Cumulates in Rhyolitic Ignimbrites: Hidden in Plain Sight

Table DR1: Proportions of phases in crystal aggregates in Snake River Plain rhyolites. * indicates that an assumed composition for this phase is used in calculations; assumed compositions are detailed in Table DR3. Phase proportions are calculated via backscattered images or photomicrographs (provided below) with areal proportions calculated using the ImageJ software.

Unit	**Mineral proportions (%)**					
	Glass	**Plagioclase**	**Pigeonite**	**Augite**	**Ilmenite**	**Magnetite**
Thorn Creek 1	0.0	67.5	19.0	3.4	1.7	8.4
Thorn Creek 2	1.0	69.0	21.5	7.0	0.0	1.5
Thorn Creek 3	0.0	36.9	41.2	8.4	3.4	10.1
CPT XIII	0.0	45.8	0.0	52.4	0.0	1.7
Dorsey Creek	2.1*	61.9*	23.5	6.7	0.0*	5.8*
Gwin Spring 1	0.0	73.2	17.6	1.7	0.0	7.5*
Gwin Spring 2	0.0	36.7	30.9	21.1	0.0	11.8*
Gwin Spring 3	1.9	7.8	79.6	2.7	0.0	8.0*
Gwin Spring 4	0.0	76.8	14.0	7.4	0.2	1.5*
Tuff of Knob 1	7.1	0.0	59.3	3.0	0.0*	30.6*
Tuff of Knob 2	0.0	84.6	9.0	5.3	0.2*	0.8*
Tuff of Knob 3	8.2	0.0	0.0	87.3	0.0*	4.5*
Tuff of Knob 4	7.2	27.2	50.5	0.0	5.0*	10.1*
Tuff of Knob 5	13.6	0.0	61.7	0.0	0.8*	23.9*
Tuff of Knob 6	5.10	0.0	44.78	47.50	0.0*	2.60*
Three Creek	0.0*	69.7*	15.6	8.0	0.1*	6.5*
McMullen Creek 1	0.0	45.6	35.1	19.2	0.0*	0.0*
McMullen Creek 2	3.1	0.0	44.5	48.4	0.0*	3.9*
Wooden Shoe 1	0.0	59.1	20.4	14.5	0.0*	6.0*
Wooden Shoe 2	0.0	63.2	24.8	7.9	0.0*	4.1*

Table DR2: Compositions of aggregates in Snake River Plain rhyolites.

Unit	Composition (wt.%)										
	SiO_2	TiO_2	MgO	MnO	Al_2O_3	FeO	CaO	Na_2O	K_2O	Cr_2O_3	Total	Alkalis
Thorn Creek 1	49.72	2.17	2.91	0.23	18.57	13.76	7.21	4.08	0.60	0.00	99.30	4.68
Thorn Creek 2	53.63	0.31	3.57	0.23	18.89	9.33	8.08	4.18	0.60	0.00	98.84	4.78
Thorn Creek 3	46.00	3.33	6.38	0.47	10.48	23.44	6.37	2.27	0.60	0.00	99.13	2.87
CPT XIII	53.65	0.56	2.12	0.34	10.86	1.69	11.77	3.42	0.76	0.00	99.33	3.42
Dorsey Creek	52.74	1.25	2.74	0.36	16.19	14.38	6.72	4.10	0.81	0.00	99.35	4.91
Gwin Spring 1	52.81	1.54	1.76	0.23	18.66	12.27	6.40	4.86	0.74	0.01	99.27	5.60
Gwin Spring 2	47.48	2.49	4.42	0.53	9.77	24.57	7.56	2.49	0.37	0.01	99.68	2.86
Gwin Spring 3	46.68	1.78	7.45	0.87	2.72	34.04	4.92	0.62	0.20	0.01	99.28	0.82
Gwin Springs 4	55.99	0.39	1.82	0.20	19.52	8.06	7.39	5.11	0.78	0.00	99.26	5.88
Tuff of Knob 1	36.04	6.17	6.03	0.65	1.63	43.75	3.36	0.24	0.40	0.02	98.28	0.64
Tuff of Knob 2	57.76	0.32	1.30	0.11	21.04	5.34	6.79	5.40	1.53	0.00	99.58	6.93
Tuff of Knob 3	49.75	1.22	7.20	0.50	1.79	23.36	14.83	0.40	0.47	0.01	99.50	0.86
Tuff of Knob 4	46.57	4.58	4.88	0.49	7.99	27.46	4.20	1.96	0.90	0.01	99.03	2.85
Tuff of Knob 5	40.66	5.26	5.99	0.63	2.29	39.49	3.03	0.41	0.76	0.02	98.52	1.17
Tuff of Knob 6	49.54	0.81	8.15	0.63	1.26	28.30	10.18	0.26	0.29	0.01	99.42	0.55
Three Creek	52.92	1.44	2.16	0.27	17.91	12.41	7.10	4.55	0.77	0.00	99.55	5.32
McMullen Ck 1	54.01	0.16	5.02	0.57	11.40	16.19	8.42	2.96	0.45	0.00	99.22	3.41
McMullen Ck 2	48.80	1.05	8.44	0.92	1.07	28.53	10.28	0.22	0.19	0.01	99.55	0.41
Wooden Shoe 1	52.74	1.28	4.44	0.31	14.70	13.05	7.88	3.89	0.72	0.01	99.05	4.61
Wooden Shoe 2	53.98	0.90	4.33	0.31	15.59	11.85	7.20	4.14	0.76	0.01	99.08	4.90

Table DR3: Assumed compositions and justifications

Mineral	Composition (wt.%)										
	SiO_2	TiO_2	MgO	MnO	Al_2O_3	FeO	CaO	Na_2O	K_2O	Cr_2O_3	Total	Alkalis
Glass	77.25	0.29	0.04	0.02	11.94	1.38	0.53	2.38	6.07	0.00	99.90	8.45
Plagioclase	59.23	0.03	0.00	0.00	25.33	0.43	7.22	6.48	1.11	0.00	99.83	7.59
Ilmenite	0.07	49.04	0.86	0.67	0.15	47.28	0.02	0.00	0.00	0.01	98.09	0.00
Magnetite	0.13	19.57	0.56	0.52	1.55	73.29	0.04	0.00	0.00	0.06	95.71	0.00
Pigeonite	49.76	0.23	11.40	0.86	0.45	32.94	4.06	0.06	0.00	0.01	99.75	0.06
Augite	50.20	0.36	8.46	0.57	0.89	21.58	17.52	0.24	0.00	0.01	99.82	0.24

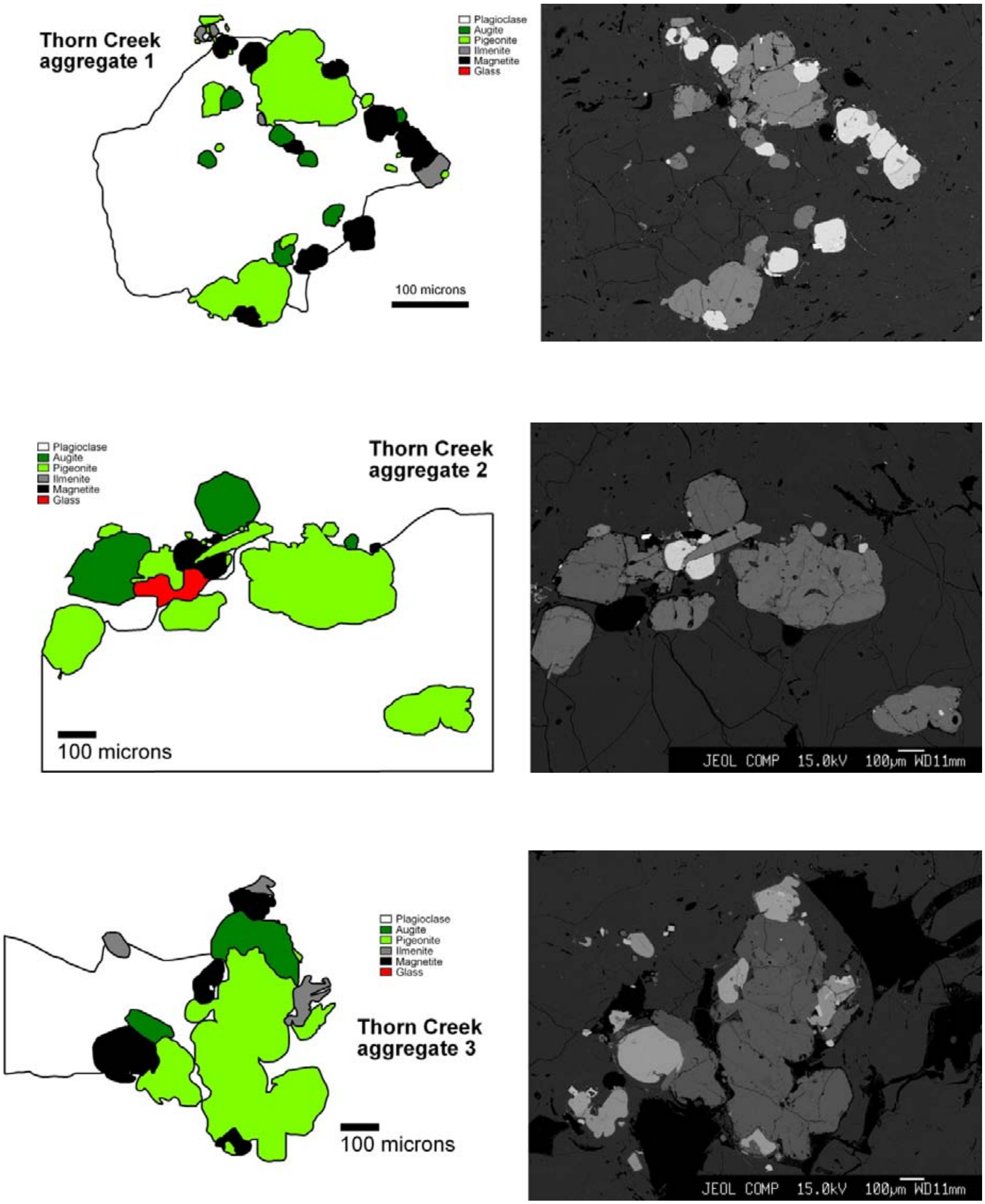
Phase	Source
Glass	Average glass composition of 169 analyses from the East Bennett Mountains from 7 ignimbrites spanning 2 Ma. Data illustrated in Figure 2
Plagioclase	Average of 539 plagioclase analyses from the same 7 ignimbrites of the East Bennett Mountains
Ilmenite	Average composition from the Cougar Point Tuff succession, 10 ignimbrites erupted over ~ 2.5 Ma, from Cathey and Nash (2004)
Magnetite	Average composition from the Cougar Point Tuff succession, 10 ignimbrites erupted over ~ 2.5 Ma, from Cathey and Nash (2004)
Pigeonite	Average composition of 480 pigeonites from the East Bennett Mountains from 7 ignimbrites over 2 Ma
Augite	Average composition of 284 augite analyses from the East Bennett Mountains from 7 ignimbrites over 2 Ma

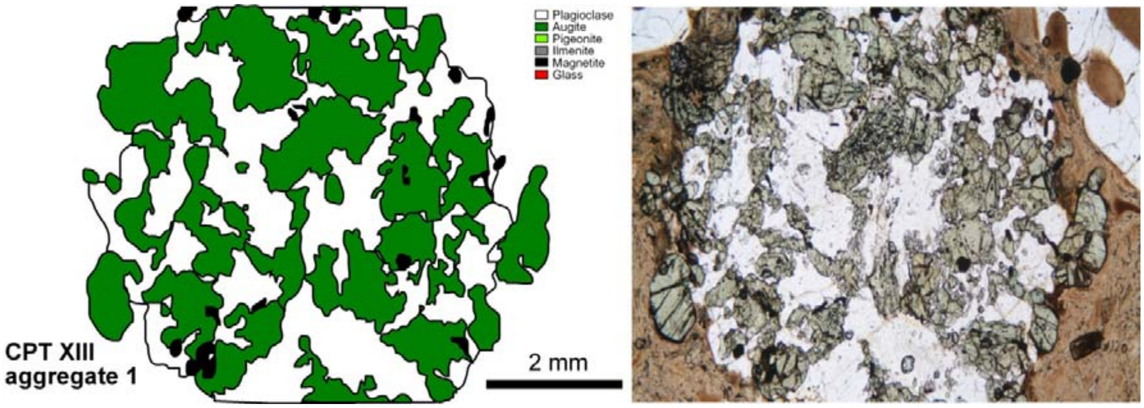
In the cases of using assumed compositions, the relative differences in mineral compositions between the rhyolites of the CSRP are slight when compared to the importance of the proportion of phases in terms of plagioclase and glass as opposed to the mafic component

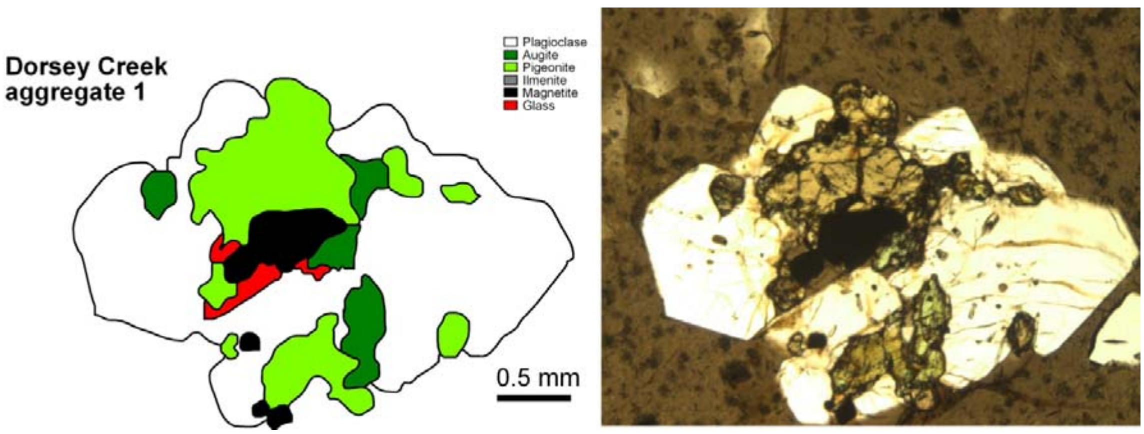
Table DR4: Examples of some representative pyroxene compositions (all in wt.%) from selected units used in this study, (p) represents pigeonite and (a) represents augite.

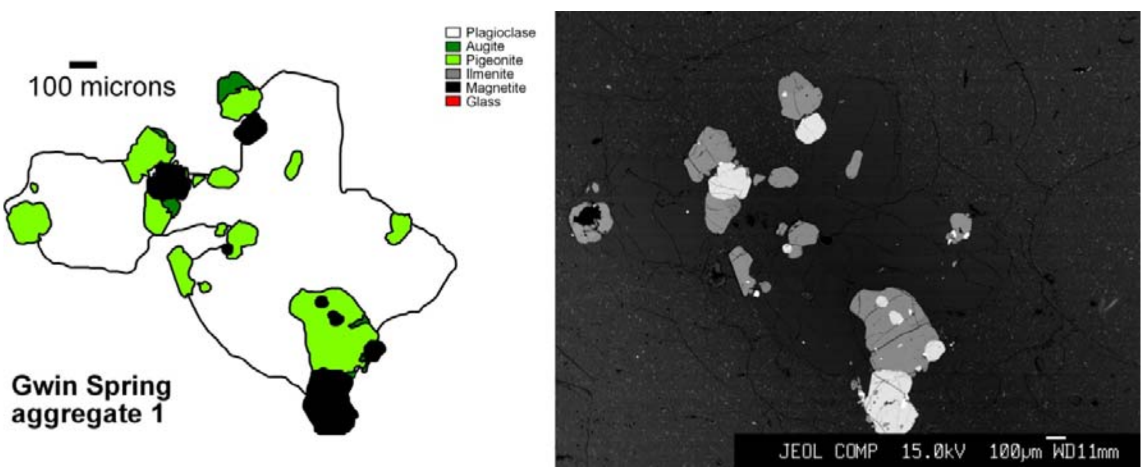
Unit	SiO_2	TiO_2	MgO	MnO	Al_2O_3	FeO	CaO	Na_2O	Cr_2O_3	Total
Three Creek (p)	49.41	0.27	9.94	1.14	0.60	33.54	5.07	0.05	0.00	100.04
Three Creek (a)	49.75	0.44	8.65	0.73	1.07	22.72	16.41	0.23	0.00	100.01
Thorn Creek (p)	49.82	0.23	13.07	0.83	0.41	31.53	4.09	0.09	0.00	100.05
Thorn Creek (a)	50.67	0.47	10.92	0.52	1.14	18.14	17.73	0.25	0.00	99.82
Knob (p)	49.43	0.25	9.29	0.84	0.40	34.98	4.77	0.05	0.03	100.04
Knob (a)	50.18	0.27	8.20	0.54	0.83	22.86	16.76	0.21	0.05	99.91
Cougar Point Tuff XIII (a)	48.85	0.32	3.81	0.63	0.64	27.01	18.43	0.24	0.00	99.94
Gwin Spring (p)	49.66	0.29	10.00	1.00	0.59	33.14	5.02	0.05	0.00	99.72
Gwin Spring (a)	50.29	0.31	7.70	0.73	0.84	23.40	16.59	0.19	0.00	100.03
Wooden Shoe Butte (a)	50.08	0.36	8.63	0.61	0.93	21.59	17.69	0.27	0.01	100.16
Wooden Shoe Butte (p)	49.64	0.30	10.60	6.18	0.50	32.02	6.18	0.09	0.00	100.18
McMullen Creek (p)	50.09	0.21	10.34	1.20	0.40	32.97	5.22	0.08	0.00	100.51
McMullen Creek (a)	50.42	0.40	8.75	0.76	0.89	22.31	16.32	0.23	0.02	100.10

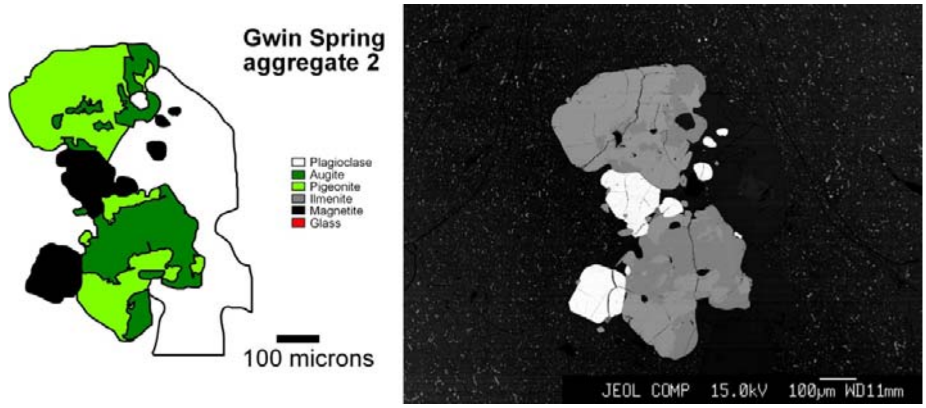
Figure DR1: Images used for determination of phase proportions of the aggregates in the CSRP rhyolites.




Plagioclase
Augite
Pigeonite
Ilmenite
Magnetite
Glass
CPT XIII
aggregate 1
2 mm


Dorsey Creek
aggregate 1
Plagioclase
Augite
Pigeonite
Ilmenite
Magnetite
Glass
0.5 mm


100 microns
Plagioclase
Augite
Pigeonite
Ilmenite
Magnetite
Glass
Gwin Spring
aggregate 1
JEOL COMP 15.0kV 100µm WD11mm


Gwin Spring
aggregate 2
Plagioclase
Augite
Pigeonite
Ilmenite
Magnetite
Glass
100 microns
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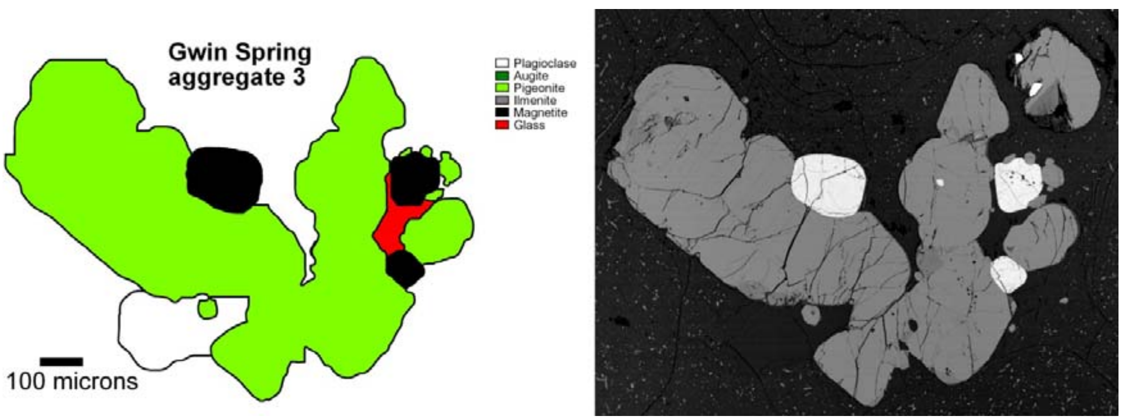
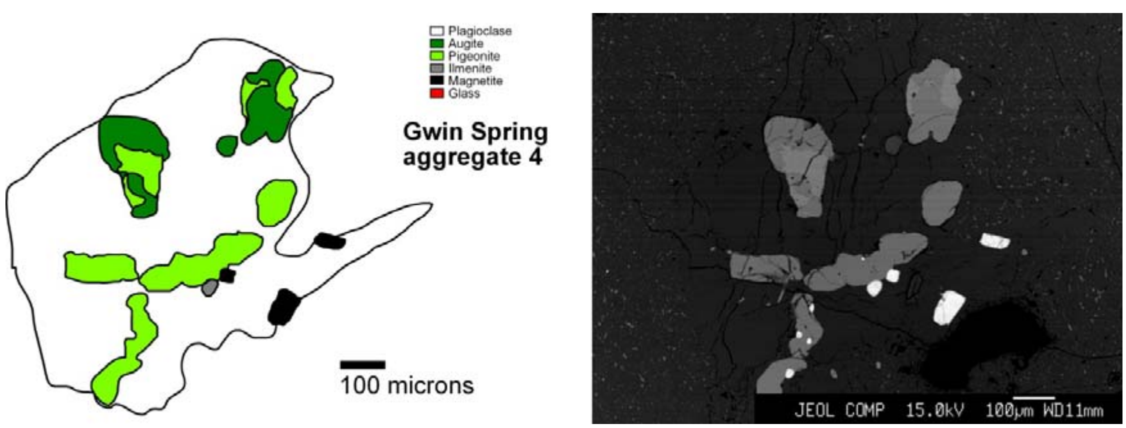

Gwin Spring
aggregate 3
Plagioclase
Augite
Pigeonite
Ilmenite
Magnetite
Glass
100 microns


Plagioclase
Augite
Pigeonite
Ilmenite
Magnetite
Glass
Gwin Spring
aggregate 4
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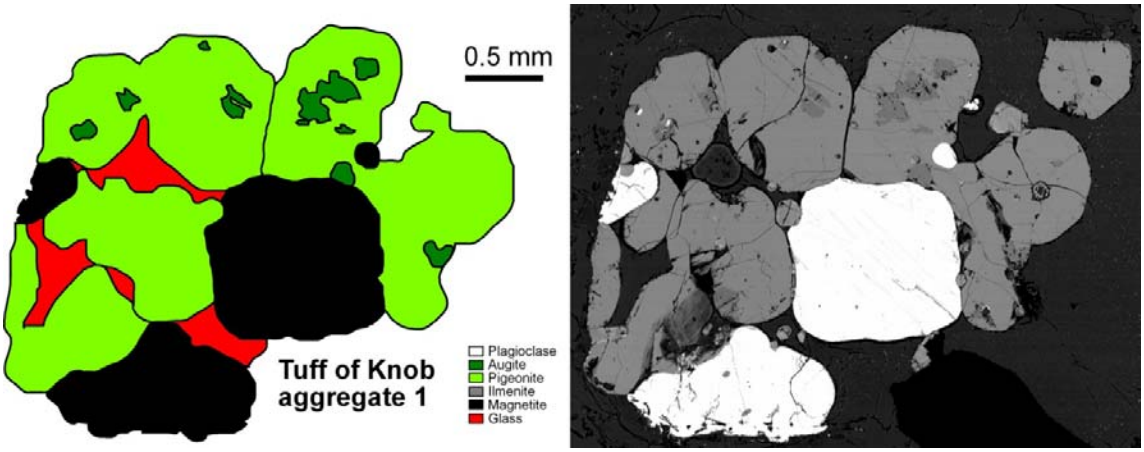
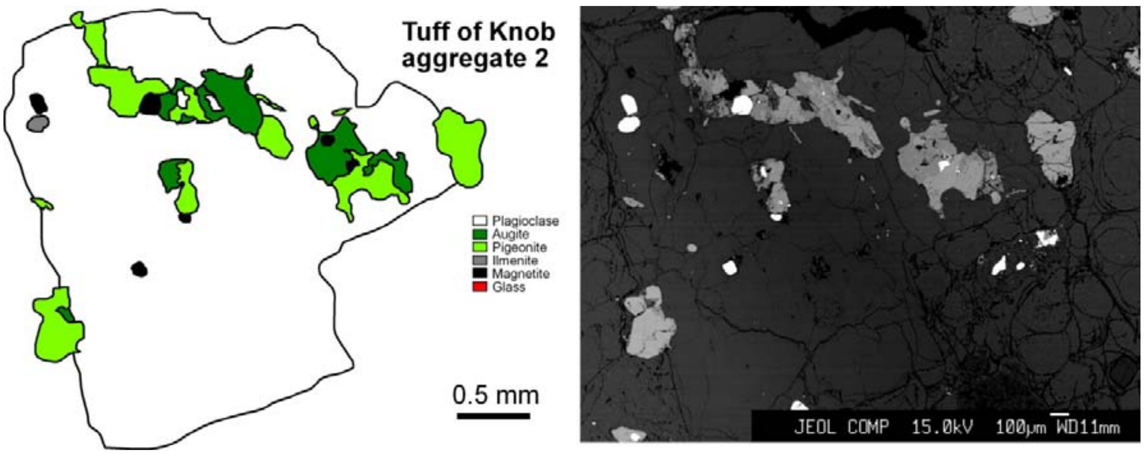
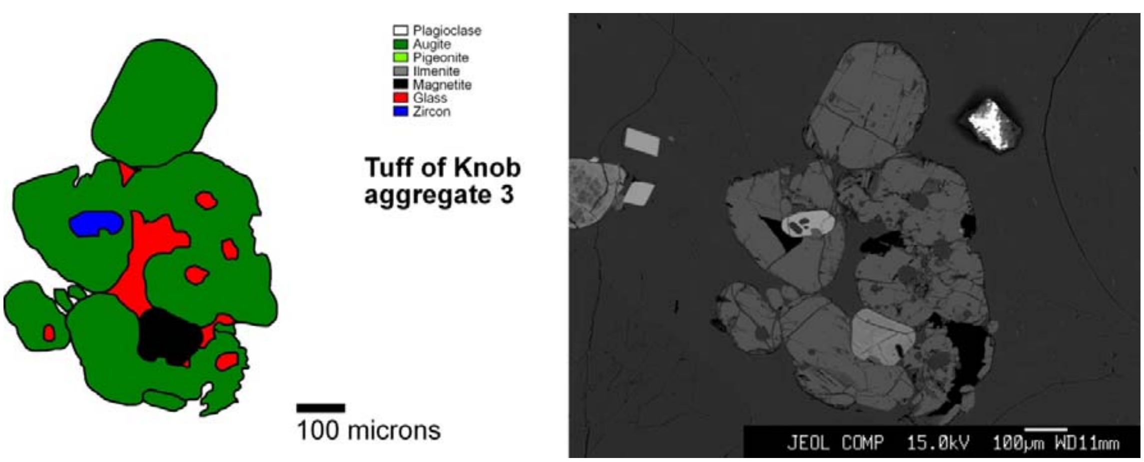

0.5 mm
Tuff of Knob
aggregate 1
Plagioclase
Augite
Pigeonite
Ilmenite
Magnetite
Glass


Tuff of Knob
aggregate 2
Plagioclase
Augite
Pigeonite
Ilmenite
Magnetite
Glass
0.5 mm
JEOL COMP 15.0kV 100μm WD11mm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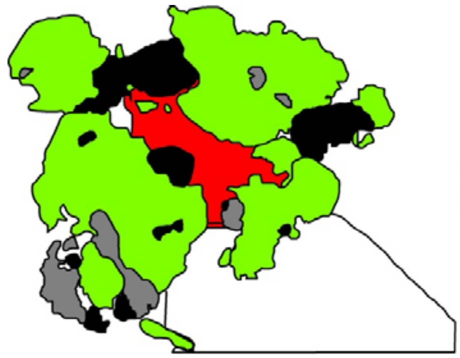
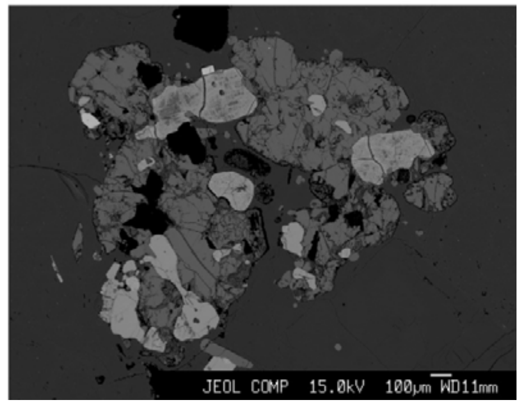
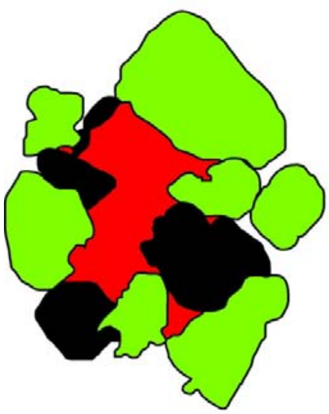
Augite
Pigeonite
Ilmenite
Magnetite
Glass
Zircon
Tuff of Knob
aggregate 3
100 microns
JEOL COMP 15.0kV 100μm WD11mm

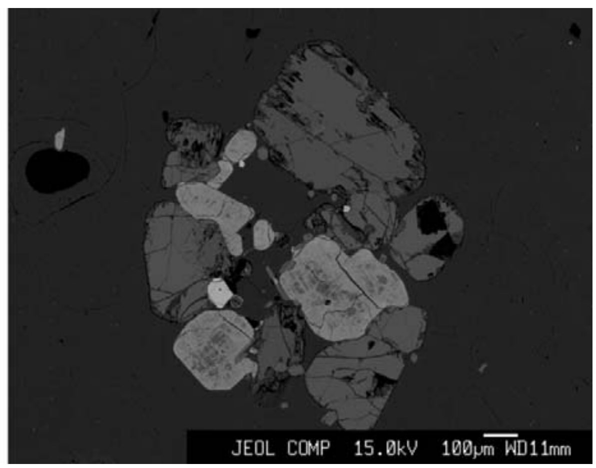


Tuff of Knob aggregate 4

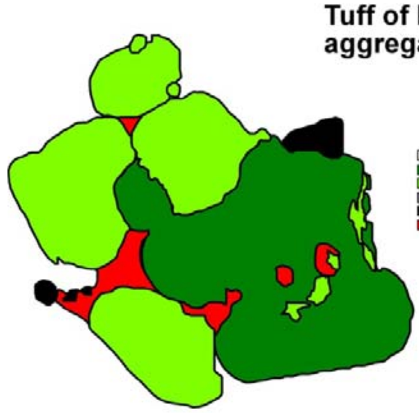


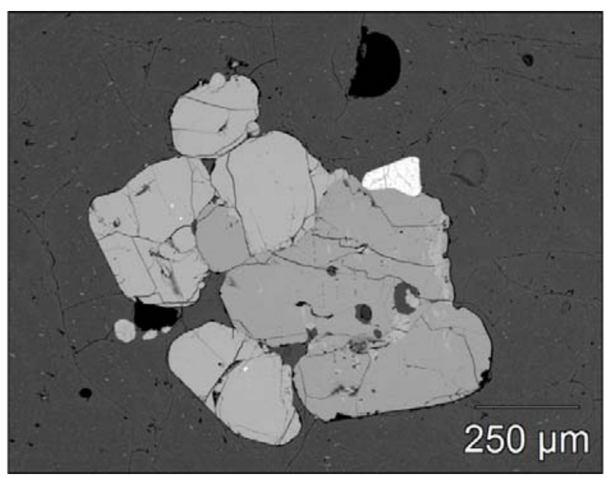


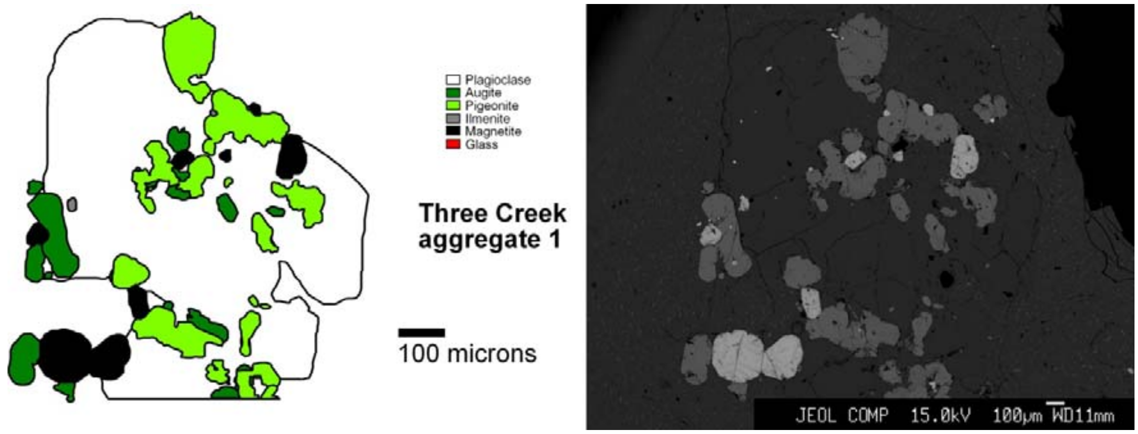
Tuff of Knob aggregate 5

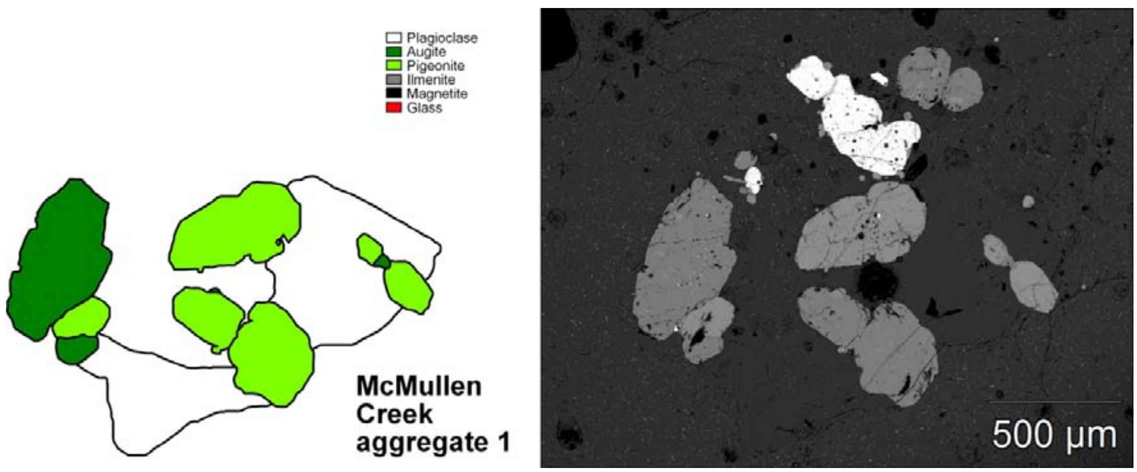


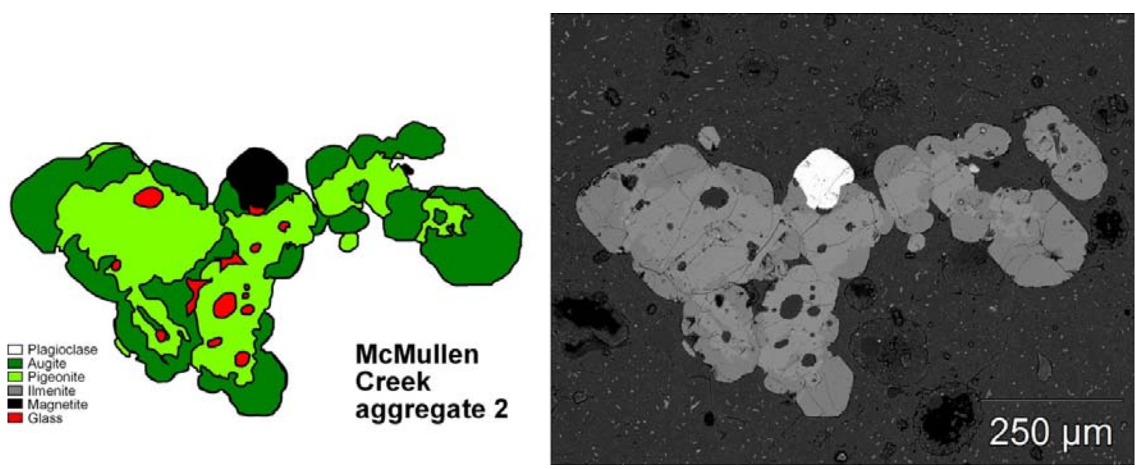
Tuff of Knob aggregate 6

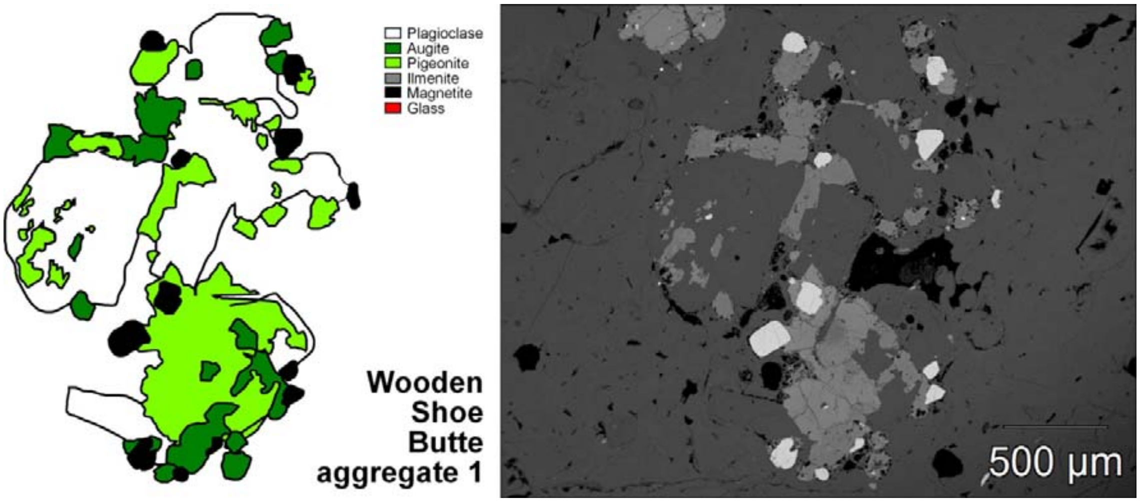


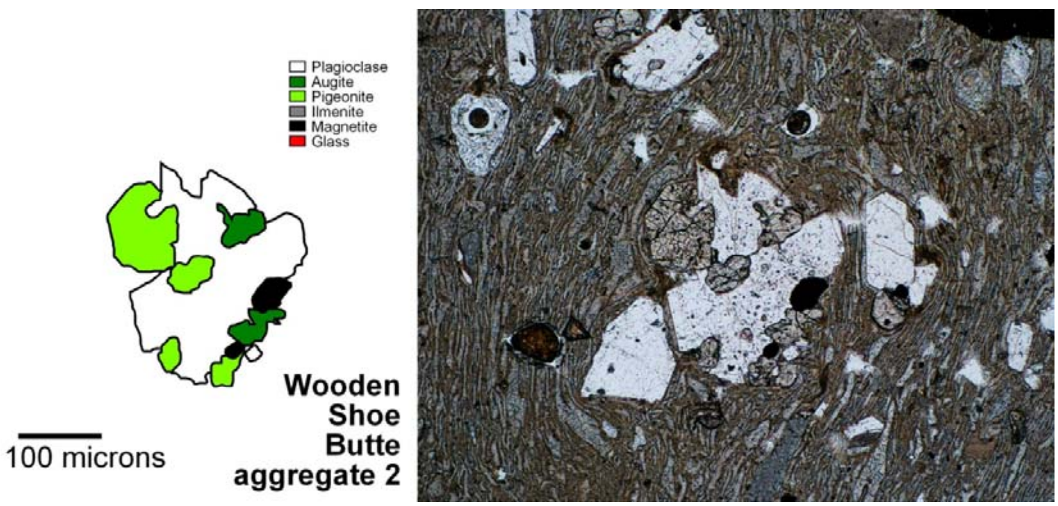



Plagioclase
Augite
Pigeonite
Ilmenite
Magnetite
Glass
Three Creek aggregate 1
100 microns
JEOL COMP 15.0kV 100µm WD11mm


Plagioclase
Augite
Pigeonite
Ilmenite
Magnetite
Glass
McMullen Creek aggregate 1
500 µm


Plagioclase
Augite
Pigeonite
Ilmenite
Magnetite
Glass
McMullen Creek aggregate 2
250 µm





Geological Background

The rhyolites of the Snake River Plain are part of the bimodal (basalt-rhyolite) Columbia River-Yellowstone province (Pierce and Morgan, 1992; Camp and Ross, 2004; Brueseke and Hart, 2008; Wolff et al., 2008). This volcanism which has been active for the past 16.5 Ma is most commonly, although not uniquely, interpreted as the product a stationary hotspot (Geist and Richards, 1993; Hooper et al., 2007). Within the Columbia River-Yellowstone province, the rhyolites of the central Snake River Plain (CSRP) include both ignimbrites and lavas that have been the subject of much recent study which has included work detailing their physical features (e.g. Branney et al., 2004, Branney et al., 2008; Ellis and Branney, 2010; Andrews and Branney, 2011; Ellis et al., 2012), their geochemistry

(Honjo et al., 1992; Cathey and Nash, 2004, 2009; Christiansen and McCurry, 2008; Ellis et al., 2010, 2013;) and isotopic compositions (Leeman et al., 1985; Wolff et al., 2011; McCurry and Rodgers, 2009; Boroughs et al., 2005, 2012). For this reason, only the most relevant details will be summarised here. Sample locations are provided in Figure DR2 and details about the units are provided in Table DR4.

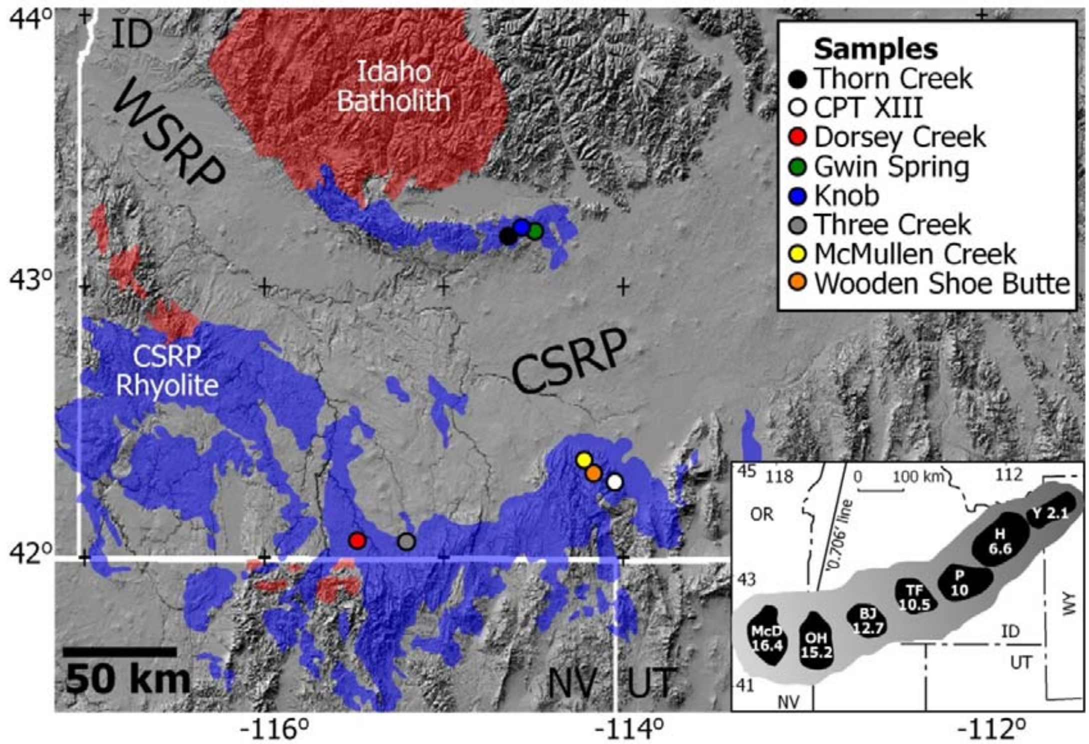


Figure DR2: Location map showing the samples used in this study and the general distribution of Snake River-type rhyolite (after Boroughs et al., 2012). Inset shows the general NE progression of silicic volcanism associated with the Yellowstone-Columbia River province.

CSRP Rhyolite Geochemistry

Snake River Plain rhyolites (both ignimbrites and lavas) are crystal-poor with up to 25% crystals and are characterised by an anhydrous mineral assemblage of plagioclase ($_{An25–50}$) ± sanidine ± quartz +augite ± pigeonite ± orthopyroxene ± fayalitic olivine ± ilmenite ± magnetite + accessory zircon and apatite (e.g. Honjo et al., 1992; Cathey and Nash, 2004; Ellis et al., 2013). As noted in the main text of the paper, crystals are also present as aggregates dominated by plagioclase, pyroxene and oxides. Multiple compositions of pyroxene and augite have been noted from single ignimbrites (Cathey and Nash, 2004; Ellis et al., 2010; Ellis and Wolff, 2012) and studies of distal fallout deposits consistently find multiple compositions of rhyolitic glass indicative of multiple liquids present prior to eruption (Perkins et al., 1995, 1998; Perkins and Nash, 2002; Nash and Perkins, 2012).

The rhyolites contain no hydrous phases such as biotite and amphibole and numerous studies using mineral thermometers have indicated that the CSRP rhyolites are significantly hotter than rhyolites in other settings, e.g. >850°C (Honjo et al., 1992; Cathey and Nash, 2004, 2009; Ellis et al., 2010). Such high temperatures allow diffusional processes to act much faster and this promotes homogeneity within mineral phases, which has been observed in major elements, trace elements and isotopic compositions of feldspars and pyroxenes (e.g. Cathey and Nash, 2004; Wolff et al., 2011). The high temperatures and associated low water contents of the CSRP rhyolites inferred from geochemical studies of natural samples have been reproduced in petrological experiments (Almeev et al., 2012).

All of the rhyolites in the CSRP are depleted in ^{18}O indicating significant assimilation of hydrothermally altered materials (e.g. Boroughs et al., 2005, 2012 and summarised by Ellis et al. 2013) a somewhat different situation to the rhyolites of the eastern Snake River Plain and Yellowstone which may have normal-$\delta^{18}O$ or low-$\delta^{18}O$ character (e.g. Bindeman et al., 2007, 2008; Watts et al., 2011).

The rhyolitic ignimbrites and lavas are similar in bulk compositions, mineralogy and isotopic character. One difference which has been noted is that unlike the ignimbrites which may contain multiple compositions of both augite and pigeonite, rhyolitic lavas appear to only contain a single composition of these phases (e.g. Cathey and Nash, 2009; Ellis and Wolff, 2012).

Eruptive Sources and Volumes

The volume-frequency relationships of rhyolites in the CSRP remain a work in progress, with only preliminary steps made to understand the potential for correlation of ignimbrites around the margins of the plain (Bonnichsen et al., 2008; Ellis et al., 2012). The total amount of rhyolite erupted from the CSRP has been estimated at between 10 and 30,000 km^3 (Bonnichsen et al., 2008; Leeman et al., 2008; Boroughs et al., 2012). The volumes of individual deposits are poorly constrained, particularly with no information on intracaldera components of ignimbrites. Boroughs et al. (2012) have estimated volumes for > 50 rhyolitic units in the CSRP, but these volumes should be considered as approximations. From the studies undertaken so far, it appears that while in some cases correlations may be made, in many cases smaller eruptions are local and broadly time-equivalent volcanism was occurring over a widely dispersed area during the ‘ignimbrite flare-up’ period, suggesting that magmas were stored throughout much of the upper crust (Bonnichsen et al., 2008). As noted by Ellis and Wolff (2012), the complexity of the crystal cargo in terms of pyroxene compositions is not related to the size of the ignimbrite.

No eruptive centres are exposed due to the later eruptions of basalt within the Snake River Plain and so little is currently known about them (Branney et al., 2008; Ellis et al., 2013). Indeed, as noted by Branney et al. (2008), lithofacies typical of intracaldera deposits have not been found in the CSRP (e.g. megabreccias, km-thick deposits, hydrothermal alteration). The lack of crucial information about proximal areas is being addressed via studies of drill cores in the CSRP (e.g. McCurry and Rodgers, 2009) but current understanding prevents anything more than the loosest spatial constraints being applied to the pre-eruptive storage of rhyolite.

Table DR5: Background information on specific rhyolites used in this study, with data from Bonnichsen et al. (2008); Ellis et al., (2010); Boroughs et al. (2012). *The McMullen Creek unit is a composite of a number of ignimbrites, the detailed stratigraphy remains unclear.

Unit name	Bulk SiO_2 (wt.%) average (n) is number of analyses	Age, or best estimate (Ma)	Magnetic Polarity	Type of unit	Volume estimate (km^3)
Dorsey Creek	73.04 (18)	~8	N	Lava	75
Three Creek	74.26 (7)	~ 8	N	Ignimbrite	20
McMullen Creek	76.23 (1)	~ 9	?	Ignimbrite	1,000*
Gwin Spring	72.73 (7)	~9.7	?	Ignimbrite	60
Wooden Shoe Butte	71.80 (15)	~10	?	Ignimbrite	100
Thorn Creek	73.28 (3)	~10	N	Ignimbrite	120
Knob	71.88 (8)	~10.6	N	Ignimbrite	150
Cougar Point Tuff XIII	75.62 (11)	~11	N	Ignimbrite	1,000

Table DR6: Examples of crystal aggregates likely representing cumulates from other settings, both hot and dry rhyolite and from the whole suite of silicic compositions. Mineral abbreviations are: px – pyroxene, plag – plagioclase, zir – zircon, ap – apatite, ox – Fe-Ti oxides, qtz – quartz, san – sanidine, cpx – clinopyroxene, ol – olivine, mag – magnetite, ilm - ilmenite, bio – biotite, hbl – hornblende, amp – amphibole, fay – fayalite. Duplication of names (e.g. px and cpx) is a result of how descriptions were reported in the original works.

Hot, Dry Rhyolites

Unit / units	Location	Bulk composition	Phases in aggregates	Phases not in aggregates	Figure	Reference
Jarbidge Rhyolite	Nevada, USA	Rhyolite	Px, plag, zir, ap, ox	Qtz, san	Yes, 6D	Brueseke et al. (*in press*)
Eucarro Rhyolite	New South Wales, Australia	Rhyolite	Px, plag, qtz	San	No	Allen and McPhie (2002)
Yardea Dacite	South Australia, Australia	Dacite	Px, plag, ox	San, rare qtz	Yes, 2	Creaser and White (1991)
Askja	Iceland	Rhyolite	Px, plag, ox	No	Yes, 4	Sigurdsson and Sparks (1981)
Krafla	Iceland	Rhyolite	Plag, qtz, pyx, mag	San	Yes, 4D	Zierenberg et al. (2013)
Central Plateau Member	Yellowstone, USA	Rhyolite	Px, plag, ox, zir	Qtz, san	Yes, 2B	Girard and Stix (2009)
Island Park Rhyolite	Yellowstone, USA	Rhyolite	Px, plag, ox, zir	Qtz, san	No	Troch et al. (*in prep*)
Heise volcanics	Idaho, USA	Rhyolite	Px, plag, ox, zir	Qtz, san	4	Watts et al. (2011)
Upper Springbok	Etendeka-Parana, Namibia	Rhyodacite / quartz latite	Px, plag, ox,	No	Yes, 9	Milner et al. (1992)
Paisano volcano	Texas, USA	Trachyte	Plag, cpx, ol, ox	San	Yes, 2	Parker (1983)
Infiernito caldera	Texas, USA	Trachyte to rhyolite	Plag, cpx, ox,	No	No	Henry et al. (1988)
McDermitt caldera	Nevada, USA	Rhyolite to comendite	Plag, pyx, ox, ap	Qtz	No	Conrad (1984)

Other Silicic Magmas

Unit / units	Location	Bulk composition	Phases in aggregates	Phases not in aggregates	Figure	Reference
White Island	TVZ, New Zealand	Andesite to dacite	Plag, pyx, ox	-	Yes, 8D	Cole et al. (2000)
Tarawera Rhyolites	TVZ, New Zealand	Rhyolite	Plag, pyx, mag, hbl	Qtz	No	Cole (1970)
Earthquake Flat	TVZ, New Zealand	Rhyolite	Plag, qtz, bio, hbl, opx, ox	"mostly composed of ferromagnesian phases"	No	Molloy et al. (2008)
15.8 ka Rotorua, Okataina	TVZ, New Zealand	Rhyolite	Plag, hbl, opx	Qtz	No	Smith et al. (2004)
Matahina eruption, Okataina	TVZ, New Zealand	Rhyolite	Plag, amp, pyx, ox, qtz	No	Yes, 2	Deering et al. (2011)
Omega Dacite	TVZ, New Zealand	Dacite	Plag, pyx, ox	No	Yes 2A	Gelman et al. (2013)
Were Ilu ignimbrites	Ethiopia	Rhyolite	Plag, pyx, mag	No	Yes, 2	Barbey et al. (2005)
1991-95 dome	Unzen, Japan	Dacite	Plag, hbl, bio, ox	Qtz? Unclear	Yes, 7A	Nakada and Motomura (1999)
Dundee Rhyodacite	New South Wales, Australia	Rhyodacite	Plag, pyx,	Qtz, bio, san	Yes, 2	Flood et al. (1977)
Loch Ba, ring-dike	Mull, Scotland	Rhyolite	Plag, hbg, ilm / Plag, fay, mag	San	Yes, 2E	Sparks (1988)
Santa Rosa-Calico	Nevada, USA	Dacite to rhyolite	Plag, pyx, ox		Yes, 7	Brueseke and Hart (2008)
Gorely eruptive centre	Kamchatka, Russia	Dacite	Plag, pyx, ox	No	No	Seligman et al. (*in press*)
Fish Canyon Tuff	Colorado, USA	Dacite	Plag, hbl, bio, ox	Qtz, san	Yes, Fig. 38	Bachmann (2001)
Egan Range	Nevada, USA	Andesite to dacite	Plag, pyx	Qtz	Yes, 4	Grunder (1992)

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