comparison of amphibole phenocrysts from the Fish Canyon Tuff and the Cottonwood Wash Tuff. (a) Amphibole from the Fish Canyon Tuff with oscillatory zoning (sample FCT A). At least half of the amphibole from the Fish Canyon Tuff shows similar optical zoning. (b) Amphibole from the Cottonwood Wash Tuff without optical zoning (sample ATL-1-70-1VA). Optical zoning is rarely seen in the amphibole of the Cottonwood Wash Tuff, occurring in less than 1% of the grains.
<table>
<thead>
<tr>
<th>Sample name</th>
<th>Grain Site</th>
<th>Site</th>
<th>Name</th>
<th>wt% SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>FeO(t)</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>F</th>
<th>Cl</th>
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<td>15.75</td>
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<td>1.65</td>
<td>1.33</td>
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<td>0.96</td>
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<td>--</td>
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<tr>
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<td>14.92</td>
<td>0.29</td>
<td>12.93</td>
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<td>1.11</td>
<td>0.80</td>
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<td>1.81</td>
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<td>0.13</td>
<td>97.76</td>
<td>1.81</td>
<td>99.57</td>
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</table>

H₂O* and OH* calculated assuming full occupancy of the hydroxyl site. Site designations are c (core), m (middle), r (rim), and e (edge). Sites were only designated as cores or rims if it was clear the actual core or rim of a crystal was sampled. If the grain did not appear intact and it was unclear where in the larger crystal it originated, it was designated as the edge or the middle.
Fig. 15. Major element variation diagrams for amphiboles in the Cottonwood Wash Tuff. (a-f) There is considerable overlap of the amphiboles in the tuff and those in the juvenile clasts. Amphibole in the evolved juvenile clasts show modest difference in some elements, particularly in lower Al$_2$O$_3$ (a) and CaO (c). Scattered points with low SiO$_2$ and high Al$_2$O$_3$ and TiO$_2$ (a & b), and low FeO(t) (e) are from the cores of a few zoned grains, and are interpreted to be xenocrysts. These are compositionally similar to the “paragsitic cores” of amphiboles in the Fish Canyon Tuff (Bachmann & Dungan, 2002). The amphiboles of the Cottonwood Wash Tuff have higher Al$_2$O$_3$ and FeO(t) and less MgO and Na$_2$O for a given SiO$_2$ content. The Cottonwood Wash Tuff lacks the high SiO$_2$ - low Al$_2$O$_3$, TiO$_2$, FeO(t) amphiboles found in the Fish Canyon Tuff. (In the pdf version, each type of sample is on a separate layer; these layers can be turned on and off.)
depending on small differences in aluminum, iron(III), and titanium (Hawthorne et al., 2012; Locock, 2014). A volumetrically small subset of the magnesio-hastingsites and pargasites (typically those with less than 43% SiO₂) are aluminum- and titanium-rich. These are found in all three types of samples, and almost exclusively in the cores of the amphibole grains with higher (normal) SiO₂ mantles. These low-silica cores are comparable to the “pargasitic” core found in a grain of amphibole in the Pagosa Peak Dacite from the Fish Canyon Tuff (Bachmann & Dungan, 2002). It may have a similar origin as a relict from an earlier pressure and temperature regime or as sparse xenocrysts. The low-silica cores have been excluded from the data used in constraining the pre-eruptive conditions of the magma.

Large variations in major elements are recorded in the Cottonwood Wash Tuff amphiboles: nearly 7 wt% for SiO₂, 5 wt% for Al₂O₃, and 3.5 wt% for FeO_total and MgO (Fig. 15). The variations are comparable to those in the amphiboles of the Fish Canyon Tuff, where SiO₂ varies by 6 wt%, Al₂O₃ by 4 wt%, and FeO_total and MgO by 3 wt% (Bachmann et al., 2002). Fish Canyon amphiboles, like the whole rocks, are more sodic than those in the Cottonwood Wash Tuff; otherwise the amphiboles all lie on the same trends. SiO₂ correlates negatively with Al₂O₃, TiO₂, FeO, MnO (not shown), and Na₂O, and positively with MgO. However, the “low-Al” population (<6 wt% Al₂O₃) in the Fish Canyon Tuff is not present in the Cottonwood Wash Tuff. Only one analysis (WARM-3-25 10e) plots with the “low-Al population” (<6.0 wt% Al₂O₃, 17% of Fish Canyon Tuff amphiboles) of Bachmann & Dungan (2002). More than 70% of the amphiboles from the Cottonwood Wash Tuff fall in the “high-Al population” (>7.75 wt% Al₂O₃) of the Fish Canyon Tuff.

Alumina concentrations in amphiboles from evolved juvenile clasts (ATL-1-70-1P-3 and KNOLL-1-38-1P-1) have a slightly smaller range (6.1 – 11.2 Al₂O₃ wt%) than amphiboles from
less evolved juvenile clasts (6.4 – 12.6 Al₂O₃ wt%) (Fig. 15a). More significantly, the range for the evolved juvenile clasts is shifted to less Al₂O₃ in comparison to amphiboles in the less evolved clasts (Fig. 16a). These amphiboles are slightly less MgO-rich in comparison to the other samples as well (Fig. 15d).

With the exception of the amphibole of the evolved juvenile clasts, and as with the other major phases, nearly the entire range of chemical compositions of amphibole can be seen in individual samples as in the dataset as a whole (Fig. 16b). For example, one less evolved juvenile clast (GOUGEWL-1-5P-1) has amphiboles that span the entire range of amphibole analyses. The amphiboles in the microdacite inclusion are indistinguishable from those in tuff and juvenile clasts (Fig. 15, 16).

Forty-seven detailed (5-50 micron point spacing) microprobe traverses across euhedral and broken amphibole grains in juvenile clasts, tuffs, and the microdacite inclusion show variability in the chemical composition and zoning (Fig. 17, Appendix D). Nearly 40% of the traverses (n=19) record only small scale oscillations (<1% wt%) of Al₂O₃ (Fig. 17b & d). Rimward decreases of Al₂O₃ (normal zonation) occurred in ~30% of the traverses (n=13, Fig. 17a), and a roughly equal number (n=15) record rimward increases of Al₂O₃ (reverse zonation, Fig. 17c). One traverse had indeterminate zonation.

Bachmann et al. (2002) report that the “typical” amphiboles in the Fish Canyon Tuff magma are reversely zoned, with cores formed at cooler temperatures (708 ± 10°C) than the rims (756 ± 15°C). Small-scale oscillatory zonation is common. In contrast, the Cottonwood Wash Tuff amphiboles are predominantly characterized by small-scale oscillatory zonation; where larger scale compositional zonation appears, normal zonation is equally as common as reverse
Fig. 16. (a) Slight compositional differences exist between the amphibole in the evolved juvenile clasts and those from the less evolved juvenile clasts. In the evolved samples, amphibole Al₂O₃ concentrations are shifted to lower values compared to the amphibole from the less evolved samples. (b) The range of Al₂O₃ in the amphibole grains from all samples show that the amphiboles in the microdacite clast are indistinguishable from the tuff and the less evolved juvenile clasts; while the amphibole in the evolved juvenile clasts lack cores with Al₂O₃ greater than ~11 wt%. Amphibole analyses from the Fish Canyon Tuff from Bachmann & Dungan (2002).
Fig. 17. Electron microprobe traverses across representative amphibole phenocrysts from the Cottonwood Wash Tuff and its juvenile clasts. Forty percent of amphibole grains show only small scale oscillatory zonation, such as 17(d). (a) Euhedral amphibole from a less evolved juvenile clast with faint optical zoning. The composition of the core is more $\text{Al}_2\text{O}_3$ rich than the rim, and the traverse shows a sharp drop in $\text{Al}_2\text{O}_3$ across the zoning boundary. (b) Normally zoned subhedral amphibole from an evolved juvenile clast. (c) Broken euhedral amphibole from an evolved juvenile clast with $\text{Al}_2\text{O}_3$ reversely zoned (increasing toward rim). Roughly 30% of the amphibole in the Cottonwood Wash Tuff show reverse zonation. (d) Broken amphibole from an evolved juvenile clast showing oscillatory chemical zonation.
zonation. Amphibole cores from the Cottonwood Wash Tuff formed at higher temperatures (907 ± 20°C, than the rims (838 ± 28°C) (calculated with the Ridolfi et al., 2010) amphibole thermometer (Table 10)). Additionally, whereas the zonation in the Fish Canyon Tuff amphiboles seems to indicate increasing Al$_2$O$_3$ concentrations (and thus higher T) toward the rim, in at least one grain in the Cottonwood Wash Tuff with visible zonation (Fig. 17a), the zoning records an abrupt drop in Al$_2$O$_3$ (from >9.0 wt% to <7.0 wt%).

**Biotite**

Large biotite books (up to 5-8 mm across) are the distinguishing field characteristic of the Cottonwood Wash Tuff. The biotite grains are euhedral to subhedral, and contain inclusions of all major and accessory phases except clinopyroxene. Typically, biotite grains are glomerophyric with inclusions of other biotite, plagioclase, and/or pyroxene grains. Throughout the Cottonwood Wash Tuff, the biotite crystals are commonly altered, most likely by post-depositional alteration. Oxidation, chloritization, and migrations of iron to opaque minerals modifies the rims and the cleavage planes of the biotite. Only grains that appeared unaltered were selected for chemical analysis. No detailed core to rim electron microprobe traverses were conducted on biotite grains; all analyses (131 grains) are either single point or two point (core and rim) analyses (Table 6).

As in the biotite from the Fish Canyon Tuff (Bachmann et al., 2002), grain-to-grain variations in major elements range up to 5 wt% absolute for FeO and MgO (Fig. 18). In the biotite from the Fish Canyon Tuff, few inter-element correlations are seen. In contrast, in the Cottonwood Wash Tuff, the evolved juvenile clast (ATL-1-70-1P-3) has biotites with the highest Fe$_{total}$ (1.21 ± 0.03 apfu) and the lowest Mg (1.44 ± 0.01 apfu), compared with the average of two less evolved samples (1.14 ± 0.03 apfu Fe and 1.28 ± 0.03 apfu Mg). Biotites from the less evolved juvenile clasts and the microdacite inclusion, lack this higher Fe – lower Mg
| Sample name | Grain | wt% SiO₂ | TiO₂ | Al₂O₃ | FeO(t) | MnO | MgO | CaO | Na₂O | K₂O | F | Cl | Sum | H₂O* | Total | Xphlog | Xsid | Xann |
|-------------|-------|----------|------|-------|--------|-----|-----|-----|-------|------|----|----|------|------|-------|--------|-------|------|------|
| ALT-1-70-1P-3 | 6c    | 34.62    | 4.99 | 14.43 | 18.98  | 0.26 | 12.45 | 0.07 | 0.41  | 9.27  | 0.55 | 0.20 | 95.96 | 3.54 | 99.50 | 0.48   | 0.29  | 0.23 |
|             | 10a   | 35.45    | 4.89 | 14.09 | 18.26  | 0.33 | 12.57 | 0.00 | 0.35  | 9.65  | 0.62 | 0.17 | 96.08 | 3.52 | 99.60 | 0.49   | 0.25  | 0.26 |
|            | GOUGEW1-1-S1-1 | 8a       | 35.84 | 5.18 | 13.85 | 18.46 | 0.18 | 12.69 | 0.00 | 0.37  | 9.46  | 0.59 | 0.11 | 96.46 | 3.57 | 100.03 | 0.49   | 0.24  | 0.28 |
|            |       | 10a       | 36.37 | 4.78 | 14.08 | 17.96 | 0.18 | 12.79 | 0.02 | 0.34  | 9.09  | 0.87 | 0.19 | 96.27 | 3.42 | 99.69 | 0.49   | 0.24  | 0.28 |
|            | GOUGEW1-1-S1-1 | 6          | 35.72 | 4.86 | 14.26 | 17.40 | 0.15 | 13.01 | 0.01 | 0.39  | 9.10  | 0.88 | 0.13 | 95.52 | 3.41 | 98.93 | 0.50   | 0.25  | 0.25 |
|            |       | 12c       | 37.08 | 5.39 | 13.96 | 16.51 | 0.16 | 13.11 | 0.03 | 0.40  | 8.94  | 0.74 | 0.11 | 96.09 | 3.52 | 99.61 | 0.50   | 0.21  | 0.29 |

H₂O* calculated assuming full occupancy of the hydroxyl site. Xphlog, Xsid, and Xann calculated after Munoz (1982).
Fig. 18. Fe/(Fe+Mg) vs Al from biotite from the Cottonwood Wash Tuff and its juvenile clasts. The biotites from the evolved juvenile clasts extend to higher Fe/(Fe+Mg) values than the less evolved juvenile clasts. The biotites from the Fish Canyon Tuff (Bachmann et al., 2002) have lower Al and lower Fe/(Fe+Mg) values compared to the Cottonwood Wash Tuff.
composition. Biotites from the less evolved clasts also have lower Al (1.26 ± 0.02, Fig. 18) that is generally lacking in the evolved juvenile clasts (1.28 ± 0.03). Biotites from the tuff, as a result of eruptive mixing, span nearly the entire range of compositions.

**Pyroxene**

Both clinopyroxene and orthopyroxene are found in the Cottonwood Wash Tuff, although the latter is rare. Pyroxene is absent in the Fish Canyon Tuff (Bachmann et al., 2002) but crystallized in the experiments of Johnson and Rutherford (1989a) at high temperatures and low water activities. Clinopyroxene grains (up to 4 mm across, but typically around 1.5 mm or smaller) contain inclusions of all major and accessory phases, except biotite. They are often found in glomerophyric clusters with other pyroxene grains, amphibole, and oxides. Twins are typical. Rounded cores of clinopyroxene, surrounded by euhedral amphibole, are common (Fig. 19a). Clinopyroxenes are commonly altered, both by post-depositional processes (oxides and iron staining in cracks), and magmatic processes (altered to hornblende, with only parts of the core remaining pyroxene). Euhedral, unaltered, and typically non-glomerphyric grains are not uncommon (Fig. 19b), however, and were selected for chemical analysis. Clinopyroxene grains from one tuff sample and two less evolved juvenile clasts (10 grains, 26 analyses) were analyzed using one to three points per grain (Table 7). Clinopyroxene from the microdacite inclusion were not analyzed. There is little compositional diversity and the majority of the clinopyroxene grains analyzed are diopside (average En₃₇Wo₄₆Fs₁₇) (Fig. 20).

The rare orthopyroxene grains are found both as cores in amphibole and corroded single grains. Only one orthopyroxene was analyzed, an enstatite with an average composition of En₅₇.
Fig. 19. Clinopyroxene from the Cottonwood Wash Tuff. (a) An unaltered, euhedral clinopyroxene (tuff sample MWASH-1-24). Note the lack of a reaction rim on crystal. b) A clinopyroxene (tuff sample SHNG-4-21) in reaction relationship with amphibole and oxides. Both types are typical in the Cottonwood Wash Tuff.
Table 7. Representative electron microprobe analyses of clinopyroxene and orthopyroxene from the Cottonwood Wash Tuff.

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<tr>
<th>Sample name</th>
<th>Grain</th>
<th>SiO$_2$</th>
<th>TiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>FeO(t)</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na$_2$O</th>
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<th>Wo</th>
<th>En</th>
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<td>0.68</td>
<td>13.07</td>
<td>21.66</td>
<td>0.26</td>
<td>99.72</td>
<td>0.45</td>
<td>0.38</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>2a</td>
<td>52.32</td>
<td>0.25</td>
<td>0.92</td>
<td>9.70</td>
<td>0.60</td>
<td>13.06</td>
<td>21.81</td>
<td>0.31</td>
<td>98.95</td>
<td>0.45</td>
<td>0.38</td>
<td>0.17</td>
</tr>
<tr>
<td>GOUGEWL-1-SP-1</td>
<td>6c</td>
<td>52.11</td>
<td>0.10</td>
<td>0.41</td>
<td>24.86</td>
<td>1.36</td>
<td>20.09</td>
<td>0.89</td>
<td>0.01</td>
<td>99.80</td>
<td>0.02</td>
<td>0.57</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>6a</td>
<td>52.60</td>
<td>0.15</td>
<td>0.41</td>
<td>24.56</td>
<td>1.44</td>
<td>19.87</td>
<td>0.90</td>
<td>0.00</td>
<td>99.92</td>
<td>0.02</td>
<td>0.57</td>
<td>0.41</td>
</tr>
</tbody>
</table>
Fig. 20. Ternary diagram of pyroxene from the Cottonwood Wash Tuff and its juvenile clasts. Experimental Fish Canyon Tuff clinopyroxene data from Carrachi & Blundy (2015). Clinopyroxene was not analyzed in evolved juvenile clasts.
Fe-Ti oxides

Euhehedral to anhedral grains of magnetite and ilmenite in the Cottonwood Wash Tuff are typically glomerophyric with amphibole, biotite, pyroxene, and other Fe-Ti oxides. The oxide phenocrysts are commonly poikilitic, with pyroxene, feldspar, amphiboles, glass, zircon, and apatite inclusions. Exsolution lamellae are present in many of the oxide phenocrysts (especially magnetite), making them unsuitable for chemical analysis.

Magnetite crystals from six samples (3 tuff, 2 juvenile clasts, and the microdacite inclusion; n = 67 analyses) were analyzed, as were ilmenite grains from five sample (3 tuff, 2 less evolved juvenile clasts; n = 60 analyses). (Ilmenite phenocrysts in the microdacite inclusion are rare and yielded low totals.) Each grain was analyzed in up to three spots, and no traverses were conducted (Table 8). The methods of Stormer (1983) were used to calculate oxide formulas. Magnetite and ilmenite were rarely found in contact with one another, and the method of Bacon and Hirschmann (1988) was used to check for equilibrium between the two phases. Only phenocrysts in equilibrium by this criterion were used in calculating intensive parameters.

Although there is some variation in the chemical composition of both magnetite and ilmenite, the majority of the samples have similar ranges (Table 8). X’usp in magnetite ranges from 0.13 – 0.21, and X’ilm in ilmenites ranges from 0.647 – 0.834. However, the magnetite and ilmenite of one tuff sample (HAM-1V) have a distinctly different chemical range (X’usp 0.07 – 0.18) from the other five samples. As the other phenocryst phases in HAM-1V do not significantly differ from the other samples, it is unlikely that the difference in magnetite and ilmenite compositions is magmatic in nature. More likely, the Fe-Ti oxides in this sample have undergone post-eruption alteration. Intensive parameters using the oxides were calculated for
Table 8. Representative electron microprobe analyses of oxides from the Cottonwood Wash Tuff.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Grain wt%</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>Re Total*</th>
<th>Probe total</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOUSEWL-1-SP-1</td>
<td>9.1</td>
<td>0.06</td>
<td>6.41</td>
<td>1.60</td>
<td>0.30</td>
<td>53.46</td>
</tr>
<tr>
<td>GOUSEWL-1-SPb</td>
<td>13.1</td>
<td>0.06</td>
<td>5.93</td>
<td>1.43</td>
<td>0.30</td>
<td>56.06</td>
</tr>
<tr>
<td>GOUSEWL-1-SPb md</td>
<td>14a</td>
<td>0.09</td>
<td>4.58</td>
<td>1.26</td>
<td>0.33</td>
<td>57.72</td>
</tr>
<tr>
<td>GOUSEWL-1-SPb md</td>
<td>2a</td>
<td>0.01</td>
<td>6.71</td>
<td>1.73</td>
<td>0.39</td>
<td>53.14</td>
</tr>
<tr>
<td>GOUSEWL-1-SPb md</td>
<td>3a</td>
<td>0.18</td>
<td>4.92</td>
<td>1.26</td>
<td>0.39</td>
<td>57.18</td>
</tr>
<tr>
<td>GOUSEWL-1-SPb md</td>
<td>9a</td>
<td>0.07</td>
<td>6.54</td>
<td>1.68</td>
<td>0.26</td>
<td>53.53</td>
</tr>
<tr>
<td>GOUSEWL-1-SPb md</td>
<td>10c</td>
<td>0.06</td>
<td>36.08</td>
<td>0.13</td>
<td>1.03</td>
<td>29.49</td>
</tr>
</tbody>
</table>

Oxides recalculated after the methods of Stormer (1983).
HAM-1V, but these results were not used in calculating the preferred temperature or oxygen fugacity.

**Glass**

Four main types of matrix are found in the Cottonwood Wash Tuff: 1) vesicular glass found in the pumice clasts, 2) branching and/or arcuate bubble-wall shards, 3) vitrophyric glass, and 4) devitrified glass, often altered to a fine mixture of microlites, clays, and calcite in the dense cognate inclusions and tuff samples. The quality of glass in the different stratigraphic sections varied according to the amount of welding and alteration. The freshest glasses from three tuff samples and one juvenile clast were analyzed (Table 9). Owing to the altered and devitrified nature of the glass in the microdacite inclusion, glass analysis was not undertaken on this sample. The analyses from the different samples span the same range of compositions (Table 9), as well as the same range as the Fish Canyon Tuff glass analyses of Bachmann et al. (2002). Glasses are high-SiO₂ rhyolite (76.5 – 78 wt% SiO₂ on a volatile free basis) (Fig. 5a), high K₂O (5.3 – 6.4) (Fig. 5b), and calc-alkalic with some analyses alkali-calcic (according to the classification of Frost et al., 2001). Unlike the bulk tuff, the glass analyses are ferroan and weakly peraluminous. The peraluminous nature of the glass likely reflects the mobility of alkalies due to hydration, as the sums of the oxides of the analyses are low (~95%).

**Accessory phases**

Accessory apatite and zircon are found as generally euhedral inclusions in all major phenocrysts, as well as in the matrix. Sulfides are rare, and when present are always found as inclusions in other phenocrysts. Titanite is not present; this helps distinguish the Cottonwood Wash Tuff from the younger, mineralogically similar Lund Tuff from the same caldera complex (Maughan et al., 2002).
Table 9. Representative electron microprobe analyses of glass from the Cottonwood Wash Tuff ignimbrite and juvenile clasts.

<table>
<thead>
<tr>
<th></th>
<th>tuff (vitrophyre glass)</th>
<th>tuff (bubble wall shards)</th>
<th>evolved juvenile clast</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HAM-1V</td>
<td>KNOLL-1-9</td>
<td>WARM-3-25</td>
</tr>
<tr>
<td></td>
<td>1b 19</td>
<td>2b 11a 3a 10b</td>
<td>3 11</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>77.48</td>
<td>76.68</td>
<td>77.29 77.79 77.67</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.12</td>
<td>0.13 0.11 0.11 0.12</td>
<td>0.08 0.13</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>12.49</td>
<td>13.00 12.64 12.49 12.61</td>
<td>12.71 12.57</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>0.52</td>
<td>0.57 0.58 0.54 0.39</td>
<td>0.85 0.68</td>
</tr>
<tr>
<td>MnO</td>
<td>0.00</td>
<td>0.00 0.00 0.00 0.00</td>
<td>0.00 0.00</td>
</tr>
<tr>
<td>MgO</td>
<td>0.06</td>
<td>0.04 0.03 0.07 0.03</td>
<td>0.07 0.08</td>
</tr>
<tr>
<td>CaO</td>
<td>0.57</td>
<td>0.83 0.88 0.83 0.84</td>
<td>0.70 0.68</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>6.20</td>
<td>2.86 2.33 2.60 2.51</td>
<td>2.60 2.72</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>6.32</td>
<td>6.33 6.20 5.51 5.87</td>
<td>5.81 5.92</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.00</td>
<td>0.00 0.00 0.00 0.00</td>
<td>0.00 0.00</td>
</tr>
</tbody>
</table>

Analytical Total 96.87 97.21 95.62 95.71 96.60 96.30 96.04 96.46

Oxide values (in weight %) have been recalculated to 100% on a volative-free basis.
Suffix (V) indicates a vitrophyre.
INTENSIVE PARAMETERS

To constrain the pre-eruptive conditions of the Cottonwood Wash Tuff magma chamber, several geothermobarometers were used to calculate temperature, pressure, $f_{O2}$, and $f_{H2O}$ (Table 10). Determining equilibrium between phases in an explosive system can be difficult, as eruptive mixing may place grains not in equilibrium in contact with one another. Individual phase parameters used in choosing grains for compositional analysis are explained in the discussion of phenocryst texture and chemistry above. In the case of zoned phenocrysts such as plagioclase and amphibole, only rims were used for calculation of intensive parameters.

The phase diagrams of Johnson & Rutherford (1989a), created using experiments with the Fish Canyon Tuff, and other experiments by Caricchi & Blundy (2015), are used to estimate a reasonable range of temperature, pressure, and volatile fugacity for the compositionally similar Cottonwood Wash Tuff (Fig. 21). The geothermobarometers tested were evaluated based on agreement with these phase diagrams and in comparison with one another. Based on these criteria, some of the geothermobarometers produce reasonable values for temperature, pressure, and volatile fugacities. Others produce values that are unrealistic for the mineral assemblage. Regardless of the geothermobarometer used, the results for juvenile clasts, tuff samples, and the microdacite inclusions are indistinguishable from one another (Table 10, Fig. 22).

Plagioclase-Glass

Putirka (2008)

Putirka’s (2008) uses plagioclase rim and glass compositions to determine temperature, pressure, and estimate water content in the melt. For the Cottonwood Wash Tuff, multiple rim analyses from a sample were paired with that sample’s average glass composition. The temperatures produced by the thermobarometer (equation 24a) were reasonable (average 794 ± 29°C, range
Table 10. Intensive parameters calculated for the Cottonwood Wash Tuff

<table>
<thead>
<tr>
<th>Phases</th>
<th>Temperature (°C)</th>
<th>Pressure (kb)</th>
<th>fO2</th>
<th>H2O (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Evolved juvenile clasts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plagioclase + melt</td>
<td>794 ± 19</td>
<td>2.5 ± 0.3</td>
<td>-12.3 ± 0.2</td>
<td>4.5 ± 0.04</td>
</tr>
<tr>
<td>Hornblende (with or without quartz)</td>
<td>797 ± 21</td>
<td>2.5 ± 0.3</td>
<td>-12.4 ± 0.3</td>
<td>4.8 ± 0.2</td>
</tr>
<tr>
<td>Hornblende (requiring quartz)</td>
<td>821 ± 11</td>
<td>2.5 ± 0.3</td>
<td>-12.4 ± 0.3</td>
<td>4.8 ± 0.2</td>
</tr>
<tr>
<td>Fe-Ti Oxides</td>
<td>789 ± 85</td>
<td>2.2 ± 0.3</td>
<td>-12.4 ± 0.3</td>
<td>4.8 ± 0.2</td>
</tr>
<tr>
<td>Fe-Ti Oxides</td>
<td>775 ± 13</td>
<td>2.2 ± 0.3</td>
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</tr>
<tr>
<td>Fe-Ti Oxides</td>
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</tr>
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<td>4.8 ± 0.2</td>
</tr>
<tr>
<td>Fe-Ti Oxides</td>
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<td>2.2 ± 0.3</td>
<td>-12.4 ± 0.3</td>
<td>4.8 ± 0.2</td>
</tr>
</tbody>
</table>

1 - Putirka, 2005  5 - Sauerzapf et al., 2008  9 - Anderson & Smith, 1995
3 - Ridolfi & Renzulli, 2012  7 - Luhr et al., 1984
4 - Andersen et al., 1993 (QUILF)  8 - Johnson & Rutherford, 1989b
### Table 10 (continued). Intensive parameters calculated for the Cottonwood Wash Tuff

<table>
<thead>
<tr>
<th>Phases</th>
<th>GOUGE-2V</th>
<th>GOUGEWL-1-1</th>
<th>HAM-1V</th>
<th>KNOLL-1-9</th>
<th>SHNG-4-34</th>
<th>WARM-3-25</th>
<th>WARM-3-40T</th>
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</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>Plagioclase + melt</td>
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<td>9</td>
<td>798 ± 3</td>
<td>7</td>
<td>796 ± 5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Hornblende (with or without quartz)</td>
<td>979 ± 18</td>
<td>10</td>
<td>820 ± 14</td>
<td>8</td>
<td>815 ± 16</td>
<td>10</td>
<td>799 ± 18</td>
</tr>
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<td>Hornblende (requiring quartz)</td>
<td>979 ± 22</td>
<td>10</td>
<td>825 ± 23</td>
<td>8</td>
<td>814 ± 32</td>
<td>10</td>
<td>785 ± 28</td>
</tr>
<tr>
<td>Hornblende</td>
<td>814 ± 13</td>
<td>10</td>
<td>834 ± 13</td>
<td>12</td>
<td>861 ± 26</td>
<td>10</td>
<td>838 ± 19</td>
</tr>
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<td>Fe-Ti Oxides</td>
<td>733 ± 52</td>
<td>61 pairs</td>
<td>788 ± 70</td>
<td>108 pairs</td>
<td>806 ± 92</td>
<td>17 pairs</td>
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</tr>
<tr>
<td>Fe-Ti Oxides</td>
<td>693 ± 27</td>
<td>61 pairs</td>
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<td>108 pairs</td>
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<tr>
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<td>61 pairs</td>
<td>773</td>
<td>108 pairs</td>
<td>797</td>
<td>17 pairs</td>
<td></td>
</tr>
<tr>
<td>Hornblende 3</td>
<td>778 ± 13</td>
<td>10</td>
<td>780 ± 4</td>
<td>7</td>
<td>776 ± 19</td>
<td>9</td>
<td>790 ± 23</td>
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<tr>
<td>Hornblende</td>
<td>780 ± 14</td>
<td>797 ± 15</td>
<td>788 ± 11</td>
<td>799 ± 16</td>
<td>813 ± 17</td>
<td>801 ± 16</td>
<td>792 ± 10</td>
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<tr>
<td>Biotite</td>
<td>729 ± 0.5</td>
<td>9</td>
<td>4.3 ± 0.5</td>
<td>7</td>
<td>4.3 ± 0.6</td>
<td>6</td>
<td></td>
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<tr>
<td>Pressure (kb)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Hornblende</td>
<td>1.2</td>
<td>1</td>
<td>2.4 ± 0.3</td>
<td>11</td>
<td>1.9 ± 0.3</td>
<td>7</td>
<td>2.5 ± 0.3</td>
</tr>
<tr>
<td>Hornblende</td>
<td>0.3</td>
<td>1</td>
<td>1.5 ± 0.3</td>
<td>11</td>
<td>1.0 ± 0.3</td>
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</tr>
<tr>
<td>Hornblende</td>
<td>0.9</td>
<td>1</td>
<td>1.4 ± 0.2</td>
<td>11</td>
<td>1.2 ± 0.1</td>
<td>7</td>
<td>1.4 ± 0.2</td>
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<tr>
<td>Plagioclase + melt</td>
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<td>9</td>
<td>4.3 ± 0.5</td>
<td>7</td>
<td>4.3 ± 0.6</td>
<td>6</td>
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<tr>
<td>$f_O_2$</td>
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<tr>
<td>Hornblende</td>
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<td>-12.2 ± 0.2</td>
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<td>-12.6 ± 0.2</td>
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<td>-12.2 ± 0.2</td>
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<tr>
<td>Fe-Ti Oxides</td>
<td>-13.5 ± 0.6</td>
<td>61 pairs</td>
<td>-12.6 ± 0.8</td>
<td>108 pairs</td>
<td>-12.1 ± 0.4</td>
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<td>-12.2 ± 0.2</td>
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<tr>
<td>Fe-Ti Oxides</td>
<td>-14.2 ± 0.5</td>
<td>61 pairs</td>
<td>-13.1 ± 0.3</td>
<td>108 pairs</td>
<td>-12.0 ± 0.7</td>
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<td>H$_2$O (wt %)</td>
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<tr>
<td>Plagioclase + liquid hygrometer</td>
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<td>1</td>
<td>4.9 ± 0.2</td>
<td>11</td>
<td>4.7 ± 0.2</td>
<td>7</td>
<td>4.3 ± 0.2</td>
</tr>
</tbody>
</table>

1 - Putirka, 2005  
2 - Holland & Blundy, 1994  
3 - Ridolfi & Renzulli, 2012  
4 - Andersen et al., 1993 (QUILF)  
5 - Sauerzapf et al., 2008  
6 - Ghiorso & Evans, 2008  
7 - Luhr et al., 1984  
8 - Johnson & Rutherford, 1989b  
9 - Anderson & Smith, 1995  
10 - Waters & Lange (in press 2015)
Fig. 21. Preferred temperatures and pressures for the Cottonwood Wash Tuff magma plotted on the $X_{\text{H}_2\text{O}} = 0.5$ and $X_{\text{H}_2\text{O}} = 1$ phase diagrams of Johnson & Rutherford (1989a) which are based on experiments using the Fish Canyon Tuff. To the extent that the two tuffs are compositionally similar, these phase diagrams suggest the Cottonwood Wash Tuff magma was not water saturated, as quartz would not have been stable under water saturated conditions.
Fig. 22. Comparison of selected geothermometers for the Cottonwood Wash Tuff. The line shows the preferred temperature of the magma body and the light blue band is one standard deviation from the average. The preferred temperature of individual samples is the average of plagioclase - melt, plagioclase - hornblende, and Fe - Ti oxides (QUILF, Sauerzapf et al. (2008), and Ghiorso & Evans (2008)) thermometers. See text for exceptions and details.
769 – 861°C). The temperatures calculated for tuff sample HAM-1V are anomalously high (848°C, due to the large range in plagioclase An content) when compared to the other samples as well as its position on the phase diagrams of Johnson & Rutherford (1989a), and have not been used in calculating a preferred temperature for this sample. While the average pressures calculated by this process are also reasonable (2.3 ± 1.6 kb), they are widely variable (1.6 – 5.2 kb) (Table 10). This barometer seems to be highly sensitive to small variations in Al₂O₃ and Na₂O in the plagioclase, which may account for the wide range of pressures.

Using Putirka’s (2008) Equation 25b, calculated H₂O concentrations in the equilibrium melt average 4.0 ± 0.4 wt% (3.0 – 4.4 wt%). If Putirka’s (2008) Model H is used, the concentration of water is significantly higher (an average of 9.6 wt%, with a range of 6.3 – 10.9 wt%). This concentration is anomalous based on a comparison to the phase diagrams of Johnson & Rutherford (1989a; their Fig. 6). Rim An content of plagioclase is used to estimate the activity of water; at An₅₀ and ~2.5 kb, the activity of water in the Cottonwood Wash melt should be between 0.75 – 1.00. As water saturation in rhyolites occurs at concentrations of ~7 wt% (Carroll & Holloway, 1994; Newman and Lowenstern, 2002; Waters & Lange, 2015), the value calculated using Equation 25b (4.0 wt%) is more reasonable.

Waters & Lange (2015)

Another hygrometer, developed by Waters & Lange (2015), also uses plagioclase rim analyses and glass compositions to calculate water concentration in the melt. This method is not strongly pressure sensitive, as varying the pressures (between 0 – 4 kb) modifies the results by a few tenths of a percentage. This method produces an average of 4.4 wt% H₂O (4.1 – 5.0 wt%), and agrees more closely with Putirka’s (2008) Equation 25b than with the much higher water concentrations of Model H (Table 10).
Amphibole

Holland & Blundy (1994) Thermometers

Plagioclase and amphibole rim compositions are used in Holland & Blundy’s (1994) thermometers. Of the two thermometers, one requires quartz, and the other can be used with or without quartz. Multiple amphibole rim analyses from a sample were used with that sample’s average plagioclase rim value. In the Cottonwood Wash Tuff, both calculations produce very similar, reasonable average values: 800 ± 25°C and 803 ± 20°C, respectively (Table 10). When the low-SiO₂ amphibole cores are used with the rims of plagioclase, the temperatures are higher by 40 – 60°C.

Johnson & Rutherford (1989a) Al-in-Hornblende Barometer

A specific phase assemblage of quartz, sanidine, plagioclase, hornblende, biotite, magnetite, ilmenite, and titanite is required to use Johnson & Rutherford’s (1989a) Al-in-hornblende barometer. While the Cottonwood Wash Tuff does not contain sanidine or titanite, the concentration of K₂O in the glass is 5.9 ± 0.8 wt%, indicating that the magma was nearly sanidine saturated, and the presence of titanite may not be critical (Johnson & Rutherford, 1989b). Using amphibole rims, the pressures calculated with this method range from 1.2 – 2.9 kb, with an average of 2.3 ± 0.4 kb (Table 10). When the low-SiO₂ cores are used, the pressures average 4.7 ± 0.5 kb, with a range of 3.4 – 5.6 kb.

Anderson & Smith (1995) Barometer

The Anderson & Smith (1995) hornblende barometer applies a temperature correction to the Al-based geobarometer but produces pressures lower by almost one kilobar, ranging from an anomalously low 0.3 to 1.9 kb, with an average of 1.4 ± 0.4 kb. Despite this, the order of
pressures from highest to lowest is the same for the Anderson & Smith barometer as for the Johnson & Rutherford barometer (1989a) (Table 10).

Ridolfi et al. (2010) Thermobarometer

Amphibole rim compositions alone are used in Ridolfi et al. (2010) thermobarometer, which is also used to calculate oxygen and water fugacity. The temperature results for the Cottonwood Wash Tuff (average 832 ± 18°C; 769 – 884°C) from this method are higher than expected for the mineral assemblage at both the preferred pressure (~2.5 kb) and the low pressures calculated by the same method (average 1.5 ± 0.3 kb; 0.8 – 2.6 kb) (Table 10). Once again, the low-SiO₂ cores give a significantly higher temperature (907 ± 22°C) and pressure (2.7 ± 0.5 kb) than the rims. Oxygen fugacity calculated using this method gives a median result of ΔQFM 2.1 ± 0.2 (range 1.6 – 2.4); this high value is common for monotonous intermediates (Bachmann et al., 2002; Maughan et al., 2002; Woolf, 2008). Water concentration in the magma is calculated to be 4.8± 0.2 wt% H₂O, which agrees reasonably with the predictions of Putirka’s (2008) Model H hygrometer discussed above (5.6%).

A series of equations in Ridolfi & Renzuli (2012) allow for the calculation of a melt composition in equilibrium with the amphiboles. When the amphibole rims are used, the melt composition results are comparable to the electron microprobe analyses of Cottonwood Wash Tuff glass (77 ± 1.5 and 77 ± 0.3 SiO₂ wt%, respectively). When the low-SiO₂ cores are used, the melt composition is more mafic (69 ± 2 SiO₂ wt%), possibly indicating these cores are relicts from an andesitic magmatic parent.

Biotite

Three geothermometers using biotite compositions were used to estimate the temperature of the Cottonwood Wash Tuff magma system. Righter & Carmichael’s (1996) experimental calibration
uses the concentration of Ti in both the melt and biotite phenocrysts, and yielded anomalously high temperatures (average 840 ± 6°C; 833 – 853°C). Henry et al.’s (2005) biotite thermometer, empirically calibrated using metapelites at comparatively high pressures, gives anomalously low temperatures, with an average of 760 ± 4°C (747 – 768°C) (Table 10). This is in contrast with the findings of Woolf (2008) in the similar Wah Wah Springs Tuff, where the temperatures calculated using Henry et al.’s thermometer were considered reasonable. Luhr et al. (1984) formulated another empirical geothermometer based on the coupled exchange of Ti and Fe²⁺ in biotite from volcanic rocks whose temperatures were estimated from Fe-Ti oxides. Results from this model are more variable than for the other biotite geothermometers, but yield temperatures (average 787 ± 14°C, 757 – 817°C) only slightly lower than the other, non-biotite thermometers (Fig. 22).

**Fe-Ti oxides**

Three geothermobarometers were used to calculate temperature and oxygen fugacity using magnetite and ilmenite pairs from four samples: one evolved juvenile clast, one less-evolved juvenile clast, and two tuff samples. Each magnetite – ilmenite pair used in calculating intensive parameters has Mg/Mn ratios consistent with equilibrium (Bacon & Hirschmann, 1988). As was discussed earlier, the oxides analyzed from the HAM-1V sample have undergone post-magmatic alteration, and were not used to calculate intensive parameters.

**QUILF**

The computer program QUILF (Andersen et al., 1993) calculates temperature and oxygen fugacity using Fe-Ti oxides. Temperatures calculated by this method are reasonable (median 790 ± 13°C, 775 – 806°C), but slightly lower than those calculated from plagioclase and amphibole. The exception to the lower temperature is from the WARM-3-25 tuff sample (806°C). Oxygen
fugacity calculated by QUILF has a median value of $2.1 \pm 0.2 \ \Delta\text{QFM} \ (1.9 – 2.3 \ \Delta\text{QFM})$, which agrees with the Ridolfi et al. (2010) results (Table 10; Fig. 23).

*Sauerzapf et al.* (2008)

Using the oxide calibration of Sauerzapf et al. (2008), temperatures were calculated for an average result of $779 \pm 21^\circ\text{C} \ (760 – 806^\circ\text{C})$, comparable to but lower than those calculated using QUILF. Once again, WARM-3-25 has a higher temperature ($807^\circ\text{C}$). Oxygen fugacity calculated using this method yields a comparable $\Delta\text{QFM}$ of $2.0 \pm 0.4$ (Table 10).

*Ghiorso & Evans* (2008)

Temperatures and oxygen fugacities were also calculated for Fe-Ti oxides using the method of Ghiorso & Evans (2008), resulting in an average temperature of $776 \pm 14^\circ\text{C} \ (767 – 797^\circ\text{C})$. The temperatures calculated this way are the lowest of all the oxides, but still in the same range as the other two methods. Again, the WARM-3-25 tuff sample gave the highest temperature ($797^\circ\text{C}$). Oxygen fugacities were calculated to be $\Delta\text{QFM} 1.7\pm 0.1$, slightly lower than the other methods (Table 10).

**Preferred intensive parameters**

Our preferred temperature of the Cottonwood Wash Tuff is $798 \pm 14^\circ\text{C}$. This is the average of all the calculated temperatures from all thermometers using plagioclase, plagioclase and amphibole, Fe-Ti oxides (excluding those for plagioclase-melt and oxides in HAM-1V), and biotite (Luhr et al. (1984) only). The microdacite has a temperature nearly indistinguishable from the average ($807 \pm 11^\circ\text{C}$). The two evolved juvenile clasts with calculated temperatures have the highest ($823^\circ\text{C}$) and one of the lowest temperatures ($784^\circ\text{C}$), while the less evolved juvenile clasts have a slightly smaller temperature range ($788 – 814^\circ\text{C}$). The temperatures of the tuffs ($780 – 813^\circ\text{C}$),
Fig. 23. Temperatures calculated using compositions of Fe-Ti oxides from the Cottonwood Wash Tuff. Tie lines link each estimate from the same sample. The average $f_{O_2}$ at the preferred temperature (~800°C, Fig. 22) is $10^{-12.7 ± 0.7}$ b (ΔQFM 2.1 ± 0.3).
scattered between the juvenile clast extremes, likely have a mixed temperature signature, as the phenocrysts were sampled from multiple parts of the magma chamber.

Our preferred pressure, 2.3 ± 0.4 kb, is calculated using the average sample pressures calculated from Johnson & Rutherford’s (1989b) Al-in-hornblende barometer. The average oxygen fugacity at this temperature was -12.7 ± 0.7 kb (ΔQFM 2.1± 0.3). Such highly oxidized magmas are common in continental subduction zones. The estimated water concentration of the magma, 4.7 ± 0.3 wt%, is the average of the water concentration calculated by Waters & Lange (2015), Ridolfi et al. (2010) and Putirka’s (2008) Eqn 25b. To the extent that the Fish Canyon magma was compositionally similar, the experimental phase diagrams of Johnson and Rutherford (1989a) suggest that the Cottonwood Wash magma was not water saturated (Fig. 21). For example, at the temperatures and pressures calculated for the magma, quartz would not have been stable in all samples, as observed. In addition, the solubility of water in rhyolite at 2.5 kb and 800°C is about 7 wt% (Newman and Lowenstern, 2002); plagioclase hygrometry suggests that the melt only contained 4.7 wt% H₂O.

PETROLOGIC IMPLICATIONS

Absence of significant co-ignimbrite glass winnowing

Tuff samples from highly explosive eruptions are not usually considered indicative of either the composition or crystallinity of the pre-eruptive magma body. The removal of small particles, usually silicic glass, from eruptive columns or from pyroclastic flows, leaves the resulting tuff layers enriched in crystals and therefore more mafic than the actual magma body. This glass winnowing is obvious in many modern, small volume eruptions (e.g. Sigurdsson & Carey, 1989; Rose et al., 2008; Scarpati et al., 2014); and has been detected in super-eruptive events such as the Fish Canyon Tuff (Bachmann et al., 2002). Juvenile fragments, unaffected by co-ignimbrite
glass elutriation and eruptive mixing, are traditionally preferred in order to constrain the phenocryst content of the pre-eruptive magma.

In the Cottonwood Wash Tuff, crystal enrichment by removal of glass is difficult to detect in the tuff, although co-ignimbrite plumes are believed to have carried ash and mineral grains up to 1000 km away (Blaylock, 1996; Kowallis et al., 2005). As measured by the point-counting of thin sections, the crystallinity of juvenile clasts is statistically indistinguishable from the crystallinity of the tuff samples. The most mafic tuff samples (0.74 – 0.79 wt% TiO₂ and ~6.5 wt% Fe₂O₃) are only slightly more mafic than several of the less evolved juvenile clasts (~0.77 wt% TiO₂ and 5.7 – 6.2 wt% Fe₂O₃). Several mafic tuff samples, as determined by whole rock major element analyses (Fig. 5a & Fig. 7) may be the result of glass winnowing. Varying the percentage of phenocrysts relative to glass by as little as 10% results in a change >0.25 wt% TiO₂ and ~3 wt% SiO₂, which is larger than the difference between the most mafic tuff (0.79 wt% TiO₂ and 61.82 wt% SiO₂) and the most mafic juvenile clast (0.77 wt% TiO₂ and 63.39 wt% SiO₂.) If 31 – 310 km³ of (mostly rhyolitic ash) material were removed by the co-ignimbrite ash plume, a small mafic shift in the remaining tuff would be expected. However, and importantly, the chemical variability of the tuff is nearly matched by the compositions of the juvenile clasts (Fig. 7 and 8). The composition of juvenile clasts shows that the pre-eruptive magma was chemically variable, and that most of the variation seen in the Cottonwood Wash Tuff samples is original to the magma.

Several hypotheses can be suggested to explain the lack of glass elutriation and crystal enrichment in the Cottonwood Wash Tuff. First, although the fines are usually considered to be primarily glass fragments, mineral grains may also be included. The smallest mineral fragments in the matrix of the Cottonwood Wash Tuff samples are as small as <0.01 mm, and many of the
glass bubble-wall shards can reach 0.5 mm in length. This difference in size may have allowed some mineral fragments to be removed as easily as much of the glass. In opposition to this theory is the crystallinity of the distal ash-fall layers. Blaylock (1996) states that the ash layers in Wyoming and Nebraska correlated to the Cottonwood Wash Tuff have a chemical composition of around 73 wt% SiO₂. It seems likely that glass fragments, rather than mineral fragments, were preferentially lofted away in the co-ignimbrite plume.

A second hypothesis is based on the role of air entrainment in reducing the density of the pyroclastic flow. In a voluminous, dense, large-vent eruption, air entrainment may not be as important as for thin, dilute, high-altitude eruption plumes. Rapid eruption of ground-hugging, concentrated pyroclastic flows (Wilson & Houghton, 2000) may not allow for large volumes of air to become trapped and then heated in the ignimbrite flow. This would lessen the chance for parts of the flow to become buoyant enough to carry away significant volumes of fines (primarily glassy ash). We believe this hypothesis is most applicable to the Cottonwood Wash Tuff and other monotonous intermediate tuffs. Although enough air was entrained at some point in the eruption to allow a co-ignimbrite plume to form, the volume carried away to be deposited hundreds of kilometers away is nearly imperceptible against the super-eruptive volume left behind to form the outflow sheet. Therefore, the range of compositions in the tuff is primarily a magmatic feature rather than an eruptive one.

Evolved juvenile clasts

As previously noted, the juvenile clasts in the Cottonwood Wash Tuff are divided into two separate groups based on whole-rock TiO₂ concentrations: an evolved group with <0.60 wt% TiO₂, and a less-evolved group with >0.66 wt% TiO₂ (Fig. 7a). The phenocrysts of the evolved juvenile clasts sampled (n=2) have a slight shift toward more evolved chemistry. The plagioclase
grains are slightly more sodic, the amphibole grains have less TiO$_2$ and Al$_2$O$_3$ and slightly more FeO(t), and Fe+Mg/Mg ratio is higher in the biotite grains from the evolved juvenile clasts. However, the evolved juvenile clasts’ phenocrystal chemical differences are too small to account for the compositional range of all the juvenile clasts. If the evolved clasts sampled a part of the magma chamber with slightly fewer phenocrysts, this could account for the lower TiO$_2$ and higher SiO$_2$, and other elemental differences. High-shear flow in the magma chamber may have created differential concentration of the phenocrysts, accounting for the most of the variation in both modal count and compositions (Cimarelli et al., 2011).

**Warming or cooling before eruption?**

Bachmann et al. (2002) have stressed the importance of a number of petrographic characteristics in the Fish Canyon Tuff that indicate thermal rejuvenation (reheating and probable mass addition of volatiles) of a nearly solid magma body just prior to eruption. Reverse compositional zoning in plagioclase and hornblende; resorption textures in quartz, sanidine, and plagioclase; late-stage crystallization of ferromagnesian phases (specifically hornblende); completely solid xenoliths with Fish Canyon magma bulk compositions; diffusion profiles across sanidine-plagioclase boundaries; and rapakivi-like textures. Each of these will be discussed in comparison with the Cottonwood Wash Tuff.

*Reverse compositional zoning in plagioclase and hornblende*

In the Fish Canyon Tuff, plagioclase phenocrysts are described as becoming more calcic from the cores to the rims with narrow calcic spikes (Bachmann et al., 2002). While almost half of the traverses from the Cottonwood Wash Tuff have rims slightly more calcic than the zones immediately adjacent toward the core, and calcic spikes next to dissolution surfaces are not uncommon (Fig. 12c and 12d), none of the plagioclase phenocrysts with detailed traverses show
distinct reverse zonation through the entire grain. Most of the grains with detailed traverses have only small-scale oscillatory zonation, and of the grains only analyzed at two points (core and rim), the majority have cores more calcic than the rims. If increasing calcium composition is a result of crystallization at higher temperatures (rather than a change in melt composition or water fugacity), this pattern may indicate that some plagioclase grains grew as the magma became hotter during final crystallization, as is proposed for the reversely zoned grains of the Fish Canyon Tuff (Bachmann et al., 2002). It is more likely, however, given the small scale of the compositional variations (typically less than An5), and the fact that at least half of the traverses indicate the rims were growing progressively less calcic, that environment changes in the magma chamber account for the variation in phenocryst zoning patterns, including the dissolution surfaces and calcic spikes. In a convecting, three kilometer-thick magma chamber, a single phenocryst may begin crystallizing in a lower pressure regime, throughout its crystallization history be moved to a higher pressure regime, and possibly back to a lower pressure area before eruption (Fig. 24b). Small scale compositional changes may be due to elemental depletion or enrichment at the mineral-melt boundary due to crystallization, shear flow convection in the viscous magma, slight changes in pressure and temperature, variable water fugacity, or degassing.

Nine out of 14 traverses across the Fish Canyon Tuff amphiboles show rimward increases in Al₂O₃, indicating heating during crystallization, and a low-Al population of cores is believed to represent a near-solidus temperature of ~715°C (Bachmann & Dungan, 2002). To maintain crystallization of amphibole during heating, Bachman & Dungan (2002) suggested that the magma also became more hydrous as it crystallized. The amphiboles of the Cottonwood Wash Tuff show the opposite trend: the cores are typically higher in Al₂O₃ than the rims, and yield
higher calculated temperatures calculated using Ridolfi et al. (2010) show similar increases between the rim temperatures (~825°C) and core temperatures (~900°C), using Ridolfi et al. (2010). Only one-third (15 of 49) of the traverses across amphiboles record rimward increases of Al₂O₃. The rest of the amphibole traverses have only small scale oscillations of Al₂O₃ (~40%, n=19) or have rimward decreases in Al₂O₃ (n=14). As with plagioclase, these compositional oscillations may be due to convection or other environmental changes in the magma chamber. In contrast to the Fish Canyon Tuff amphiboles analyzed by Bachmann & Dungan (2002), but similar to those from the Wah Wah Springs Tuff analyzed by Woolf (2009), the majority of Cottonwood Wash Tuff amphiboles crystallized either during cooling or at a steady temperature prior to eruption.

Although cathodoluminescence images of the Fish Canyon Tuff quartz are not available for comparison, quartz phenocrysts in the Cottonwood Wash Tuff show a cooling pattern similar to those seen in plagioclase and amphibole, with more than 60% of analyzed grains showing normal zonation (darker rims indicating a lower Ti and lower T rimward).

Resorption textures in quartz, sanidine, and plagioclase

As is the case in the Fish Canyon Tuff, plagioclase grains from the Cottonwood Wash Tuff typically have euhedral terminations. Sieve textures are also common in plagioclase in both tuffs, indicating that plagioclase phenocrysts were at times unstable in the magma chamber, likely due to changes in pressure, temperature, or water concentration. Quartz in the Cottonwood Wash Tuff differs from quartz in the Fish Canyon Tuff in one respect; while “euhedral terminations are never observed on…quartz” in the Fish Canyon Tuff (Bachmann et al., 2002), the Cottonwood Wash Tuff quartz grains commonly have one or more euhedral faces. However, embayments and terminations rounded by resorption are typical in the grains from both tuffs. More than 80% of
the quartz grains in the Cottonwood Wash Tuff have resorbed rims, often accompanied by deep embayments. The late-stage rim resorption can be explained by the instability of quartz during decompression of water undersaturated magma during eruption. As mentioned above, quartz phenocrysts of the Cottonwood Wash Tuff are complexly zoned. Multiple crystallization events separated by resorption horizons indicate that, like plagioclase, quartz was at times unstable in the magma chamber.

*Late-stage crystallization of ferromagnesian phases*

Euhedral and poikiolitic amphiboles are common in both the Fish Canyon Tuff and the Cottonwood Wash Tuff. The presence of all major phases, including quartz, as inclusions in amphiboles in the Cottonwood Wash Tuff indicates simultaneous crystallization was occurring throughout much of the magma chamber’s history. The late-stage crystallization of ferromagnesian phases in the Fish Canyon Tuff is used as evidence for a buoyant, water-rich melt mixing with the high-SiO$_2$ rhyolite melt during rejuvenation (Bachmann et al., 2002). There is no evidence of such melts in the Cottonwood Wash Tuff. The glass analyses are uniformly high-SiO$_2$ rhyolites, and mineralogical hygrometers, the phase assemblage, and the experiments of Johnson & Rutherford (1989a) all show that the Cottonwood Wash Tuff magma was not water saturated before eruption. There is no need to invoke crystallization of amphibole and biotite during heating accompanied by feldspar and quartz solution as suggested by Bachmann et al. (2002).

*Completely solid xenoliths of similar chemical composition*

Although the Cottonwood Wash Tuff does have partially crystallized juvenile clasts of similar chemical composition to the bulk tuff (the microdacite inclusions), these are characterized by glassy matrices, unlike those described in the Fish Canyon Tuff (Bachmann et al., 2002).
Phenocrysts in the microdacite are euhedral, indicative of growth and not shaped by incomplete melting of a once solid rock. It is possible that the inclusions from both tuffs are indications of magma chilling against the walls of the magma chamber, with the Fish Canyon Tuff inclusions having fully crystallized whereas those from the Cottonwood Wash Tuff did not. Diffusion profiles across sanidine-plagioclase boundaries, rapakivi and granophyre textures, and grain-boundary melting

As the Cottonwood Wash Tuff lacks sanidine, rapakivi-like textures of plagioclase mantling sanidine and granophyre overgrowths on sanidine in the Fish Canyon Tuff (Bachmann et al., 2002) do not exist. However, the thin melt zones at the contacts between inclusions and the host crystals and melt channels found in feldspar and quartz of the Fish Canyon Tuff have not been seen in the Cottonwood Wash Tuff.

MODEL FOR MAGMA CHAMBER AND ERUPTION

Bachmann et al. (2002) state “Whether or not the same mode of genesis [rejuvenation] applies universally to the class of voluminous ignimbrites classed by Hildreth (1981) as Monotonous Intermediates remains to [be] seen, but many of these units have the same general characteristics as the Soufriere Hills and Fish Canyon magmas.” We believe we can answer that question—the same mode of genesis does not apply universally. The Cottonwood Wash Tuff and its allied monotonous intermediates (the Wah Wah Springs (Woolf, 2008) and Lund Tuffs (Maughan et al., 2002)) do not share these characteristics. Unlike the Fish Canyon Tuff, the Cottonwood Wash Tuff was not warming just prior to eruption. For the Cottonwood Wash Tuff, a scenario different from the Fish Canyon Tuff-inspired near-solidus rejuvenation is needed to reconcile the characteristics described in this paper. We propose the following model.
During the transition of the Farallon Plate from flat-slab to steeply dipping subduction, voluminous amounts of basalt were generated and intruded into a mid-crustal MASH zone (Best et al., 2013). Hybridized andesitic and rhyolitic magma mixtures rose buoyantly from the MASH zone. These magmas may have been near-liquidus, as there is little evidence of a cargo of minerals beyond the volumetrically minor dark CL cores in some quartz grains the low-SiO$_2$ cores of plagioclase and amphibole. Large volumes of crystals were either not entrained in the magma as it rose from the MASH zone, or were completely re-homogenized while rising or during the long residence time in a shallow chamber.

The magmas stalled at the brittle-ductile barrier, where a large magma chamber began to form at around 2.3 kb, or ~8 km deep (Fig. 24). Magma accumulated here over time, possibly as much as one million years, as determined from using Caricchi et al.’s (2014) estimates for repose times between voluminous eruptions, as well as the intervals between the eruptions of the Cottonwood Wash Tuff, the massive Wah Wah Springs Tuff, and the Lund Tuff (Best et al., 2013b). During the long residence time, it is possible that the magma chamber acted as an open system, with hotter mafic magmas intruding into the growing chamber. The sudden calcic spikes seen in the plagioclase traverses are likely due to inject of a hotter, more mafic magma into the system. Other possible evidence for open system behavior includes the reverse zoning seen in some phenocrysts of plagioclase and amphibole and some resorption textures in other phenocrysts. However, the lack of highly complex embayments and resorption textures and no major reverse zoning in phenocrysts indicates that, if the magma chamber was an open system, most of the evidence beyond the calcic spikes in plagioclase has not been preserved. The minor reverse zoning and resorption textures present in the Cottonwood Wash Tuff phenocrysts could alternatively be the result of the convection of a very large system through warmer and cooler
Fig. 24. Schematic drawing of the Cottonwood Wash Tuff magma chamber. Hybridized andesitic and rhyolitic magma rose buoyantly from a deeper MASH zone, stalling at the brittle-ductile (BD) transition, ~8 km deep. A large dacitic magma chamber accumulated over time. (a) Crystallization took place as the magma chamber slowly cooled, eventually approaching 50% crystallinity. Phenocrysts developed primarily small scale oscillatory zonation in response to changes in pressure, temperature, and melt composition. (b) Convection generated by warm magma rising from the floor and cool magma descending from the roof stirred the magma chamber, keeping the phenocrysts suspended and preventing major chamber-wide compositional variation from developing. Growing crystals may have developed zonation in response to changing pressures throughout the thick chamber. (c) Magma chamber convection may have also generated regions of shear, which become phenocryst depleted. Low shear areas would have become crystal enriched (Cimarelli et al., 2011). (d) Small, euhedral phenocrysts may have formed along the chilled margins of the magma chamber, eventually becoming the source of the microdacite juvenile fragments. (e) Crystallization along the chilled margin may have established a zone of rigid, crystal-rich “mush” (Bachmann & Bergantz, 2003). As the rock above the chamber became weakened, extensional ring faults developed on the edges. Eventually, the faults intersected the magma chamber, reducing pressure and causing an explosive super-eruption in which 2000 km$^3$ of crystal rich dacite were deposited on the surrounding landscape.
areas. The small-scale oscillations present in plagioclase, quartz, and amphibole are likely caused by either localized boundary crystallization processes (Fig. 24a) or crystallization in varying pressure regimes in the convecting chamber (Fig. 24b). Slow convection of the magma, caused by warm, buoyant magma rising from the floor and cool, dense magma falling from the roof, would allow for some homogenization of the chamber, preventing the formation of a zoned magma chamber. Rather than falling to the floor of the chamber, phenocrysts would have remained suspended and in equilibrium with the melt, and the interstitial melt itself would be less likely to accumulate in a separate, rhyolitic pool at the roof (Maughan et al., 2002). The variation in juvenile clast crystallinity (36 – 57 % total phenocrysts, dense rock equivalence) and chemical composition (0.4 – 0.8 wt% TiO₂) indicates that this mixing was imperfect, and may be related to convection induced shear sorting. Experiments by Cimarelli et al. (2011) show convection in a magma chamber can vary the phenocryst concentration in an otherwise homogeneous magma. High-shear regions will be phenocryst depleted, and low-shear regions will be crystal enriched (Fig. 24b). Crystallization along the walls or the roof may be source of the microdacite inclusions, while the lack of quartz in the microdacite inclusion may indicate the wall-rock crystallization occurred before quartz was stable in the chamber (Fig. 24c). Chilled margin crystallization may have established a zone of rigid, crystal-rich “mush” (Bachmann & Bergantz, 2003) in the lowermost regions of the magma chamber (Fig. 24d). The presence of this mush zone is speculative, however, as the high crystallinity would have hindered sampling during eruption.

As the magma chamber grew in size, the rocks above the chamber became elevated and stretched, generating extensional faults on the edges (Fig. 24). Eventually, as the faults intersected the magma chamber, the roof rocks failed, sinking into the more buoyant magma in
the chamber below (Christiansen, 2005; Roche et al., 2000). When this occurred, the pressure in
the chamber was reduced, which caused the magma to become fluid-saturated, fracturing many
of the melt inclusion-rich phenocrysts (Best & Christiansen, 1997). The magma rushed
explosively out of the extensional faults, entraining small volumes of limestone and volcanic
country rocks. The roof rock foundered into the emptying magma chamber, further forcing
magma out of the vents, and creating the caldera. If the Cottonwood Wash Tuff erupted in a
manner similar to the Bishop Tuff, in a matter of less than a week (Wilson & Hildreth, 1997),
2000 km³ of crystal-rich dacite were deposited on the surrounding landscape, covering an area of
approximately 12,000 km².

CONCLUSION

The dacitic Cottonwood Wash Tuff erupted 31.1 million years ago from a crystal-rich,
chemically variable magma chamber. While the magma was heterogeneous, likely because of
variations in crystal/melt ratios due to shear in the magma chamber, the resulting tuff deposit
lacks any systematic compositional zonation, with the exception of a volumetrically minor
evolved portion as represented by evolved juvenile clasts. The presence of juvenile clasts with
crystallinities similar to the tuff indicates that the compositional variation of the Cottonwood
Wash Tuff (0.33 – 0.79 wt% TiO₂) is not a result of differing amounts of fines (mostly silicic
glass) removed during eruption and emplacement. Rather, the variation is original to the magma.

The tuff contains abundant phenocrysts (~50%) of plagioclase, quartz, hornblende,
biotite, magnetite, ilmenite, clinopyroxene, zircon, apatite, and pyrrhotite. Although the caldera
was likely engulfed in later super-eruptions in the Indian Peak – Caliente volcanic field, the
estimated volume for the Cottonwood Wash Tuff is 2000 km³. Mineral compositions and
experimental phase relationships show the magma crystallized at \(~800^\circ\text{C}\) under 2.3 kb of pressure, and in water-undersaturated (4.7 wt\% H\textsubscript{2}O) but oxidized conditions ($\Delta$QFM = 2.1).

Zoned phenocrysts of plagioclase and amphibole exhibit small-scale oscillatory zonation; normal and reverse zonation are equally likely to occur where systematic compositional zonation exists. The majority of quartz phenocrysts show normal zonation with late-stage resorption.

The Cottonwood Wash Tuff magma system did not undergo rejuvenation from a near-solidus state, as is postulated for the Fish Canyon Tuff and other crystal-rich ignimbrites. Like the Wah Wah Springs Tuff (Woolf, 2008), the next-erupted monotonous ignimbrite erupted from the Indian Peak – Caliente volcanic field, the Cottonwood Wash Tuff magma was undergoing cooling prior to eruption, as is recorded by a majority of normally zoned phenocrysts. While the rejuvenation model may be appropriate to the Fish Canyon Tuff, it is not a model that should be applied to all crystal-rich ignimbrites.
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Appendix A. Chemical and modal data for the Cottonwood Wash Tuff ignimbrite and juvenile clasts can be found in a Microsoft Excel spreadsheet attached to the pdf version of this work.

Appendix A1. Whole rock chemical composition
Appendix A2. Modal proportions
Appendix A3. Sample locations
Appendix A4. Plagioclase chemical analyses
Appendix A5. Amphibole chemical analyses
Appendix A6. Biotite chemical analyses
Appendix A7. Magnetite chemical analyses
Appendix A8. Ilmenite chemical analyses
Appendix A9. Pyroxene chemical analyses
Appendix A10. Glass chemical analyses
Appendix B. Thin section descriptions

ATL-1-70-1P-1

Plagioclase
- Twinned and oscillatory zoned (some not zoned)
- Several with resorbed cores and nice rims—several with clinopyroxene/amp blebs
- Subhedral, some almost euhedral
- Largest 2+mm, average large size between 0.25 to 0.5mm
- Melt inclusion holes, cracked bits that might have been glomerophyric
- Some glomerophyric
- Apatite and zircon inclusion

Quartz
- Most between 1.0-2.0 mm, largest 2.3mm
- Most subhedral—many phenoclastic
  - Some with altered but still visible larger glass shards connecting them together
- Melt inclusion remnants
  - Many with cracks from/to melt inclusions
- Most not undulatory
- Apatite inclusion

Biotite
- Pleochroic dark red to brown orange
- Largest 3mm by 2mm, average large size 0.25 – 0.75 mm, many 1mm
- Some with feldspar inclusions, Fe-Ti oxides, dark—altered?
- Mostly oriented in side on view, but also oriented jumbled

Hornblende
- Largest 1.5mm
  - Most between 0.25 and 0.50 mm
- Typically euhedral
  - Some subhedral, some anhedral
- pleochroic red brown to brown green
- altered to Fe-Ti oxides
- rarely in reaction relationship with pyroxene

Fe-Ti oxides
- Anhedral
- Largest 1mm, average large size is 0.25-0.40 mm

Clinopyroxene
- glomerophyric with hornblende but more often with biotite
- little pieces
- altered to Fe-Ti, hornblende
- subhedral to anhedral
- <0.5mm (commonly small pieces 0.25 mm)
- Some twinned

Groundmass
- A little altered, calcite in places
- Slight foliation, not as obvious as WARM-2P

ATL-1-70-1P-2

Plagioclase
- Lots of phenoclastic plagioclase crystals
  - Many with “holes”—old melt inclusions?
- Many altered with holes, dim
- Some with cores with hornblende or pyroxene blebs
- Some alteration
- Twinned, some oscillatory zoning
- Largest 3mm, many 2mm, range from 0.5-1.5mm
- Some look glomerophyric
- Most sub, some euhedral or anhedral
- Minor apatite/zircon

Quartz
- Range 0.5 mm to +3 mm
- Melt inclusion exploded crystals (phenoclastic)
- Some euhedral, many subhedral, many anhedral
- Some small apatite inclusions

Biotite
- Pleochroic red brown-dark red brown or green to brown
- Seem to be altered dark red
- Biggest in excess of 3-4 mm, average large 0.75-1.0mm
- Euhedral to sub, not as many side-on
- Plagioclase inclusions, Fe-Ti oxide in some

Hornblende
- Largest 2mm, average 0.5mm
- Many plucked with only rims left
- Euhedral to subhedral
- Pleochroic red brown to green
- Glomerophyric with self
- Altered to Fe-Ti oxides

**Fe-Ti oxides**
- one big (1mm) one, most 0.5 mm or smaller
- clustered in little groups in big (possible) xenocrysts?

**Clinopyroxene**
- Some resorbed with optically different rims
- one really big on 2.5 mm across
  - most are small, 0.25 mm
- euhedral to anhedral
- big one is in a glomerophyric bundle with Fe-Ti oxide clusters, biotite, altered amp, and more clinopyroxene
- some have clinopyroxene

**Groundmass**
- glass
- not altered so much to calcite
- some discernable glass shards between broken crystal pieces
- slightly foliated
- little crystals

**ATL-1-70-1P-3**

**Plagioclase**
- one HUGE one 9mm across
  - complexly zoned, hornblende blebs in outer rim
  - subhedral
- majority subhedral, some euhedral
- cracks
- average large size 0.5-1.5mm range, 0.25-3mm
- complexly zoned and twinned
- many glomerophyric
- phenoclastic with large shards
- minor apatite and zircon
- melt inclusions—not as many as quartz have

**Quartz**
- range from 0.5 mm to 1.5mm, largest 3.5 mm
- Euhedral and embayed
  - most sub to euhedral
- melt inclusions, embayed features on most
- some “crackled” quartz
- Phenoclastic, but have glass shards holding together
- minor apatite

**Hornblende**
- pleochroic red brown to brown green
- Euhedral to anhedral
- some surrounding cores of pyroxene—reaction relationship
- largest (1.5-2mm)
  - broken and plucked
  - majority between 0.25 to 0.75mm
- some broken, but lying next to each other
- some with Fe-Ti oxide inclusions or plagioclase, one quartz inclusion
- glomerophyric with pyroxene, quartz, feldspar, oxides, clumped together

**Biotite**
- largest 2mm, majority <1mm, range 0.25-1.5 mm
- pleochroic green to brown
- not real strong preferred orientation
- not badly oxidized
- inclusions:
  - feldspar, oxides
  - rarely glomerophyric with self
- most subhedral
  - some euhedral

**Fe-Ti oxides**
- Largest 0.5mm, most <0.25mm
- Glomerophyric with amphibole and clinopyroxene

**Clinopyroxene**
- associated with amphibole
  - in reaction
  - in cores
  - glomerophyric with amphibole
- largest 1mm
- most anhedral
  - at least two euhedral crystals
  - “growing” oxides

**Groundmass**
- Still glassy
- Slightly foliated
- Not badly altered
- Some small crystals
ATL-1-70-1V

Plagioclase
- Subhedral
  - Mostly phenoclasts with broken edges, but also euhedral crystal edges
- Twinned and zoned
- Some with inclusion rich cores (hornblende, plagioclase, pyroxene)
- Some sieved textured
  - At least one with a little rim around it
- Largest 3mm
  - Range around 0.5 – 2 mm
  - Most around 1.5 mm
- Glomerophyric with self
- Some melt inclusions

Quartz
- Melt inclusions, embayed
- Mostly anhedral
  - Several with some crystal faces
- Plagioclase inclusions
- Largest 3.5 mm
  - Range 1 mm to 2mm

Biotite
- Some oxidized
- Showing some foliation
- Red-brown to orange
- Inclusions
  - Feldspars, oxides, apatite
- Largest 4 mm
  - Average 2 mm

Hornblende
- Pleochroic green to brown
- Euhedral to anhedral
- Inclusions of oxides, quartz, plagioclase
- Some with broken and altered core
- Largest 1.5 mm
  - Average 1mm
- Some altered to pyroxene

Fe-Ti Oxides
- Magnetite shaped
- Glomerophyric with self
- Largest 1 mm
  - Average 0.5 mm and smaller

Clinopyroxene
- Inclusions of hornblende
- Anhedral
  - Mostly broken
  - A few crystal faces
  - Average 0.5 mm
  - Some as big as 1mm

Groundmass
- Glassy matrix
- Some devitrification
- Groundmass crystals of all phases
- Brown glass

Pumice
- Squashed
- Some spherulites
- altered
- Some crystals
  - Especially plagioclase

Xenolith
- Many small (< 1.0 mm) euhedral crystals
  - Mostly plagioclase
  - Some biotite, hornblende
- Glass matrix
- 6 mm across, 4 mm wide

BULLG-1

Plagioclase
- Largest 4 mm
  - Average size 1.5mm and smaller
- Phenoclasts with some crystal edges
- Some inclusion-rich cores
  - Hornblende, biotite, plagioclase, pyroxene
- Some sieve textured
- Twinned and zoned
- Melt inclusions

Quartz
- Very embayed
- Phenoclasts
  - Some crystal edges
  - Exploded melt inclusions
- Cracked (not crackled)
- Largest 3mm
  - Average size 1.5 mm or smaller

Biotite
- Reddish brown-orange
- Largest 3 mm
  - Average 2 mm or smaller
- Inclusions
  - Oxides, feldspar, apatite
- Shows some foliation
• Some alteration and oxidization

**Hornblende**
- Most euhedral
  - Some phenoclasts
- Largest 1.5 mm
  - Average 1.0 mm or smaller
- Yellow-green to brown pleochroism
- Twinned

**Fe-Ti oxides**
- Inclusions
  - Pyroxene
- Largest 1.2 mm
  - Average <1mm

**Clinopyroxene**
- Some euhedral
- Inclusions
  - Hornblende, oxides, apatite
- Some as cores of hornblende
- Most 0.5mm or smaller

**Groundmass**
- Glass shards
  - Some squashed
- Little crystals of all phases
- Not very devitrified or firmly welded

**FAIRV-32**

**Plagioclase**
- Altered
  - Lots of stained cracks
- Twinned and zoned
- Largest 3.5 mm
  - Average 2 mm or smaller
- Subhedral phenoclasts
  - Some anhedral
- Inclusions
  - Plagioclase
  - Some melt inclusions
    - Rings of blebs

**Quartz**
- Largest 3 mm
  - Average 2.5 mm or smaller
- Many melt inclusions
  - Some broken
    - Not with shards
- Lots of cracks
- Mostly phenoclasts with some crystal faces

**Biotite**
- Very altered
- Included with oxides, plagioclase
- Largest 3 mm
  - Average 1.5 mm or smaller
- Brown-red

**Hornblende**
- Very altered
  - Almost completely eaten by oxides and clays
- Euhedral to fragmented
- Average large size 1.5 – 1mm

**Fe-Ti oxides**
- Difficult to tell originals
- <1 mm

**Clinopyroxene**
- Not very altered
  - Clean
- Largest 1.5 mm
- Some euhedral
  - Lots of fragments
- Some as cores of hornblende
- Glomerophyric with oxides

**Groundmass**
- Glass and devitrified glass
- No shards remain
- Stained reddish
- Cracks of phenocrysts stained red
- Really altered sample
- Small crystals of plagioclase, other phases

**GOUGE-1-133-9**

**Plagioclase**
- Phenocrystals and other fragments
- Twinned and zoned
- Some sieve textured
- Some with blebbby inclusion rings or cores
  - Inclusions
    - Hornblende, pyroxene, oxides, self, apatite
  - Melt inclusions
- Glomerophyric with self
- Largest 3.5 mm
  - Average 1mm to smaller

**Quartz**
- Largest 2.5 mm
Devitrified melt inclusions
• Apatite accessory
• Almost euhedral to anhedral
  • Some phenocrysts

Some phenocrasts
• Biotite
  • Very altered
    • Rimmed, spotted with oxides
    • Similar alteration to hornblende in this sample
• Orange-brown to yellowy brown
• Largest 2.3 mm
  • Most <1.0 mm
• Inclusions
  • Apatite, oxides, feldspars
  • Some foliation
  • Glomerophyric with big pyroxene phenocryst

Hornblende
• Very altered
  • rimmed and spotted with oxides, dark
  • similar alteration to the biotite in this sample
• Euhedral to anhedral fragments
• Green-brown to brown
• Inclusions
  • Self, oxides, feldspar
  • Glomerophyric and in reaction with pyroxene
• Biggest 1.5 mm
  • Average <1 mm

Fe-Ti oxides
• Euhedral to anhedral
• Sometimes bunched together
• Largest 1mm
  • Commonly <0.5 mm
• Abundant

Clinopyroxene
• Some fragments
• Largest 2mm
  • Average <1 mm
• Subhedral to anhedral
  • A few euhedral
• Inclusions
  • Oxides, quartz with apatite, self
  • Rarely rimmed with hornblende
  • Sometimes in reaction relationship with hornblende

Groundmass
• Some spherulites
• Devitrified
• Light brown-pink
• Small crystals
• Some orientation
• Piece or two of possible squashed pumice

GOUGEWL-1-1

Plagioclase
• Largest 3mm
  • Average 1.5 mm to smaller
• Phenocrysts
  • Mostly subhedral
• Inclusions
  • Hornblende, pyroxene, oxides, apatite, self
  • Melt
• Some with blebbly cores
• Some sieve textured

Quartz
• Largest 2mm
  • Average 1mm to smaller
• Euhedral to phenocryst
• Inclusions
  • Melt inclusions
    • Bubble-crack exploded ones
  • Plagioclase, apatite

Biotite
• Altered, chloritized?
  • Bright interference colors
• Inclusions
  • Oxides, plagioclase, quartz, apatite
  • Melt inclusion
• Largest +4mm
  • Average 2mm to <1mm
• Orange to light orange-green
• Glomerophyric with self
• Not really orientated

Hornblende
• Most euhedral amphibole shape, some fragments
• Twinned
• Green to brown green
• Inclusions
  • Oxides, biotite, self, apatite
• Largest 1.5 mm
Average 1mm to smaller
- Reaction relationships with pyroxene and quartz

**Fe-Ti oxides**
- Subhedral, most
- Largest <1 mm
- Inclusions
  - Plagioclase or apatite

**Clinopyroxene**
- Often altered to amphibole, with quartz there too
- Inclusions
  - Apatite
  - Largest 1 mm
  - Subhedral
  - Sparse

**Groundmass**
- Some alteration and devitrification
- Bubble wall shards still typically unaltered
- Small crystals

**GOUGEWL-1-15**

**Plagioclase**
- Largest 3mm
  - Average 1 mm to 2mm
- Subhedral to anhedral
- Inclusions
  - Typical
  - Twinned and zoned
  - Rings and cores of crystal blebs
  - Melt inclusions
  - Sieve textured ones
  - Glomerophyric tiny crystals with hornblende and oxides

**Quartz**
- Phenoclastic—very broken
- Some anhedral
- Several large 3mm
  - Average 0.5 to 1mm
- Exploded melt inclusions with no visible shards
- Sparse apatite

**Biotite**
- Largest 4 mm
  - Average 1 mm to 2 mm
- Inclusions
  - Oxides, plagioclase, hornblende
  - Some heavily altered

**Hornblende**
- Largest 1.5 mm
  - Average 1 mm to smaller
  - Reddish-orange to red-brown
  - Twinned
  - Euhedral to anhedral
  - Inclusions
    - Oxides, self
    - Rimming and/or in reaction with pyroxene
    - Glomerophyric with oxides and plagioclase

**Fe-Ti Oxides**
- Typical
  - <1mm

**Clinopyroxene**
- Often in reaction relationship with hornblende
- Anhedral
- Largest 1mm
  - Average <1mm
- Inclusions
  - Oxides, plagioclase, hornblende

**Groundmass**
- Very altered and devitrified
- Rare bubble wall shards

**Pumice**
- Squashed and devitrified

**GOUGEWL-1-19**

**Plagioclase**
- Sieve textured
  - These seem to have a lot of blebs, too
  - Twinned and zoned
  - Usual inclusions
    - Rings of them
  - Sparse melt inclusions
  - Largest 5 mm (sieve textured one)
    - Average 1 mm to 2 mm
  - Subhedral to anhedral

**Quartz**
- Largest 3mm
  - Average 1mm to smaller
  - Phenoclastic—some crystal edges
  - Devitrified melt inclusions
• No other visible inclusions

**Biotite**
- Inclusions
  - Plagioclase, oxides, apatite
- Biggest 3.5 mm
  - Average 1.5 to smaller
- Reddish brown to light green brown
- Some orientation
- Some alteration

**Hornblende**
- Largest 1.5 mm
  - Average 0.5 mm to smaller
- Twinned
- Euhedral to phenoclastic
- Green to brown
- Inclusions
  - Oxides, pyroxene reaction, quartz

**Fe-Ti Oxides**
- Typical but slightly bigger than normal (>1mm)
- Hornblende inclusion

**Clinopyroxene**
- In reaction with hornblende
- Sparse
- Mostly anhedral, one or two euhedral
- Inclusions
  - Oxides, self, possible apatite
- <1mm

**Groundmass**
- Devitrified
- Some alteration
- Clay-rich
- Light brown
- No glass
- Welded

**GOUGEWL-1-5P-1**

**Plagioclase**
- Complexly zoned, twinned (Carlsbad and polysynthetic)
- Some remnant melt inclusions
- Some with optically different cores
- A few sieve textured ones
- Inclusions
  - Plagioclase
  - Sparse hornblende blebs
- Largest 2mm
  - Average 0.25 – 1mm

**Quartz**
- Melt inclusions (devitrified and broken)
- Some euhedral, most anhedral/broken
- Faintly cracked
- One with hornblende inclusion
- Sparse apatite
- Phenoclastic
- Average range 0.25 – 1 mm

**Biotite**
- An odd poikolitic? glomerophyric? grain
  - Large optically continuous biotite grain
  - Lots of little grains of hornblende
    - Plagioclase, oxides
- Largest 2.5 mm
  - Range 0.5 to 1 mm
- Most are oriented side on, some hexagons
- Not badly oxidized

**Hornblende**
- Twinned
- Some euhedral
  - Many broken, sub or anhedral
- Many with pyroxene cores or glomerophyric with pyroxene
- Inclusions of oxides, plagioclase, self
- Rarely glomerophyric with self
- Broken, often lying next to optically continuous bits
- Largest about 1 mm
  - Average 0.25 – 0.5mm

**Fe-Ti Oxides**
- Rare square-shaped
- Found with hornblende, biotite, clinopyroxene
- Range from <0.25mm to 0.5mm
- Inclusions of hornblende, plagioclase

**Clinopyroxene**
- Found as cores of hornblende
- Also in reaction relationships with hornblende
- Also “alone” or with oxides
- Some with twins
- Euhedral
- Some altered
- Max size about 0.65mm, most smaller

**Groundmass**
- Devitrified brown
- Isotropic
  - No real preferred orientation
- Some alteration (green, chloritic?) in veins
- Welded

**Xenolith**
- Microcrystalline
  - Brown, foggy

**GOUGEWL-1-5P-2**

**Plagioclase**
- Twinned and complexly zoned
- Melt inclusion remnants
- Inclusions
  - Zircon
  - Apatite
  - Oxide
  - Sparse hornblende
- Most sub to anhedral
  - A few euhedral
- Largest 3+mm, average larger size 0.5-1mm
  - Several large ones

**Quartz**
- Largest 1.25mm
  - Average 0.25 – 0.75mm
- Subhedral to anhedral
  - Lots of embayment
- Melt inclusions
  - Lots of cracks (conchoidal)
  - Growth rim? No, lucky break (spalling)
- Possible inclusion of plagioclase??
- Looks like melt inclusions may have broken the quartz crystals, but the matrix is squished and devitrified

**Biotite**
- Pleochroic brown orange to orange
- Inclusions: oxides, feldspar, plagioclase
- Some oxidation
- No preferred orientation—both laths and hexagons
- Average large 0.5mm to 0.75mm
  - Largest 3.25mm
- Euhedral/subhedral

**Hornblende**
- In reaction with pyroxene
  - Many with cores of yucky pyroxene
- In glomerophyric bunches with quartz, oxides, clinopyroxene
- Pleochroic green and yellow green
- Many sub to anhedral
  - Rare with euhedral shape
- Range 0.25 mm to 0.75 mm
  - Largest <1mm

**Fe-Ti oxides**
- Inclusions of plagioclase, clinopyroxene
- Included in plagioclase, biotite, hornblende, pyroxene
- Blobby
- Round
- Largest almost 2mm
  - More large ones
  - From <0.25mm to 1.5mm

**Clinopyroxene**
- Anhedral
  - Often as corroded cores (hornblende) or in reaction with hornblende
- Biggest almost 1.5mm
  - Most are small shards (0.5mm)
- Glomerophyric with quartz, inclusions of oxides

**Groundmass**
- Welded
- Little pore space
- Devitrifying—brown
- Some alteration
- Isotropic

**GOUGEWL-1-5Pb-md**

*Much smaller phenocrysts than in the pumice attached to this sample (GOUGEWL-1-5Pb-P). Every phase is significantly more included, most notably with comparatively large apatite inclusions in the groundmass and phenocrysts.*

**Plagioclase**
- Heavily included
  - Apatite, hornblende, self, oxides, biotite, zircon
- Euhedral
- Complex oscillatory zoning
- Largest 1mm, most <0.5mm

**Quartz**
- None

**Biotite**
- Pleochroism: Red brown, red, light red
- Largest ~1 mm, most <0.75mm
Included: oxides, zircons, large apatites

**Hornblende**
- Optically zoned
  - Commonly patchy, not banded
- More abundant than on pumice side
- Euhedral to sub, rare broken
- Rare glomerophyric with self, biotite
- Inclusions: oxides, zircon, biotite, large apatite

**Fe-Ti oxides**
- Glomerophyric with self
- ~0.5 mm
- Interesting junctions—almost polygonal aggregate like

**Clinopyroxene**
- None

**Groundmass**
- Devitrified glass
  - Slightly spherulitic
  - Light green
  - No preferred orientation
- Abundant large apatite phenocrysts

**GOUGEWL-1-5Pb-P**

**Plagioclase**
- Oscillatory zoning
- Fritted zones in some grains
  - Some inclusion-rich cores
- Euhedral or broken
- Largest: 2mm
- Apatite, zircon, oxides, biotite, hornblende, melt inclusions

**Quartz**
- Embayed, resorbed, anhedral
- Melt, apatite, zircon, hornblende inclusions
- Largest: ~2mm

**Biotite**
- Pleochroic dark brown, red brown, red-tan
- Typical biotite cleavage
- Some altered
- Plagioclase, oxide inclusions
- Largest: 1.75 mm

**Hornblende**
- Pleochroic light green, green, red-brown
- Euhedral and broken, some anhedral
- Rare faint optical zoning
  - Patchy commonly, rare banding
- Some reaction rims
- Largest: 1mm

**Fe-Ti oxides**
- Anhedral, rare euhedral
- Glomerophyric with amphibole typical

**Clinopyroxene**
- Euhedral to anhedral
- Twinned
- No reaction rims or in reaction with hornblende
- Oxide inclusions
- Largest: 0.75 mm

**Groundmass**
- Dark red glass, some altered, some still clean

**Xenoliths**
- Microdacite
  - Biotite, hornblende, oxides, rare plagioclase and no quartz

**GOUGEWL-1-5V**

**Plagioclase**
- Twinned and zoned
- Included rings and cores
  - Oxides, apatite, hornblende, pyroxene, self
- Largest: 3mm
  - Average 2mm to smaller
- Melt inclusions
- Some sieve texture

**Quartz**
- 3.5 mm largest
  - 1 mm average
- Melt inclusions
  - Exploded, but no visible bubble wall shards
- Subhedral to phenoclastic
- Inclusions
  - Sparse apatite

**Biotite**
- Largest: 3mm
  - Average 2mm to smaller
- Some alteration, bright interference colors, not as bad as GOUGEWL-1-1
- Green brown to dark brown
• Inclusions
  o Feldspar, oxides, apatite

**Hornblende**
• Green to green brown
• Twinned
• Sub to anhedral
• Largest 2 mm
  o Most <1 mm
• Some glomerophyric with plagioclase, oxides, hornblende,
  o All bundled together
• Inclusions
  o Self, oxides, biotite, plagioclase

**Fe-Ti Oxides**
• Anhedral to subhedral
• <1 mm
• Glomerophyric

**Clinopyroxene**
• Some in reaction with hornblende
• Largest 1 mm
• Inclusions
  o Quartz, plagioclase, oxides
• Some euhedral, some anhedral fragments

**Groundmass**
• Glassy, shards
• Little orientation
• Small crystals
• Doesn’t seem to be much altered

**Pumice**
• Mostly squished to glass patches
• Crystals of hornblende, plagioclase, biotite, oxides
• Some as large as 8 mm

**GOUGEWL-1-mid-IP**

**Plagioclase**
• Funny, jigsaw puzzle types
  o In a line through the middle of the section
  o Some optically continuous, some not
• Melt inclusions (devitrified)
• Inclusions
  o Oxides, plagioclase, hornblende
• Cores with hornblende blebs
• Twinned and complexly zoned
• Apatite and Zircon accessory
• Some embayment, some sieved too

• Euhedral to subhedral
  o Some anhedral, especially jigsaw
• Max 3 mm
  o Range 0.25 to 2 mm

**Quartz**
• Largest 2 mm
  o Average large size 0.5 – 1 mm
• Subhedral to anhedral
• Devitrified melt inclusions
  o Some have been burst apart, but if there were glass shards they have all been plucked or they have been...I don’t know
• Apatite and zircon
• Embayed

**Biotite**
• Really altered—altered rims, dusting on entire crystal
• Oxidized, dark, speckled with oxides
• Inclusions
  o Plagioclase, oxides
• Max 2.5 mm
  o Average 0.75 mm
• Not many hexagons, most wider laths, a few slim laths
• Pleochroic green, light orange, dark brown

**Hornblende**
• Really altered too
• Dark, rims of oxides
• Looks like some big ones
  o All broken up and optically moved but still close
• Inclusions: plagioclase, oxide, pyroxene
• Subhedral to anhedral
• Rare twins
• Largest 0.75 mm
  o 0.25 – 0.75 mm, average
• Some association with clinopyroxene, not much

**Fe-Ti oxides**
• Blobby
• Max 0.5 mm

**Groundmass**
• Spherelitic
• Definitely secondary alteration
• Dirty—some devitrification, some calcite
• Some foliation
**Sanidine**
- At least two grains
- One Carlsbad twin?
- Location
  - If label is on the left hand edge, the sanidine is on the southwest bottom, close to the label and bottom

**HAM-7**

**Plagioclase**
- Largest 3mm
  - Some 2mm, most <1mm
- Euhedral
- Broken
- Inclusions: apatite, zircon, plagioclase, clinopyroxene, hornblende
- Some inclusion-rich cores and/or rims
- Zoned and twinned
- Some sieve textured

**Quartz**
- Largest 3mm
  - Some 2.5 – 2 mm, most <1mm
- Inclusions: hornblende, melt, apatite
- Embayed
- Broken
- Resorbed
- Some crystal faces

**Biotite**
- One large one 4mm
  - Some 2mm, most <1mm
- Red-brown to dark brown
- Broken on cleavage planes
  - Some euhedral
- Some anisotropy to the orientation, parallel with compacted glass bands
- Inclusions: oxides, quartz, feldspar
- Some oxidation

**Hornblende**
- Largest 1mm
  - Most <1mm
- Oddly sparse
- Some euhedral, some resorbed
- Orange-green to brown
- Inclusions: oxides, feldspar, zircon
- Not in reaction to clinopyroxene

**Fe-Ti oxides**
- Largest 1mm
  - Most <0.5mm
- Inclusions: feldspar

**Clinopyroxene**
- Largest 1mm
  - Most <0.5mm
- Inclusions: oxides
- Anhedral
- Simple twins

**Groundmass**
- Slightly squashed pumice
- Glassy
  - Some clays
- Pumice
  - With all phases present
  - Slightly squashed
- Anisotropic

**Xenolith**
- Very large (+10mm)
- Glassy matrix with little subhedral crystals

**HFW-21D**

**Plagioclase**
- Oscillatory zoned, twinned
- Apatite and zircon and hornblende
- Cleavage has reddish stuff inside them
- Euhedral broken embayed
- Melt inclusion
- Glomerophyric with self
- Sieve textured
- Ave. 2-1.5mm, some as big as 3.5, 4mm

**Quartz**
- Majority 1.5mm (range from 2mm to .7mm)
- Melt inclusions
- Embayed
- Euhedral to subhedral
- Broken

**Biotite**
- Most 1.5 to 2mm, some 4mm
- Some alteration (oxidation? to Fe-Ti oxides)
- Some with lots of holes that are filled with microcrystalline stuff—used to be plag,
  - Probably, some with feldspar
- Cleavage cracks have quartz?
- Euhedral to subhedral—some cut so that the six-sided shape is visible
- Oxide rims/altered to chlorite
**Hornblende**
- altered/recrystallization
- euhedral, broken—some with parts next to each other
- some quite altered
- Fe-Ti oxide inclusion

**Fe-Ti oxides**
- “bleeding” into groundmass and other crystals

**Clinopyroxene**
- altered mostly
- just cores of pyroxene with alteration all the way around

**Groundmass**
- coarsely devitrified groundmass
- spherulitic to granophyric
- secondary silica
- little oxides
- pumices? devitrified
- groundmass—zircon

**Sanidine**
- euhedral and subhedral
- embayed
- melt inclusions, almost completely crystallized
- inclusions of quartz, more feldspar?
- 1.2mm

**HFW-21V**

**Plagioclase**
- Largest 3mm
  - Most <1.5 mm
- Inclusions: zircon, apatite, melt, hornblende, oxides, clinopyroxene
  - Melt inclusions are cryptocrystalline now
- Twinned and zoned
  - Oscillatory zonation
- Broken, but with crystal edges
- Embayed
- Somewhat glomerophyric with Fe-Ti oxides, hornblende, and self
- Some inclusion-rich cores

**Quartz**
- Melt inclusions
- Embayed
- Cracked and broken (phenoclastic)

**Biotite**
- Largest 3mm, several
  - Most <0.8mm
- Subhedral, broken on cleavage planes
  - Side on
- Inclusions: plagioclase, Fe-Ti oxides

**Hornblende**
- Subhedral
  - Some euhedral, some broken, some lathe shaped
- Inclusions: Fe-Ti oxides and plagioclase
- Not too altered
- Most <1mm

**Fe-Ti oxides**
- ~0.5mm

**Clinopyroxene**
- Altered to hornblende and Fe-Ti oxides
  - Reaction relationship
  - Reddish halo around oxides included in clinopyroxene
- Subhedral
- Glomerophyric with self
- Most ~0.7 mm

**Groundmass**
- Partially devitrified
- Bubble wall shards visible
- Slightly foliated

**Xenolith**
- Volcanic rock
  - ~1.2 mm

**Sanidine**
- 1mm
- Subhedral and embayed
- Fuzzy, altered on edges
- Apatite inclusion

**KNOLL-1-2**

**Plagioclase**
- Zoned and twinned
- Glomerophyric with self
- Inclusions: self, zircon, apatite, hornblende
- Broken, with euhedral sides
- Rare inclusion-rich cores
- Largest 2 mm
  - Few 1-2 mm
  - Most <1 mm

**Quartz**
- Embayed
- Resorbed, broken, few crystal faces
- Melt inclusions, zircon, apatite, hornblende, plagioclase
- Largest 3 mm
  - Several 2 mm
  - Most <1 mm

**Biotite**
- Largest 2.5 mm
  - Some 1-2 mm
  - Most <1 mm
- Most side on, some broken
- Fairly clean/unaltered
- Light orange to dark orange
- Inclusions: plagioclase, rare oxides, self
- Rare glomerophyric with feldspar

**Hornblende**
- Light green to olive green
- Inclusions: oxides, feldspar, apatite
- Broken pieces, some euhedral
- Some few pyroxene cores
- Simple twins
- Largest 1 mm
  - Most <1 mm

**Fe-Ti oxides**
- Clean edges
- Inclusions of feldspar
- Largest 0.5 mm
  - Most <0.5 mm

**Clinopyroxene**
- Rare cores in hornblende
- Most broken, resorbed
- Inclusion: oxides
- In reaction on edges

**Groundmass**
- Clean
- Glassy
  - Bubble wall shards, etc
- Pumices
  - Small <0.5 mm
  - Not squashed

**KNOLL-1-20**

**Plagioclase**
- Zoned and twinned
- A few inclusion-rich cores
- Some with euhedral edges, some resorbed
- Inclusions: pyroxene, hornblende, oxides, zircon, apatite, melt
- Largest 2.5 mm (several)
  - Most <1 mm

**Quartz**
- Melt inclusions
  - With plagioclase inside
- Accessory zircon
- Embayed
  - Some deeply
- Phenoclastic
- Resorbed
- Largest +2.5 mm (several)
  - Most <1 mm

**Biotite**
- Most lathe shaped, anisotropic fabric
- Largest 3 mm
  - Most <1.5 mm
- Some alteration/oxidation
  - Calcite between sheets
- Inclusions: feldspar, oxides, zircon
- Dark brown to light orange

**Hornblende**
- Light yellow-green to light green
- Euhedral crystals to broken
- Simple twins
- Inclusions: oxides, possible feldspar core?
- Some in reaction relationship with clinopyroxene
- Several glomerophyric with oxides or oxides and self
- Largest 1.5 mm
  - Most <0.75 mm

**Fe-Ti oxides**
- Glomerophyric with hornblende
- Inclusions: feldspar
- Most <0.5 mm

**Clinopyroxene**
- Some in reaction with hornblende
- Some not
- Simple twins
- Euhedral with some broken faces
- Largest 1 mm
Groundmass
- Devitrified
  - No glass shards
- Some calcite crystals
- Foliated
- Rare pumice
  - Slightly compacted, devitrified

Xenoliths
- ~4.5 mm
- Badly altered with calcite, small <<0.5 mm phenocrysts (plagioclase, amphibole, biotite, oxides) and indeterminate groundmass

KNOLL-1-38-1P-1
Plagioclase
- Largest 2mm, range 0.5mm to 1.5
- Complexly zoned, twinned
- Cores that are different optically from rims
- Minor zircon and apatite
- Melt inclusion remnants
- Some rather spectacular blow apart crystals
- Sieve texture
- Some with amp blebs in cores, some with blebs in outer rim area

Quartz
- Largest 3mm across
  - 0.25-1.2mm + the big ones
- At least phenoclast, "hooked" with shards
- Melt inclusions in some
- Some euhedral, most subhedral
- No visible accessory minerals
- Most isotropic, few slightly undulatory
- Some crackled

Biotite
- Pleochroic green brown to dark brown
- Some oxidized dark opaque
- Some broken but in same general area
- Subhedral or side-on
- Largest about 1mm (several)
  - Average range 0.25 – 1mm
- Some with plagioclase phenocrysts inside
  - Some included with oxides

Hornblende
- Appears to be plucked a lot
- Larger 2.3mm to +1mm
  - Average range 0.25 – 1mm

Fe-Ti oxides
- Range 0.5 mm to <<0.25 mm
- Associated with biotite and hornblende

Clinopyroxene
- Some with optically different cores
- Small, average 0.5 – 0.25mm
- Euhedral and anhedral
- Glomerophyric with hornblende and self

Groundmass
- Very altered
- Calcite everywhere
- Foliated, small crystals
- Still some glass

Sanidine
- 2mm across
- Broken grain
- Only one area
  - If label is on the left hand side, grain is found in the upper northwest corner, close to the top and label

KNOLL-1-38-1P-2
Plagioclase
- Another jigsaw type—very big 4mm
  - Optically continuous
- Some big 1.5 – 2 mm
  - Most between 0.75 and 1.2 mm
- Euhedral to anhedral
- Twinned and zoned
- Some really eaten ones
- Hornblende included cores
- Some sparse melt inclusion evidence
- Apatite inclusion
- Some glomerophyric with biotite

Quartz
- Phenoclasts
  - Too much alteration to even see shards
- Melt inclusions
  - Devitrified and altered
- Some embayment
- Max 2 mm
  - 0.25 to 1.5 mm
- Some crackled quartz
- Minor apatite, zircon
- Anhedral, some phenoclastic

**Hornblende**
- Twinned
- Anhedral
- Glomerophyric with oxides, oxide inclusions
- Sparse—possibly plucked
- Largest 1 mm
  - Most shards/pieces around 0.50 mm
  - Possibly glomerophyric with self

**Biotite**
- Largest 2 mm
  - Average 0.25 to 0.50 mm
- Also looks plucked
- Inclusions of plagioclase, oxides
- Glomerophyric with plagioclase (some)
- Oxidized—most heavily on {001}
- Some subhedral, some perfect octagons, many books side on
- No real orientation

**Fe-Ti Oxides**
- Some glomerophyric with hornblende
- Some round, some blobby
- Average 0.25 to 0.30 mm
- Inclusions of feldspar

**Groundmass**
- Lots of alteration—huge calcite crystals
- Beyond the calcite, hard to see anything
- Devitrified

**KNOLL-1-38-1P-3**

**Plagioclase**
- Largest 4mm
  - Average 0.25mm to 1.2mm
- But I don’t see glass shards between the pieces
- Melt inclusions
- Glomerophyric with self
- Twinned and complexly zoned
- Inclusions of hornblende and plagioclase, apatite
- Badly fragmented pieces all of same crystal
- Hornblende rich blebby cores
- Sub to anhedral
- Embayed and holed

**Quartz**
- Very large crystals
  - Largest 5+mm
  - Average large 2-3 mm
- Range of smaller 0.75 – 1.3 mm
- Some cracked
- Melt inclusions (devitrified and cracked)
  - One not cracked, with possible bubble
- Phenoclastic
- Subhedral or anhedral
  - Some almost euhedral broken
- Minor apatite and possible zircon

**Hornblende**
- Pleochroic brown to green
- Subhedral to anhedral shards
  - Some amphibole shapes
- Inclusions of oxides, plagioclase
- Plucked often
- Glomerophyric with self, pyroxene, oxides, quartz
- Twinned
- Found with pyroxene
  - Reaction relationship, pyroxene cores in hornblende
  - Crystals surrounding pyroxene
- Majority concentrated around a large, broken pyroxene “clast”
- Largest 2mm
  - Average size 0.5 – 0.75 mm
- Some in many broken pieces right next to each other, optically continuous but separate

**Biotite**
- Glomerophyric with pyroxene
- Euahedral and subhedral
- Inclusions of oxides and plagioclase
- Largest 3mm
  - Average range 0.25 to 1.5 mm
- No preferred orientation
- Some oxidization

**Fe-Ti oxides**
- From <<0.1 mm to 0.85
• Glomerophyric with hornblende, clinopyroxene, biotite

**Clinopyroxene**
- One especially large (4mm), broken, optically continuous one
  - Glomerophyric with two others, also large (1mm), broken
  - Surrounded by many small hornblende, oxides, quartz
- Sparse elsewhere
  - Small, subhedral crystals
  - Broken, some in reaction with hornblende
  - 0.25-0.50mm

**Groundmass**
- Glassy still
- Foliated slightly (flow?)
- Little crystals
- Altered with lots of calcite, some visible vesicles, some glass shards

**KNOLL-1-38-2**

**Plagioclase**
- Abundant calcite in cracks
- Largest 3mm
- Oscillatory zoning
- Mostly euhedral, most broken
- Apatite, zircon, hornblende, and oxide inclusions

**Quartz**
- Embayed, resorbed
- Largest: 1.5 mm
- Melt inclusions
- Rare apatite and zircon

**Biotite**
- Heavily altered
- Lots of oxide inclusion
- Layers of an individual biotite separated out by growth of calcite
- Pleochroic: red brown, light orange, nearly black
- Largest: 2mm

**Hornblende**
- Some faint optical zoning
- Small, typically less than 1mm
- Reaction rims
- Pleochroic green to red-brown
- Oxide inclusions

• Euhedral to anhedral

**Fe-Ti oxides**
- Glomerophyric with self
- <0.5 mm

**Clinopyroxene**
- None

**Groundmass**
- Flooded with calcite
- Devitrified
- Some bubble walls still visible

**KNOLL-1-40**

**Plagioclase**
- Twinned and zoned
- Broken, with euhedral edges to resorbed subhedral
- Melt inclusions, apatite, hornblende, zircon, oxides, clinopyroxene
- Inclusion-rich cores
- Some sieve texture
- Largest 3 mm
  - Several 2 mm
  - Most <1mm

**Quartz**
- Embayed, resorbed
  - Some crystal faces
  - Broken
- Inclusions: feldspar, oxides, self
- Several not as embayed as other sections
- Largest 2.5 mm
  - Several 2 – 1 mm
  - Most <1 mm

**Biotite**
- Some fresh, some quite altered
- Largest 2.5 mm
  - Some 2mm
  - Most <1 mm
- Inclusions: feldspar, oxides, self
- Light red-brown to dark red-brown
- Some {001} faces, most side on
- Some foliation

**Hornblende**
- One mantling an oxide
- Light orange to medium orange
- Glomerophyric with oxide, feldspar?
- In reaction with clinopyroxene
- Anhedral/broken
Very rare euhedral Fe-Ti oxides
- Rare hornblende mantles
  - ~1.5 mm
  - Largest 1 – 1.5 mm
  - Most <0.5 mm

Clinopyroxene
- All in reaction with hornblende
- Inclusions: oxides
- Most <0.5 mm

Groundmass
- Devitrified, clay-rich
  - Some calcite
- Faint foliation
  - Some slightly squashed pumices

Xenoliths
- Possibly from the microdacite
- Carbonate xenolith

KNOLL-1-9

Plagioclase
- Inclusions: hornblende, melt, apatite, zircon
- Largest 2 mm
  - Most <1 mm
- Sieve texture
- Broken, euhedral sides, resorbed some
- Rare glomerophyric with hornblende
- Some inclusion-rich cores
- Zoned, twinned

Quartz
- Embayed, broken
- Most resorbed, but some crystal faces
- Inclusions: zircon, feldspar, melt
- Largest 3.5 mm
  - Several 2.5 mm
  - Most <1 mm

Biotite
- Rare glomerophyric with plagioclase
- Inclusions: oxides, feldspar
- Largest 4 mm
  - Some 3-2 mm
  - Most <1 mm
- Orange to dark orange
- Shows foliation
  - Most are side-on
- Not badly altered

Hornblende
- Light brown to medium brown
- Simple twins
- Euhedral, often broken
- Inclusions: oxides
- Some glomerophyric with oxides and pyroxenes
- Largest 1.5 mm
  - Most <0.5 mm
- Some reaction relationship with pyroxene

Fe-Ti oxides
- Inclusions: hornblende, plagioclase
- Largest 0.75 mm
  - Most <0.5 mm

Clinopyroxene
- Often in reaction with hornblende
- Broken, resorbed
- Glomerophyric with oxides and hornblende
- Largest 1.5 mm
  - Most <0.5 mm

Groundmass
- Iron stained, but still glassy
  - Bubble wall shards
- Pumices

MWASH-1-1
Difficult to describe, many xenoliths, pumices, and altered gm. Interesting cracked textures, however.

Plagioclase
- Euhedral faces, typically broken (jigsaw)
- Twinned and zoned
- Melt inclusions, apatite, hornblende, zircon
- Largest 4 mm
  - Several 2-3 mm
  - Many <1 mm
- Some sieve textured

Quartz
- Melt inclusions, apatite
- Resorbed edges when not broken
- Often embayed
- Largest 2.5 mm
  - Several 1-1.5 mm
  - Many <1 mm
- Showing same jigsaw as plagioclase

Biotite
- Oddly sparse—altered away?
- Inclusions: oxides, feldspar, apatite
• Light orange to medium brown
• Badly altered to clays and oxides
• No real orientation

Hornblende
• Inclusions: feldspar, oxides, self
• Glomerophyric with self
• Pleochroic green to olive brown
• Some euhedral, but often broken
• Sometimes small crystals surrounding pyroxene
• Quite a few lathe-shaped
• Largest 1.5 mm
  o Many <0.5 mm

Fe-Ti oxides
• Blobby—looks like overgrown
• Often bunched with biotite, hornblende
• <0.5 mm
• Inclusions of feldspar

Clinopyroxene
• Some subhedral to euhedral
• Largest 0.8 mm
  o More <0.5 mm
• Glomerophyric with self, oxides
• Inclusions: feldspar, oxides, hornblende?

Groundmass
• Very altered to clays and some microlites
• Any banding obliterated

Pumice
• Very altered, but visible stretched vesicles
• Normal complement of phases and sizes
• +5mm largest

Xenoliths
• Microdacite
• Lava type (feldspar microlites)

MWASH-1-10

Plagioclase
• Complexly zoned, simple twins
• Inclusions: zircon, apatite, self
• Largest 2.5 mm
  o Some 1.5 – 1 mm
  o Many <0.5 mm
• Euhedral to subhedral
  o Often broken
• Melt inclusions
• Some sieve texture, often with euhedral crystal phases

Quartz
• Deeply embayed
• Melt inclusions
• Some crystal faces, but very embayed
• Some broken (phenoclastic)
• Several largest +3mm
  o Some 2 mm
  o Many <1mm

Biotite
• Orientated side-on
• Light orange brown to dark brown
• Some fresh
• Many with oxides
• Largest 3mm
  o Many <1.5 mm
• Inclusions: oxides, feldspar

Hornblende
• Light green to dark brown olive
• Euhedral to subhedral, many broken
• Simple twins
• Glomerophyric with self, oxides
• Inclusions: zircon, oxides
• Several largest 1mm,
  o Most <0.5 mm

Fe-Ti oxides
• Glomerophyric with hornblende
• Largest 1mm
  o Most <0.25 mm

Clinopyroxene
• Resorbed
  o Rare crystal sides, some broken pieces
• Simple twins
• Inclusions: oxides, feldspar, apatite
• Largest 0.75 mm
  o Many 0.5 mm
  o Most <0.25 mm

Groundmass
• Light brown, fairly altered
  o Occasional bubble wall shards
• All phases in tiny crystals
• Orientated in same direction as biotites
• Numerous pumices, squashed

MWASH-1-24

Plagioclase
• Zoned and twinned
Inclusions: apatite, hornblende, oxides, zircon, clinopyroxene, melt inclusions
- Euhedral to broken
- Some sieve textured
- Some with optical rims
- Largest 2.5 mm
  - Some 2 - 1.5 mm
  - Most <1 mm

Quartz
- Embayed, melt inclusion rich
- Resorbed
  - Some crystal faces, many broken
- Inclusions: zircon and apatite
- Largest 3mm
  - Many +2mm
  - Most <1 mm

Biotite
- Long and skinny
- Longest +4.5 mm, but only <0.25 mm thick
  - Most <1 mm
- Medium brown to dark
- Inclusions: feldspar, oxides

Hornblende
- Olive green to orange brown
- Often altered to oxides
- Inclusions: oxides, clinopyroxene (in reaction and as cores), apatite, zircon
- Simple twins
- Some euhedral sides, mostly subhedral and broken
- Largest 1 mm
  - Most <0.75 mm

Fe-Ti oxides
- Euhedral to subhedral
- Largest 0.75,
  - Most <0.5 mm

Clinopyroxene
- One with hornblende core, pyroxene rimming
- Many in reaction relationship with hornblende
- Inclusions: oxides
- Glomerophyric with oxides
- Mostly broken, some euhedral
- Largest 1 mm
  - Most <0.5 mm

Groundmass
- Pumice pieces, squashed
- Welded
- Small crystals
- Brown, moderately altered, some clays
- Little unaltered glass, mostly in pumices

MWASH-1-60

Plagioclase
- Euhedral to broken
- Largest 3.5 mm
  - Some 2.5-2 mm
  - Most <1 mm
- Inclusions: melt inclusions, apatite, hornblende
- Zoned and twinned

Quartz
- Deeply embayed, broken
  - But with some crystal faces (often resorbed)
- Largest 3 mm
  - Some 2 mm
  - Most <1 mm
- Melt inclusions
- Inclusions: apatite

Biotite
- Altered to clays and oxides
  - Especially between sheets
- Light orange to medium brown
- Some orientation, side on
- Inclusions: feldspar, oxides
- Largest (in squashed pumice) 4 mm, nearly square
  - Most long and skinny
  - Some 3 mm x 0.25 mm
  - Most <1.0 mm x <0.5 mm

Hornblende
- Green to light orange
- Some relatively clean, some altered with clays and oxides
- Inclusions: oxides, feldspar
- Largest 1 mm
  - Most < 1mm
  - Some euhedral, most broken

Fe-Ti oxides
- Inclusions: hornblende, feldspar
- Largest 1mm, most <0.5 mm

Clinopyroxene
- Simple twins
- Inclusions: oxides, hornblende
• Most <0.75 mm
  ○ Largest 2mm
• Also possible orthopyroxene
  ○ 2 mm

Groundmass
• Pumices (squashed, some visible stretched vesicles)
• Compacted
• Mostly devitrified, spherulites, clays
  ○ Very altered

MWASH-1-84
Plagioclase
• Complexly zoned, simple twins
• Inclusions: apatite, melt, amphibole, oxides
• Mostly broken, some crystal faces
• Largest 2.5 mm
  ○ Some 2 mm
  ○ Most <1 mm
• Some inclusion rich cores
• Some sieve textures

Quartz
• Largest 2mm
  ○ Some 1.5 mm
  ○ Most <0.75 mm
• Abundant melt inclusions
• Calcite in cracks
• Embayed, broken, some resorbed
  ○ Some quartz bi-pyramidal faces

Biotite
• Oxidized, altered
  ○ Clays between sheets, oxides
  ○ Calcite in cracks, between sheets
• Inclusions: oxides, feldspar
• Glomerophyric with plagioclase
• Dark red-brown to light brown
• Some orientation
• Largest 2.5 mm (square)
  ○ Most side on, larger 1.5 – 2mm x <0.5 mm
  ○ Most <0.5mm

Hornblende
• Often altered, rimmed with oxides
• Light orange to dark brown
• Some amphibole shapes, many broken
• Inclusions: oxides
  ○ In reaction with clinopyroxene, mantling

• Simple twins
• Largest 0.75 mm
  ○ <0.5 mm

Fe-Ti oxides
• One big 2.5 mm glomerocryst with equant plagioclase
• Inclusions: plagioclase
• Larger ones 0.7mm
  ○ Most <0.5mm

Clinopyroxene
• some in reaction to hornblende
• anhedral
• glomerophyric with oxides
• oxide inclusions
• largest 1.5 mm
  ○ most <0.5 mm

Groundmass
• Calcite infused
  ○ spherulites, clays
• devitrified
• anisotropic
• squashed pumices, also devitrified
  ○ some rare visible glass in pumices (bubble walls)

MWASH-1-97
Plagioclase
• zoned and twinned
• euhedral to broken, some resorbed
• inclusions: hornblende, melt, apatite, zircon
• some sieve textured
• largest 3.5 mm
  ○ some 2.5 – 2 mm
  ○ most <1 mm

Quartz
• melt inclusions, rare apatite
• embayed, resorbed, broken
  ○ some crystal faces
• largest 4 mm
  ○ several 2.5 – 3.5 mm
• most < 1mm

Biotite
• red brown to light orange brown
• some alteration/oxidation
• many lathe-shaped, some almost square
• inclusions: plagioclase, oxide
• very weak foliation
• largest 2.5 mm
Hornblende
- light orange to medium brown
- some altered, oxide-speckled
- some euhedral, many broken
- some in reaction with pyroxene
- largest 1.5 mm
  - most <0.75 mm
  - possible hornblende with hornblende core
- some 1.5 mm
- most <1mm

Fe-Ti oxides
- glomerophyric with self
- inclusions: feldspar
- largest 1 mm
  - most <0.5 mm

Clinopyroxene
- resorbed, some crystal faces
- inclusions: oxides
- often in reaction with hornblende
- largest 1.5 mm
  - most <0.25 mm

Groundmass
- not as calcite rich as 1-84
- devitrified, clay rich
  - not much glass left
- some (mostly devitrified) squashed pumices
- foliated

SHNG-4-21
Plagioclase
- Several inclusion rich
- Rare eaten by oxides
- Largest +3mm
  - Several +2mm
  - Most <1mm
- Inclusions: apatite, zircon, melt, self
- Most with crystal shape but broken
- A few sieve texture

Quartz
- Calcite in cracks
- Many deeply embayed
- Most resorbed, broken pieces
  - Some with crystal faces
- Largest +3 mm
  - Several 2.5 mm
  - Most <1 mm
- Melt inclusions
  - No visible accessory minerals

Biotite
- Dark brown-almost opaque to medium orange-brown
- Altered and oxidized
  - Calcite, clays, oxides between sheets
- Inclusions: apatite, oxides, feldspars
- Moderate foliation
- Largest 3 mm
  - Most <1mm

Hornblende
- Medium red-brown to light green
- Inclusions: feldspar, self
- Glomerophytic with self, oxides
- Many euhedral sides
  - Many broken
- Some alteration
- Rare clinopyroxene cores
- Largest 2 mm
  - Most <1mm

Fe-Ti oxides
- Some pumice
  - A few not squashed
    - Some rare glass (bubble wall shards) seen
  - Devitrified, clay-rich
  - Brown

Clinopyroxene
- Some in reaction with hornblende
- Most <0.5mm
- Broken

Groundmass
- Some pumice
  - A few not squashed
    - Some rare glass (bubble wall shards)
  - Devitrified, brown, clay-rich

Xenoliths
- Possible microdacite
  - Glomerophytic hornblende, clinopyroxene, oxides, with hornblende rimming it
- Lava-like clot of feldspar lathes, tiny euhedral hornblende, fairly altered
  - Without defined edges

SHNG-4-33.5
Interesting textures
**Plagioclase**
- Largest 3.5 mm
  - Many +2 mm
  - Most <1 mm
- Twinned and zoned
- Some with inclusion-rich cores
- Sieve texture with crystal faces
- Inclusions: hornblende, melt, and self
- Some embayed
- All types from broken but euhedral to anhedral

**Quartz** (many plucked)
- Largest +5 mm
  - Several 2 mm
  - Most <1 mm
- Embayed and resorbed
  - But not all broken
- Inclusions: zircon, rare apatite, melt inclusions
- Some bi-pyramidal sides

**Biotite**
- 3.5 mm largest
  - Some 1.5 mm
  - Most <1 mm
- Oxidized, altered to clays
- Some orientation, but all faces represented
- Light green to red brown
- Inclusions: feldspar, oxides

**Hornblende**
- In reaction with pyroxene
- Glomerophyric with self
- Red brown to light green
- Euhedral but broken
- Largest 4 mm
  - Several 1 mm
  - Most <0.75 mm
- One really big hornblende with large clinopyroxene core
  - 4 mm across

**Fe-Ti oxides**
- Largest 0.75 mm
  - Most <0.50 mm
- Inclusions: feldspar
- Mildly glomerophyric with amphibole

**Clinopyroxene**
- In reaction with hornblende
- Also stand alone
- Inclusions: oxides, feldspar
- Broken, resorbed
- Most <1 mm

**Groundmass**
- Foliated
- Brown
- Some altered, but large amounts of glass
  - Bubble walls, shards

**Xenoliths**
- Feldspar microlite lava?
  - Surrounded by spherulites
- Feldspar amphibole oxides in devitrified glass
  - ~1.5 mm
- Almost intrusive looking one (possible microdacite)
  - ~2 mm
  - Feldspar (inclusion rich (zircon, apatite, hornblende, oxides), sieve texture, eaten, embayed), oxide speckled, euhedral hornblendes

**SHNG-4-34**

**Plagioclase**
- Largest 2.5 mm
  - Some +2 mm
  - Most <1 mm
- Zoned and twinned
- Inclusions: clinopyroxene, hornblende, apatite, oxides, melt
- Some euhedral, some resorbed, some broken
- Some sieve texture (inclusion rich)

**Quartz**
- Euhedral, broken, many resorbed
- Embayed
- Zircon accessory
- Melt inclusion
  - Several with inclusions of hornblende
- Largest 3 mm
  - Several 1.5 mm
  - Most <1 mm

**Biotite**
- Light green to red-brown
- Altered
  - Calcite between sheets
- Inclusions: feldspar, apatite, oxides
- Euhedral
• All faces, but majority side-on
• Some anisotropy
• Largest 3.5 mm
  o Several 2-3 mm
  o Most <1 mm

Hornblende
• Light green to red-brown
• Some with pyroxene cores
  o In reaction relationship with pyroxene
• Glomerophyric with self
• Largest 1.5
  o Most <1mm
• Many with euhedral sides, several broken

Fe-Ti oxides
• Often glomerophyric with hornblende
• Inclusions: feldspar
• Largest 2 mm
  o Most <0.75 mm

Clinopyroxene (often plucked)
• Some in reaction relationship with hornblende
• Some not
• Euhedral to broken

Groundmass
• Foliated
• Devitrified
  o No visible glass
• Brown

Xenoliths
• Microdacite
  o Hornblende with clinopyroxene and oxides

SHNG-4-42
Plagioclase
• Rarely glomerophyric with self
• Inclusions: melt, zircon, apatite, self
• Zoned and twinned
• Many broken, but several crystal faces
  o Some corroded edges
• Some sieve textures
• Largest 4 mm
  o Several 2-3 mm
  o Most <1 mm

Quartz (often plucked)
• Resorbed
  o But still visible crystal faces
  o Embayed
• Largest ~3 mm (probably larger, but plucked)
  o Several 2 – 2.5 mm
  o Most <1 mm

Biotite
• Somewhat altered
  o Calcite between sheets
• Not foliated
  o All crystal faces seen
• Green to orange-brown
• Inclusions: plagioclase, oxides
• Largest 2.5 mm
  o Most <1mm
• Rare glomerophyric with amphibole, biotite, oxides, feldspar

Hornblende
• Rimmed with oxidation
• Dark orange to light brown
• Broken euhedral to subhedral
• Some in reaction with pyroxene
• Inclusions: feldspar, oxides
• Largest 1.5 mm
  o Most <1mm

Fe-Ti oxides
• Largest 0.75 mm
  o Most <0.5 mm
• Inclusions: plagioclase

Clinopyroxene
• Often in reaction with hornblende
• Inclusions: hornblende, oxides, feldspar
• Broken, resorbed
• Largest 0.75 mm
  o Most <0.5 mm

Groundmass
• Devitrified
• Brown
• Some foliation
• Squashed pumices

Xenolith
• Microdacite
  o ~4mm

SHNG-4-6
Moderate plucked grains
Plagioclase
- broken, but crystal faces still visible
- twinned and zoned
- inclusions: apatite, zircon, hornblende, devitrified and non-devitrified melt, oxides
- glomerophyric with self
- largest 3 mm
  - many 2.5–1.5 mm
  - more <1 mm

Quartz (often plucked)
- embayed
  - some deeply
- resorbed edges, broken
- inclusions: melt, rare zircon
- largest 3.5 mm
  - several 2.5 mm
  - most <1 mm

Biotite
- quite a bit of oxidization (tiny oxides and calcite between sheets)
- dark brown-red to light green brown
- inclusions: feldspar, oxides
- glomerophyric with plagioclase
- no orientation, all faces of biotite seen
- largest +2 mm
  - some 2 mm
  - most <1 mm

Hornblende
- light green to red brown
- calcite in cracks, dark rimmed
- inclusions: oxides, feldspars, clinopyroxene, self
- Euhedral
  - many broken
- largest 2 mm
  - many little euhedral <0.5 mm

Fe-Ti oxides
- several glomerophyric with self or biotite
  - clotted together
- largest 1.5 mm
  - most <0.5 mm

Clinopyroxene (often plucked)
- Euhedral shape
- some cores of hornblende
  - in reaction with hornblende
- some stand alone

Groundmass
- not strongly foliated
  - Pumices show some compaction, elongation
  - devitrified
    - altered to clays
    - no glass

Xenolith
- microdacite
  - clot of hornblende, pyroxene, quartz, feldspar, oxides
  - 3 mm

SHNG-4-63
Plagioclase
- Inclusion rich cores
- Inclusions: melt, apatite, self, zircon, hornblende
- Euhedral but broken
- Some severely corroded
- 2.5 mm largest
  - Many 1-2 mm
  - Most <1 mm

Quartz
- Embayed, resorbed, some crystal sides
- Melt inclusions
- Largest 2.5 mm
  - Some 1.5–2 mm
  - Most <1 mm

Biotite
- Badly altered to clays, oxides, and feldspars
- Inclusions: feldspars, oxides
- Dark red-black to medium brown
- Anisotropic, but all faces visible
- Largest 3 mm
  - Several 2 mm
  - Most <1.5 mm

Hornblende
- Altered severely
  - Dark oxidized rim around most
- Red brown to orange brown
- Broken, but many with euhedral sides
- Inclusions: feldspar, oxides, clinopyroxene
- Rare glomerophic
- Several with clinopyroxene cores
- 2 mm largest
  - most <1 mm

Clinopyroxene
- few euhedral, most broken
- largest 2 mm
• most <0.5 mm
• some in reaction with hornblende, some not
• inclusions: oxides

**Groundmass**
• no glass
  • completely devitrified
  • brown
  • altered to clays
• some squashed pumices
• faint anisotropy

**SHNG-4-78**

**Plagioclase**
• largest 2.5 mm
  • few 1-2 mm
  • most <1mm
• zoned and twinned
• inclusions: melt, apatite, zircon, clinopyroxene, hornblende, oxides
• some sieve textured
• some inclusion-rich cores
• often broken
  • many with euhedral rims

**Quartz**
• melt inclusions (some devitrified), apatite
• embayed, resorbed
• some calcite in cracks
• typically broken
• 2.5 mm largest
  • Few 1-2 mm
  • Most <1 mm

**Biotite**
• Inclusions: oxides, feldspar
• Oxidized and altered to clays
• Red brown to brown
• Isotropic, mostly
  • All faces seen
• Largest 2.5 mm
  • Most lathes, <1mm

**Hornblende**
• Euhedral but often broken
• Altered and rimmed with oxides
• Inclusions: oxide, zircon, feldspar
• 1.5 mm largest
  • Most <1 mm

**Fe-Ti oxides**
• Sometimes blobby

• Largest <0.5 mm

**Clinopyroxene**
• Some cores of hornblende
• Inclusions: feldspar, oxide, hornblende
• Resorbed, broken, few euhedral
• Largest 1.5 mm
  • Most <1 mm

**Groundmass**
• Not foliated
• Some pumice
• Devitrified
  • No glass
• Altered to clays
  • Brown

**Xenolith**
• Feldspar, hornblende, oxides, and calcite/clays

**WARM 4P**

**Plagioclase**
• Some glomerophyric with self
• Cracked (some)
• Twinned (Carlsbad as well as polysynthetic)
• Oscillatory zoned
• Sieve texture—maybe a lot of bubbles or melt inclusions?
• Melt inclusions—some cracked
• Cores
  • Some optically different than rims
  • Some with hornblende and clinopyroxene blebs
• One glomerocryst +5mm
  • Average size from 0.25mm to 3mm
• Euhedral to subhedral

**Quartz**
• Some crackled quartz
• Largest 3mm
  • Average range 0.5mm to 2mm
• Subhedral
  • Some almost euhedral but embayed
• Melt inclusion—phenocryst
• Minor apatite inclusions
• Some have large glass shards in cracks

**Biotite**
• Maximum size 1mm
  • Average 0.25 to 0.75 mm
• No specific preferred orientation
Some on sides, some hexagons
- Euhedral to subhedral
- Inclusions of feldspar, oxides, quartz (?)
- Oxidized some—especially those on hexagonal face

**Hornblende**
- Pleochroic green to green brown
- Twinned
- Some cores of pyroxene
- Often plucked
- Sparse
- Largest 1mm
  - Average size 0.25mm
- Inclusions of feldspar, oxides
- Anhedral

**Fe-Ti oxides**
- Largest 0.5mm
  - Most <0.25
- Round, blobby
- Inclusions of pyroxene and feldspar

**Clinopyroxene**
- Glomerophyric with biotite, oxides
- Altered to oxides
- In reaction with hornblende (cores of hornblende)
- A few euhedral
  - One at least 1mm

**Groundmass**
- Foliated
- Frothy
- Small calcite specks throughout

**WARM-2P**

**Plagioclase**
- between ¼ - 1 mm, largest 1.5 mm, about 6-7 around that size
- Oscillatory zoned, twinned
- Euhedral to subhedral, some anhedral
- Zircons and apatite
- Some with cores of different composition, core with hornblende blebs and pyroxene blebs
- Some melt inclusions, some even with bubbles!
- A few mildly glomerophyric
- Not very altered
- Clean

**Quartz**
- Several 1.5 mm big, not many in 0.5-1 mm range
  - Not many smaller (<0.5mm) fragments
- Euhedral to subhedral
- Many with melt inclusion holes (some with large vesicular glass inside, exploded
  - Cracks radiating from bubbles
- Apatite and zircon
- Some crystals held together by glass shards
- One with amp/clinopyroxene above or in it
- Isotropic

**Biotite**
- Pleochroic orange brown to brown
- Compacted—few to none anything but side-on
- Some with Fe-Ti oxides inclusions, plagioclase (or sometimes unidentified feldspar)
- Euhedral, some subhedral
- Range ½ to 1mm, some as big as 1.5mm, in length, few wider than ¼ mm

**Hornblende**
- Pleochroic green brown to brown orange
- Some with euhedral, some not
- Twinning
- Euhedral to anhedral, most sub to an
- Majority ¼ to ½ mm, some (biggest) still <1mm
- Typically clean
- Not as directional as biotite
- Some associated with clinopyroxene, some with Fe-Ti oxides

**Fe-Ti oxides**
- Range <<1/4 to 0.5mm (just one that big), most ¼ or smaller
- Blobby, associated with amp and biotite and groundmass

**Clinopyroxene**
- Rare, associated with amp
- Sub to anhedral
- <1/2 mm

**Groundmass**
- Foliated
- Fairly glass still
- Several plucked areas
- Vesicles, small crystals
• Altered in some areas,

**WARM-3-(-2)**

**Plagioclase**
- zircon and apatite
- broken, resorbed, some with some euhedral sides
- majority between .4 to .6mm (range from .2 to .8mm)
- oscillatory zoned, twinned

**Quartz**
- broken, few with crystal sides
- not many seem to be embayed, but a few are
- melt inclusions
- ave. 4. to .6mm

**Biotite**
- lying on edges
- ave. length: .7mm
- longest: 1.5mm
- many undulatory
  - murky, with Fe-Ti oxides
  - some with quartz veining in cleavage
  - some with oxide rims

**Hornblende**
- not many amp-shaped ones
- less euhedral than other samples
- broken/bits
- some with Fe-Ti oxides, most clear
- few with clinopyroxene cores
- range from .2 to .4mm
- zircon

**Fe-Ti oxides**
- gm size
- also phenocrysts .2 to .4mm

**Clinopyroxene**
- broken, resorbed bits of clinopyroxene
- Rarely with hornblende
- some with oxides on
- ~.2mm

**Groundmass**
- quite altered/devitrified brown-grey
- some bubble wall glass shards visible
  - but few Y-shaped shards, most are simple arcs
- Fe-Ti oxides
- small bits of murky crystals
- still, a lot of the gm is glass
- apatite
  - starting to devitrify, lots of voids
  - some with large pieces of plagioclase

**Xenoliths**
- volcanic rock

**WARM-3-2**

**Plagioclase**
- twinned oscillatory
- majority euhedral but broken
- some very embayed
- majority .7mm to 1.3mm
  - some 2.5-3mm
- some with inclusion rich cores (plagioclase, hornblende)
- apatite and zircon
  - glomerophyric with self

**Quartz**
- very embayed
- some crackled
- melt inclusions
- larger phenocrysts (>2mm)
- many have some euhedral edges
- broken
- larger pieces around 1mm
  - smaller less than .7mm
- melt inclusions

**Biotite**
- couple of big <2mm pieces
- majority around 1mm
- not very altered
- many lying on edges as always
- some broken, mostly laths
- Fe-Ti oxides, plagioclase, quartz inclusions
- quartz in fractures and cleavages
- glomerophyric with hornblende

**Hornblende**
- ~1mm, largest 2mm
- glomerophyric with biotite
- fairly fresh
- many in rough amp shape, many in angular form
- some broken, many euhedral
- several with pyroxene core
- twinned
• many with slightly “eaten” holes in centers
• many Fe-Ti oxide inclusions with quartz
• zircon inclusions?
• apatite, too
• also some resorbed (possibly embayed)

**Fe-Ti oxides**
• many black sort-of hexagonal shapes
• about .4-.5mm
• with little white crystals insides
• some reddish ones

**Clinopyroxene**
• some highly fractured
• euhedral but broken and embayed
• <1mm

**Groundmass**
• glass wall bubble shards
• partially devitrified
• small bits of crystals
• some calcite

**Sanidine?**
• one piece, almost uniaxial negative
• two hornblende inclusions, one with a Fe-Ti oxide
• euhedral, but broken and possibly embayed
• 1.2mm long
• in upper 1/3 left center of slide

**WARM-3-25**

**Plagioclase**
• biggest 3mm, majority around 1-.7mm
• some melt inclusions
• some with inclusion-rich cores (hornblende, biotite)
• apatite, zircon
• oscillatory, twinned
• embayed, broken
• somewhat glomerophyric

**Quartz**
• majority of the big ones around 2mm, some as big as 3-3.5mm
  • small ones <1mm
• melt inclusions, some glass
• embayed
• some with crystal shapes—euhedral
• some anhedral
• broken, too—with pieces lying right next to each other

**Biotite**
• with plagioclase and Fe-Ti oxides
• many on edges, as ever
• quartz in seams along planes
• majority ~1mm
  • some as big as 2mm
• some broken, many just laths

**Hornblende**
• a few altered to reds
• Zircon, Fe-Ti oxides, quartz inclusions
• euhedral amp shape as well as subhedral
• some broken with pieces lying right next to each other
• lots of tabular pieces
• twinned
• majority <1mm, ~.5mm, some as big as 1.2mm

**Fe-Ti oxides**
• majority .3mm
• typically six sided shape

**Clinopyroxene**
• mostly anhedral, one or two euhedral
• some surrounded, eaten by hornblende
• some not in reaction with hornblende
• <1mm

**Groundmass**
• bubble wall glass shards, partially devitrified
• Fe-Ti oxides
• has calcite
• slightly foliated—just the biotites
• groundmass altered about the same as WARM-3-40T
• Pumices
  • large—one big one right on the edge 4mm across
  • devitrifying
  • plagioclase, hornblende
  • most around 1-1.5mm

**Sanidine**
• <1mm, about .7mm
• euhedral
• sitting right on the optic axis, very nice
• complexly zoned
• has an apatite in it
• very fresh
• I think there was only the one
Xenoliths
- sparkly quartz one
- limestone one—calcite
- igneous rock

WARM-3-40P

Plagioclase
- broken
- zoned oscillatory twinned
- glomerophyric with clinopyroxene and self
- from 1mm to +4mm
- most around 2.5mm
- inclusion rich core, hornblende, clinopyroxene

Quartz
- largest 2.5mm, ave size about 1mm
- embayed
- subhedral
- few melt inclusion

Biotite
- broken
- plagioclase and oxide inclusions
- zircon
- glomerophyric with pyroxene
- cleavage filled with quartz
- about 1-3mm in size
- several opaque with Fe-alteration

Hornblende
- twinned
- phenoclastic
- about 1mm

Fe-Ti oxides
- less euhedral ones
- but still some six-sided
- many blobby ones
- .5mm or less

Clinopyroxene
- often glomerophyric with plagioclase and biotite
- broken subhedral-euhedral
- one with messed up rim
- inclusions of Fe-Ti oxides
- <1mm mostly

Groundmass
- Ample calcite
- Crystals relatively clean

- Some iron staining
- Calcite in phenocryst cracks

WARM-3-40T

Plagioclase
- twinned and zoned like others—tarten twinning?
- majority 1.5mm or less, but some as big as 4mm long
- inclusions of hornblende, zircon, apatite
- Melt inclusions
- most are broken, many embayed
- euhedral to subhedral
- glomerophyric with self

Quartz
- crackled quartz (splotchy, marbely)
- melt inclusions (some with crystals, some with glass)
  - cracked around the inclusions
  - apatite inclusions
  - broken and embayed—euhedral-subhedral or completely broken
    - rarely resorbed
  - majority 1.5-1mm, some as big as 4mm
  - some fractures “healed” by calcite

Biotite
- glomerophyric with feldspar, Fe-Ti oxides
  - lying on edges
  - 1mm long to .5mm long, majority
  - some as big as 2-2.5mm long
  - some altered to opaque reds and browns
  - inclusions: feldspar, oxides, hornblende

Hornblende
- has inclusions of feldspars, Fe-Ti oxides
- some euhedral, quite a lot of fragments
- majority around <1mm
- several altered to opaque reds

Clinopyroxene
- glomerophyric with hornblende and self
- altered to hornblende, Fe-Ti oxides
- twinned
- plagioclase inclusions
- biggest 1mm
- most <.7mm

Groundmass
- altered
- calcite
• partially devitrified
• slightly foliated
• bubble wall shards
• small crystals
• calcite
• Some secondary silica filling little cracks
• More alteration in groundmass—calcite quite a bit more
• Pumice
  • some slightly oriented in same direction as biotites
  • much altered to calcite
  • devitrifying
  • minerals: clinopyroxene, hornblende, feld, quartz

Xenoliths
• limestone? calcite rich
  • resorbed
  • small <.5mm

**WARM-3-58**

**Plagioclase**
• from 3.5mm to <.5mm, majority 1mm
• apatite and zircon
• twinned (both)
• some oscillatory zonation
• melt inclusions (some growth bubbles on optic boundaries)
• some with inclusion of hornblende or biotite
• glomerophyric with selves
• more broken than embayed, but both present

**Quartz**
• majority 1mm, but range from 3.5 to <.5mm
• melt inclusions—some crystallized now, some just glass
• some with crystal sides
• most broken (phenoclastic)
• many embayed
• not undulatory
• some (few) resorbed

**Biotite**
• 3mm max, majority 1.5mm
• a lot on their sides, again
• inclusion: Fe-Ti oxides, quartz, plagioclase (feldspar, some), seams of quartz cleavage, euhedral, mostly not really that broken

• some altered completely red-brown

**Hornblende**
• majority .3mm, some as big as .7 to 1mm
• has inclusions: quartz, empty holes, Fe-Ti oxides
• several altered
• red brown
• euhedral to subhedral

**Fe-Ti oxides**
• everywhere—in groundmass, in crystals, in phenocrysts
• mostly .7mm some much smaller

**Clinopyroxene**
• altered to hornblende
• small <.7mm
• euhedral to subhedral (broken)
• Fe-Ti oxides, too
• twinned

**Groundmass**
• slightly foliated
• bubblewall shards
• small pieces of biotite, hornblende, plagioclase, quartz
• partially devitrified
• alteration (some) calcite
• pumice
  • largest about 1.5-2mm
  • plagioclase and hornblende phenocrysts inside
  • slightly devitrified

**Xenoliths**
• igneous
• intrusive or volcanic

**WARM-3-70**

**Plagioclase**
• from <.5mm to 3mm
• little rows of bubbles (melt inclusions) following the growth rings
• polysynethetically twinned, carlsbad twinned
• glomerophyric with selves
• some embayed, some broken
• inclusion-rich core (the inclusions have melt inclusions?)
  • blobby clinopyroxene and biotite inside largest plagioclase crystal
• Zircon, apatite, biotite, oxides, clinopyroxene
- melt inclusions (partially crystallized)
- complexly zoned, oscillatory
- largest 3mm, most <1 mm
- Euhedral crystal faces, broken, majority subhedral. Size doesn’t matter—euhedral small ones, large broken ones, and vice versa
- One sieve textured plagioclase clumped with a biotite that is sieve, too, with lots of Fe-Ti oxides—cognate inclusion autolith? Edged by brown rust, with frothy pumice on one edge

**Quartz**
- from <.5mm to 2mm
- some embayed features
- melt inclusions (still glass? Good possibility)
- one shaped like a hexagon, with edges, mostly (2mm across)
- minor accessory apatite
- not undulaty
- phenoclastic
- resorbed edges/broken angular

**Biotite**
- abundant
- majority euhedral, some anhedral long, skinny laths
- sizes 3mm long
  - Typically thin .5mm)
- 2-3mm long, only <.5mm wide
- some not in lath shape
- some oxidized, reddish

**Hornblende**
- pleochroic green brown, to brown, or red-brown to brown
- subhedral to euhedral
- .5mm or smaller, majority, largest .7mm or so
- might be magmatic alteration—picture

**Fe-Ti oxides**
- .2mm to .4mm
- some up to .5mm or .6mm
- anhedral

**Clinopyroxene**
- sparse
- largest .5mm down to .2mm or so
- subhedral to euhedral
- cleavage somewhat obvious

- some are in reaction relationship with hornblende

**Groundmass**
- Some alternation (calcite/clays)
  - phenocrysts quite fresh (some of the biotite is altered).
- Slightly anisotropic (biotites)
  - foliated
- Non-welded
- Pumices aren’t compacted at all or only slightly
- Partially devitrified
- Bubble wall glass shards
- Pumice, feldspar, small hornblende and biotite bits
- Pumices
  - 2-3 mm across or smaller
  - minerals
    - Fe-Ti oxides, clinopyroxene (brown), hornblende, plagioclase (embayed and broken)
  - tube vesicles

**WARM-3-87**

**Plagioclase**
- ~1mm majority
- twinned
- banded oscillatory zoning
- broken
- melt
- apatite/zircon
- some embayment
- subhedral broken

**Quartz**
- melt inclusions
- apatite
- <4mm, majority around 1.5-2mm
- sometimes embayed
- sometimes corner and edges speckled
- broken and embayed crystals
- subhedral

**Biotites**
- ~3.5mm, majority 2mm long
- often have large plagioclase inclusions
- again many on edges
- sometimes altered to Fe-Ti oxides
  - oxidation
- reaction relationships
Hornblende
- Largest 1.2mm majority ~.5mm
- Sometimes altered to Fe-Ti oxides
- Mingled with clinopyroxene (altered the clinopyroxene)
- Majority sub to anhedral
- Some twinning
- Some alteration—reddish

Fe-Ti oxides
- Mag?
- <.5mm
- Clumpy sometimes

Clinopyroxene
- Not stable
- ~1mm
- Reaction relationship with hornblende

Groundmass
- Bubble wall shards
- Small shards and pieces of crystals: feldspar, quartz, mag, hornblende
- Description
- Some devitrification
- Slight foliation
- Some carbonates
- The crystals are fresh
- Some secondary silica
- Pumices
  - Not squashed

Xenoliths
- Small light brown speckled lithics
- Resorbed and broken—limestones??
  - Carbonates in them
Appendix C1. Core-to-rim electron microprobe traverses across plagioclase phenocrysts.
Appendix C1. (cont.) Core-to-rim electron microprobe traverses across plagioclase phenocrysts.

Transects without photomicrographs
Appendix C2. Anorthite in plagioclase by sample.

- **ATL-1-70-1P-3**: Evolved juvenile clast.
- **GOUGEWLI-1-5P-1**: Less evolved juvenile clast.
- **GOUGEWLI-1-5Pb-Pumice**: Less evolved juvenile clast.
- **GOUGEWL-1-5Pb-Microdiorite**: Microdacite juvenile clast.
- **ATL-1-70-1P-3**: Tuff.
- **KNOLL-1-38-2**: Less evolved juvenile clast.
- **GOUGEWLI-1-5Pb-Microdiorite**: Tuff.
- **GOUGEWLI-1-1**: Tuff.
- **HAM-1V**: Tuff.
- **KNOLL-1-9**: Tuff.
- **SHNG-4-34**: Tuff.
- **WARM-3-25**: Tuff.
Appendix D1. Electron microprobe traverses across amphibole phenocrysts from the Cottonwood Wash Tuff ignimbrite and juvenile clasts.
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Appendix D2. Electron microprobe traverses across amphibole phenocrysts from the Cottonwood Wash Tuff ignimbrite and juvenile clasts. (Without photomicrographs.)