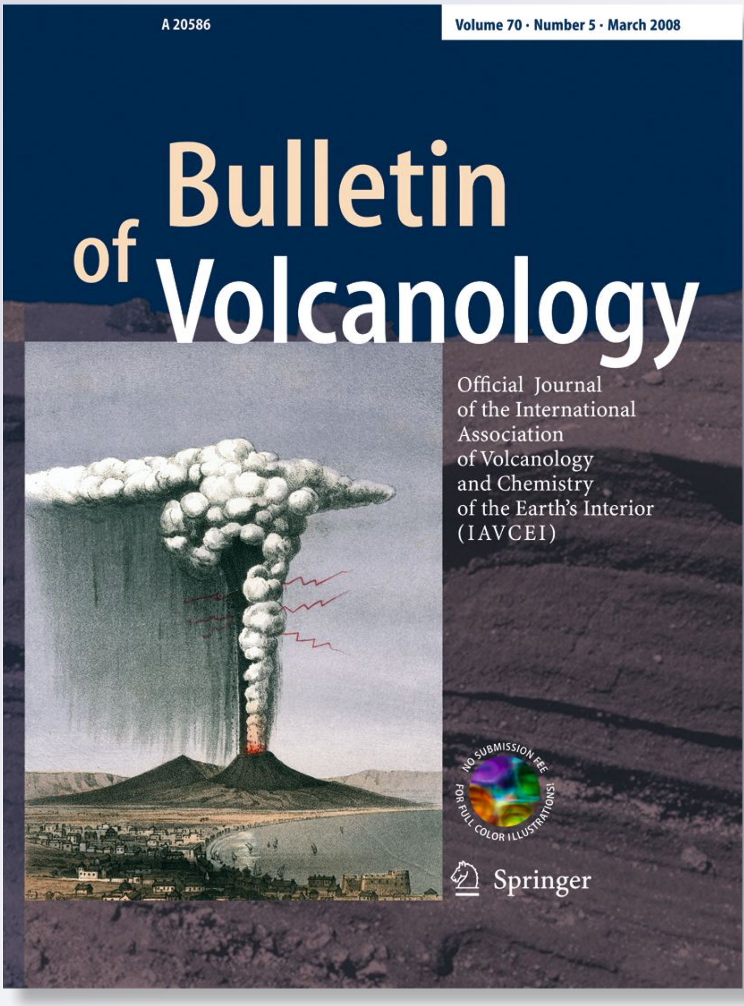
Geochemical correlation of three large-volume ignimbrites from the Yellowstone hotspot track, Idaho, USA

Ben S. Ellis, M. J. Branney, T. L. Barry, D. Barfod, I. Bindeman, J. A. Wolff & B. Bonnichsen

Bulletin of Volcanology
Official Journal of the International Association of Volcanology and Chemistry of the Earth`s Interior (IAVCEI)

ISSN 0258-8900
Volume 74
Number 1

Bull Volcanol (2012) 74:261-277
DOI 10.1007/s00445-011-0510-z



Springer

Bull Volcanol (2012) 74:261–277
DOI 10.1007/s00445-011-0510-z

RESEARCH ARTICLE

Geochemical correlation of three large-volume ignimbrites from the Yellowstone hotspot track, Idaho, USA

Ben S. Ellis · M. J. Branney · T. L. Barry · D. Barfod · I. Bindeman · J. A. Wolff · B. Bonnichsen

Received: 5 October 2010 / Accepted: 25 May 2011 / Published online: 9 August 2011

Abstract Three voluminous rhyolitic ignimbrites have been identified along the southern margin of the central Snake River Plain. As a result of wide-scale correlations, new volume estimates can be made for these deposits: ~350 km^3 for the Steer Basin Tuff and Cougar Point Tuff XI, and ~1,000 km^3 for Cougar Point Tuff XIII. These volumes exclude any associated regional ashfalls and correlation across to the north side of the plain, which has yet to be attempted. Each correlation was achieved using a combination of methods including field logging, whole rock and mineral chemistry, magnetic polarity, oxygen isotope signature and high-precision $^{40}Ar/^{39}Ar$ geochronology. The Steer Basin Tuff, Cougar Point Tuff XI and Cougar Point Tuff XIII have deposit characteristics typical of 'Snake River (SR)-type' volcanism: they are very dense, intensely welded and rheomorphic, unusually well sorted with scarce pumice and lithic lapilli. These features differ significantly from those of deposits from the better-known younger eruptions of Yellowstone. The ignimbrites also exhibit marked depletion in $\delta^{18}O$, which is known to characterise the SR-type rhyolites of the central Snake River Plain, and cumulatively represent ~1,700 km^3 of low $\delta^{18}O$ rhyolitic magma (feldspar values 2.3–2.9‰) erupted within 800,000 years. Our work reduces the total number of ignimbrites recognised in the central Snake River Plain by 6, improves the link with the ashfall record of Yellowstone hotspot volcanism and suggests that more large-volume ignimbrites await discovery through detailed correlation work amidst the vast ignimbrite record of volcanism in this bimodal large igneous province.

Keywords Yellowstone · Geochemistry · Ignimbrite · Rhyolite · Snake River Plain

Editorial responsibility: M.A. Clynne

Electronic supplementary material The online version of this article (doi:10.1007/s00445-011-0510-z) contains supplementary material, which is available to authorized users.

B. S. Ellis · M. J. Branney · T. L. Barry
Department of Geology, University of Leicester,
University Road,
Leicester LE1 7RH, UK

D. Barfod
SUERC, NERC Argon Isotope Facility,
Rankine Avenue, Scottish Enterprise Technology Park,
East Kilbride GL75 OQF, UK

I. Bindeman
Geological Sciences, 1272 University of Oregon,
Eugene, OR 97403, USA

B. S. Ellis (✉) · J. A. Wolff
School of Earth and Environmental Sciences,
Washington State University,
Pullman, WA, USA
e-mail: ben.ellis@wsu.edu

B. Bonnichsen
927 East 7th Street,
Moscow, ID 83834, USA

Introduction

The past decade has seen numerous studies of large-volume, explosive silicic eruptions (e.g. Christiansen 2001; Bachman et al. 2002; Maughan et al. 2002; Gardner et al. 2002). Extremely large-volume eruptions have never been witnessed by mankind, and all information about them have to be derived from the deposit record. Some studies have examined the potential for these eruptions to cause widespread global temperature fluctuations (e.g. Rampino and Self 1992; Rampino 2002; Jones et al. 2005), whilst others have focused on the mechanics of generating, storing and erupting such vast volumes of magma (e.g. Jellinek and De Paolo 2003; Baines and Sparks 2005; Bindeman et al. 2007; Bachman and Bergantz 2008).

Here, we investigate ignimbrites from the older part of the Yellowstone hotspot track that have previously been described as voluminous (e.g. Perkins and Nash 2002; Cathey and Nash 2004; Boroughs et al. 2005; Branney et al. 2008) but hitherto have not been traced laterally along the margins of the plain. Extensive reconnaissance work, logging and chemical analyses (Ellis et al. 2010) have enabled us to concentrate here on parts of the stratigraphy that present the greatest scope for lateral correlation.

The Columbia River–Yellowstone province in the north-western contiguous USA has been the site of voluminous basalt–rhyolite volcanism since the mid-Miocene. The source of volcanism is most often attributed to a mantle plume, suggested to presently underlie Yellowstone (Pierce and Morgan 1992; Camp 1995; Camp and Ross 2004; Jordan et al. 2004; Hooper et al. 2007; Camp and Hanan 2008; Shervais and Hanan 2008; Wolff et al. 2008). However, other explanations have been proposed such as feedback between upper mantle convection and regional tectonics (see Christiansen et al. 2002) or upper plate processes (Manea et al. 2009; Leeman et al. 2009). The rhyolitic volcanism was initially widely dispersed around central Oregon and northern Nevada (e.g. Dooley Mountain, Oregon, 16–14.7 Ma, Evans 1992; High Rock Caldera, Nevada, 16.5–15 Ma, Coble and Mahood 2008; Jarbidge rhyolite, Nevada 16.2–16 Ma, Henry et al. 2006; Santa Rosa–Calico volcanic field, Brueseke and Hart 2008; and McDermitt volcanic field, Nevada 16.5–15 Ma, Rytuba and McKee 1984). Thereafter, it became more focused with a general younging pattern from the Owyhee Humboldt area at ca. 14 Ma, eastwards along the Snake River Plain, to the present day Yellowstone volcanic field (Lanphere et al. 2002). In the central and eastern Snake River Plain (Fig. 1), the vents of the rhyolitic ignimbrites are inferred to be either a series of discrete eruptive centres (Bonnichsen 1982; Pierce and Morgan 1992) or overlapping, shingled calderas (Godchaux and Bonnichsen 2002; Branney et al. 2008). Further insight into the sources of the ignimbrites is obscured by later basalt lavas, phreatomagmatic tuffs and sediments which cover the eruption sites (e.g. Bonnichsen and Godchaux 2002; Shervais et al. 2006).

Volcanism in the central Snake River Plain

Rhyolites of the central Snake River Plain (CSRP) have similarities to A-type granites in terms of high field strength elements and low calcium contents (e.g. Cathey and Nash 2004). They have anhydrous mineral assemblages variously containing sanidine, quartz, plagioclase, augite, pigeonite, fayalitic olivine, ilmenite and magnetite, with accessory zircon and apatite (e.g. Bonnichsen and Citron 1982; Honjo et al. 1992; Cathey and Nash 2004). The mineral assemblages are consistent with high (>900°C) magmatic temperatures, as inferred from a number of geothermometers (Honjo et al. 1992; Cathey and Nash 2004; Andrews et al. 2008). Crystal contents of the CSRP ignimbrites range between approximately 2% and 20% which may vary slightly within a unit ±2%.

The central Snake River Plain includes two inferred eruptive centres, the Bruneau–Jarbidge and the Twin Falls centres (Fig. 1). These produced rhyolitic ignimbrites, ashfall layers and lavas between approximately 13 and 6 Ma (Pierce and Morgan 1992; Bonnichsen et al. 2008). The volcanic deposits make an unusual lithofacies association that has been taken to represent a distinct newly defined category of volcanism, known as Snake River (SR)-type volcanism (Branney et al. 2008). The ignimbrites of SR-type volcanism are intensely welded to the extent that many can be described as 'lava-like' in hand specimen (Henry et al. 1988; Branney and Kokelaar 1992) and exhibit intense rheomorphism (Andrews and Branney 2011). The ignimbrites are exceptionally well sorted and dominated by ash rather than pumice lapilli, with deposits typically containing less than 5 wt.% lapilli-sized material (Branney et al. 2008). The ignimbrites contain few lithic clasts, but abundant clasts of non-vesicular rhyolitic glass. Fall deposits are poorly exposed and dominated by well-sorted, parallel-bedded coarse to fine ash (Ellis and Branney 2010), often containing glass shards large enough to be seen clearly in hand specimen. Framework-supported, angular pumice lapilli that typify fall deposits in most rhyolitic provinces are rare.

The ignimbrites are well exposed in steep-sided canyons and fault scarps on the margins of the plain with cliff-forming outcrops separated by slope-forming units variably consisting of primary and reworked volcaniclastics and soils. Exposed sections may be up to 100 km apart and contain successions of ignimbrites that are similar in terms of appearance (e.g. welding intensity, lack of lithic clasts and phenocryst assemblage) and broad chemical composition (all rhyolites). Ashfall deposits are poorly exposed, so tracing their predictable stratigraphy between mountain ranges is not a viable method of correlation in the CSRP. Correlating ignimbrites by field appearance is notoriously difficult given the variation in thickness and lithofacies that may occur over short distances as a response to topography (e.g. Grey's Landing ignimbrite, Andrews et al. 2008). The stratigraphies of the various regions have been developed independently by different

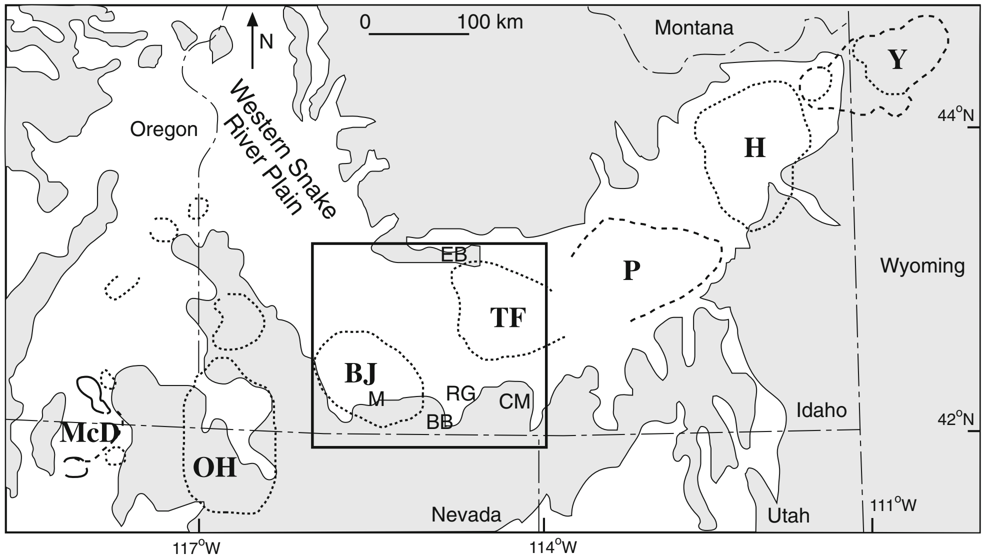


Fig. 1 Location map showing the putative eruptive centres of the Yellowstone hotspot; abbreviations are: *McD* McDermitt, *OH* Owyhee Humboldt, *BJ* Bruneau–Jarbidge, *TF* Twin Falls, *P* Picabo, *H* Heise and *Y* Yellowstone. The *black rectangle* represents the area of this study, the central Snake River Plain, coincident with the type area of SR-type volcanism. Other abbreviations are place names referred to in the text, *RG* Rogerson Graben, *CM* Cassia Mountains, *BB* Brown's Bench, *EB* East Bennett Mountains and *M* Murphy Hot Springs. *Grey fill* broadly represents areas of relatively high topography

workers and are described below. This study concentrates on the rhyolites along the southern margin of the Snake River Plain in the Cassia Mountains, the Rogerson Graben, on the Brown's Bench escarpment and in the Bruneau–Jarbidge region and for the first time correlates the products of individual eruptions between these locations.

Bruneau–Jarbidge region

The canyons of the Bruneau and Jarbidge rivers in southern Idaho and northern Nevada expose a >500-m-thick succession of Miocene silicic volcanic rocks which overlie Eocene rhyodacites of the Bieroth succession (Bonnichsen and Citron 1982). The Miocene rocks comprise the Cougar Point Tuff, a succession of nine rhyolitic, intensely welded ignimbrites (III, V, VII, IX, X, XI, XII, XIII and XV) and a series of rhyolitic lavas which were predominantly erupted following the cessation of explosive volcanism. The Cougar Point Tuff ignimbrites were erupted between 12.82±0.03 Ma and ~10.5 Ma (Bonnichsen et al. 2008; ages corrected to Fish Canyon Tuff age of 28.201 Ma, Kuiper et al. 2008) with the primary volcanic deposits forming cliffs separated by slopes comprising reworked volcaniclastic material. The Cougar Point Tuff succession is proposed to be the main product of the Bruneau–Jarbidge eruptive centre (Figs. 1 and 2; Bonnichsen 1982). The eruptions that produced the Cougar Point Tuff succession are thought to have been regionally devastating (e.g. Perkins et al. 1995; Branney et al. 2008), and the petrology of these rocks has been described in detail (Cathey and Nash 2004).

Brown's Bench

The N-S trending Brown's Bench fault exposes at least 13 rhyolitic units which have the potential to correlate with the Cougar Point Tuff succession but about which little is known. The succession has been described preliminarily by Bonnichsen et al. (2008) who named the units present in the escarpment numerically from 1 (oldest) to 12 (youngest). The Grey's Landing ignimbrite which fills the nearby Rogerson Graben is found overlying the Brown's Bench succession (Andrews et al. 2008). Bonnichsen et al. (2008) provided $^{40}Ar/^{39}Ar$ ages on two of the units, 7 and 9, which gave ages of 11.05±0.07 Ma and 10.35±0.09 Ma, respectively.

Rogerson Graben

Bounded to the west by the Brown's Bench fault, the Rogerson Graben (Fig. 3) contains a number of rhyolitic ignimbrites interbedded with volcaniclastic sediments. The base of the succession is not exposed, and the uppermost part is overlain by basaltic lavas. The oldest unit in the Rogerson Graben is the Jackpot Member which comprises seven informal sub-units, hereafter termed Jackpot 1–7. Jackpot 1–6 reach >100 m in thickness, and the base is not exposed. Overlying Jackpot 1–6 are Jackpot 7 and five other SR-type rhyolitic ignimbrites (the Rabbit Springs,

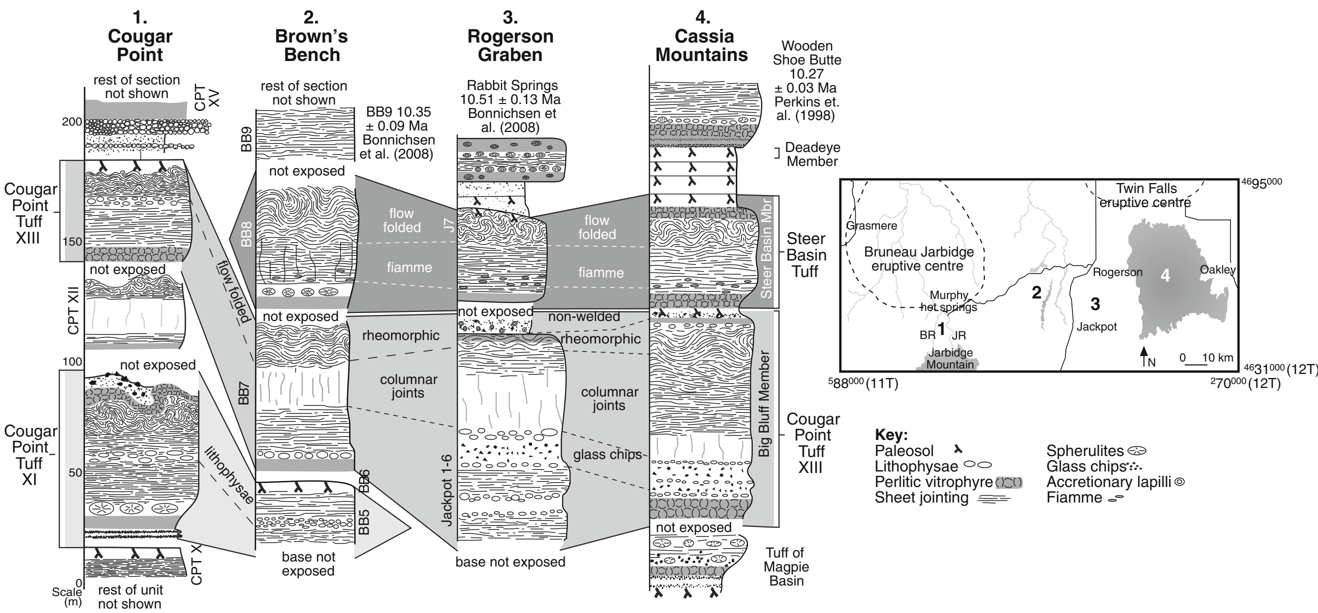


Fig. 2 Generalised vertical sections of the Cougar Point Tuff, Brown's Bench, Rogerson Graben and Cassia Mountain successions, developed after (Bonnichsen and Citron 1982; Andrews et al. 2008; Bonnichsen et al. 2008). *BR* represents the Bruneau River, *JR* represents the Jarbidge River, *J7* represents Jackpot 7 of Andrews et al. (2008) and abbreviation *BB* is for Brown's Bench units of Bonnichsen et al. (2008). *Inset* shows the location of the sections

Browns View, Grey's Landing, Coyote Creek and Sand Springs Members) which are separated by volcaniclastic sediments and palaeosols (Andrews et al. 2008). The Rabbit Springs Member has a $^{40}Ar/^{39}Ar$ age of 10.51±0.13 Ma (recalculated from Bonnichsen et al. 2008; Fig. 2).

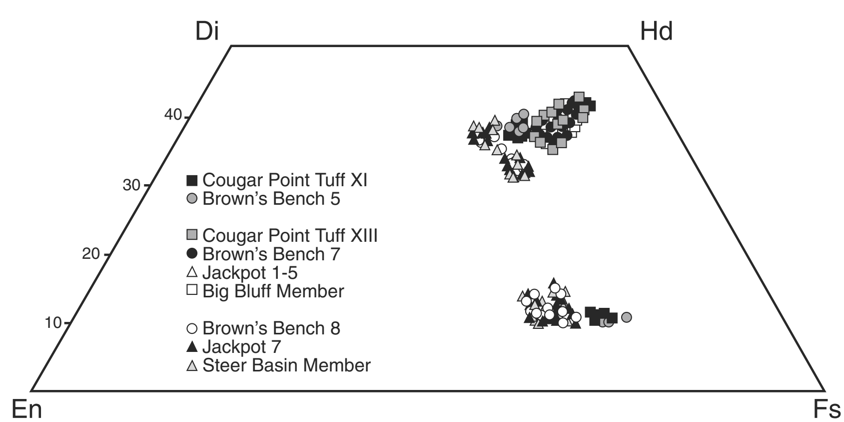
Cassia Mountains

Some 30 km east of the Rogerson Graben, the Cassia Mountains (Fig. 2) contain a series of rhyolitic ignimbrites and intercalated sediments which overlie Permian limestone as mapped by Williams et al. (1990). The succession contains at least nine ignimbrites which range in appearance from intensely welded and lava-like to entirely non-welded and of phreatomagmatic origin (Ellis et al. 2010; Ellis and Branney 2010). The thickest unit in this succession is the Big Bluff Member which reaches 75 m and has a $^{40}Ar/^{39}Ar$ age of 10.98±0.07 Ma (Ellis et al. 2010). The geochemical and O isotopic characteristics of the Cassia Mountain ignimbrites are reported by Ellis et al. (2010).

Hotspot track volumes

The younger eruptive centres of the Yellowstone hotspot have individual eruption volumes that are well constrained. The 2 Ma–present Yellowstone volcanic field has produced three voluminous ignimbrites ranging in volume between 280 and 2,500 km^3 (Christiansen 2001). The four large ignimbrites of the 6.6–4.5 Ma Heise eruptive centre have volumes between 300 and 1,800 km^3 (Morgan and

Fig. 3 Pyroxene compositions of the ignimbrites in this study



McIntosh 2005). By contrast, volumes for individual eruptions from the CSRP are poorly constrained with unit volumes only estimated to an order of magnitude (e.g. Boroughs et al. 2005; Andrews et al. 2008). The total volume of rhyolite in the CSRP has been estimated on the basis of the thickness of rhyolite exposed in the regions surrounding the CSRP as between 7,000 and 14,000 km^3 (Bonnichsen et al. 2008; Leeman et al. 2008), whereas estimates of erupted material based on ashfall give erupted volumes on the order of 10,000 km^3 for just the Cougar Point Tuff succession (Perkins and Nash 2002). The older McDermitt eruptive centre in northern Nevada is thought to have produced a number of ignimbrites with individual volumes between 40 and 400 km^3 (Rytuba and McKee 1984).

Methodology

Hitherto, correlation between individual ignimbrites of adjacent areas has not been attempted in the CSRP. However, rhyolite lavas and ignimbrites have been divided into broad composition and time (CAT) groups on the basis of their whole rock composition (particularly TiO_2 and FeO contents), limited geochronology, relative stratigraphic position and magnetic polarity (Table 1; Bonnichsen et al. 2008). Individual CAT groups may include as many as eight units (lavas and ignimbrites) from the various uplands that surround the CSRP. Within a CAT group, some of the ignimbrites may derive from a single eruption, but, conversely, inclusion within a CAT group does not necessarily indicate this, and, for example, a single CAT group may contain a number of units that can be seen to be stratigraphically separated in a single succession. A simplified version of the CAT group stratigraphy covering the units examined in this work is provided in Table 1.

Central Snake River Plain rhyolites often exhibit geochemical heterogeneity on a hand specimen scale. This heterogeneity may be used to characterise the products of a particular eruption and allow correlation on a geochemical basis. Many CSRP ignimbrites contain multiple compositional populations of pigeonite and augite (e.g. Cathey and Nash 2004; Ellis et al. 2010), and crucially for correlation, the compositions of the clinopyroxenes remain constant vertically through a deposit although the proportions of the modes may change. Importantly, multiple analyses on single phenocrysts suggest that individual clinopyroxene crystals are compositionally homogeneous—a result also reported by Cathey and Nash (2004). Detailed analysis of clinopyroxene compositions (based on more than 1,000 clinopyroxene analyses from more than 30 units, Ellis 2009) has shown that when used in concert with other techniques, clinopyroxene compositions can provide a method for distinguishing individual eruption units. In addition to the clinopyroxenes, all of the units in this study contain two feldspars which further help to constrain correlation. The presence of sanidine allows precise geochronology, and plagioclase composition can vary between units (see below).

Mineral compositions were determined from a combination of thin sections and mineral separates using a JEOL JXA-8600S electron microprobe at the Department of Geology of the University of Leicester using operating conditions of 15 keV, 30 nA and a beam diameter of 10 μm. Synthetic and natural minerals were used as standards, and a ZAF correction was applied; full details are available in Ellis (2009).

Single sanidine and plagioclase crystals were dated using the $^{40}Ar/^{39}Ar$ technique at the NERC Argon Isotope Facility, SUERC. A next-generation ARGUS noble gas multi-collector mass spectrometer was used for isotope measurements (Mark et al. 2009). Weighted averages calculated using Isoplot v3.0 (Ludwig 2003) were used to derive the ages for the stratigraphic units (for data that display normal distributions). Data are reported with 2σ

Table 1 Simplified version of the CAT groups of Bonnichsen et al. (2008), containing the units comprising the correlations examined in this study

CAT group	Age (Ma)	Bulk TiO_2 wt.%	Magnetic polarity	Grasmere area (Fig. 2)	Bruneau–Jarbidge area	Twin Falls area	Northern margin of CSRP
8	10.4–10.7	0.30–0.67	N		CPT XV	Steer Basin Member BB8 Jackpot 7	High Springs rhyolite tuff of Knob
7	10.7–11.0	0.22–0.38	N		CPT XIII	Big Bluff Member BB7 Jackpot 1-6	Frenchman Springs rhyolite Henley rhyolite
5	11.2–11.5	0.26–0.43	R	Ignimbrite of Grasmere Escarpment	CPT XI	BB6 BB5	Windy Gap rhyolite Deer Springs rhyolite tuff of Fir Grove

The ages for CAT groups quoted in the table do not agree perfectly with the ages in this study as the CAT groups were based on geochronology using older standard ages. Units on the N sides of the Snake River Plain are those described by Bonnichsen et al. (2008)

BB Brown's Bench, *CPT* Cougar Point Tuff uncertainties. Summary geochronological data are shown in Table 2, and detailed methodology and full data are provided in the Electronic supplementary material. To allow comparison of our geochronological data to previous age determinations, ages from earlier studies are recalculated to the Fish Canyon Tuff standard age of 28.201 Ma (Kuiper et al. 2008) and quoted to the original reference.

Oxygen isotope analyses were performed at the University of Oregon stable isotope laboratory with data and methodology provided in Electronic supplementary material. In this work, we explore the possibility of using variations in oxygen isotopes as a stratigraphic correlation tool. CSRP rhyolites show a significant and variable depletion in $\delta^{18}O$, with magmatic plagioclase values ranging from −1.4‰ to 3.8‰ (Boroughs et al. 2005). The range of magmatic $\delta^{18}O$ (5.2‰) from the CSRP allied to the precision on the measurements based on standards (better than 0.1‰) suggests oxygen isotopes should be a correlative tool in addition to the methods previously described. All the analyses used here are averages of at least two analyses on plagioclase phenocrysts, and errors on analyses are quoted as two standard deviations. Previously published data (Boroughs et al. 2005) are taken as having an error of ±0.2‰ (Boroughs 2009, personal communication).

Combined correlation evidence

In this section, we combine available field evidence, mineral chemistry, stable isotope compositions and high-precision geochronology to assess correlations of units along the southern margin of the Snake River Plain.

Cougar Point Tuff XI–Brown's Bench 5 (R polarity)

Cougar Point Tuff XI is part of the Cougar Point Tuff succession inferred to have been produced by the Bruneau–Jarbidge eruptive centre (Bonnichsen 1982; Bonnichsen and Citron 1982; Cathey and Nash 2004). It is exposed across southern Idaho and northern Nevada where it forms prominent erosional columns and has a well-exposed fall deposit stratigraphy beneath the ignimbrite. The fall deposits are composed of well-sorted parallel-bedded ashfall layers of centimetre thickness (Fig. 2). The lower part of the ignimbrite contains spherulites that reach more than a metre in diameter, and the top of the unit is a non-welded deposit that contains abundant non-vesicular clasts of black glass.

Brown's Bench 5 located on the Brown's Bench Escarpment (Bonnichsen et al. 2008) is an intensely welded, crystal poor (<5%) rhyolitic unit that has a vesicular upper section. Neither the top nor the base of Brown's Bench 5 is exposed, and its exposed thickness is ~30 m.

Although Cougar Point Tuff XI and Brown's Bench 5 bear no physical similarities to one another, they have identical clinopyroxene compositions (Figs. 3 and 4), with a single mode of pigeonite and two compositions of augite (Fig. 4). The significance of the restricted pigeonite and augite compositions is illustrated in Fig. 4 with respect to the compositions present in CSRP rhyolites as a whole. Plagioclase crystals in both Cougar Point Tuff XI and Brown's Bench 5 are oligoclase, and sanidine is markedly more abundant in these two units than in any other of the ignimbrites studied here.

Average oxygen isotope compositions of plagioclase in the two units are $\delta^{18}O$ 2.60±0.20‰ for Cougar Point Tuff XI

Table 2 Summary data for the units in each correlation

Unit	TiO_2 bulk	Magnetic polarity	Pigeonite Mg wt.% (*n*)	Augite Mg wt.% (*n*)	$^{40}Ar/^{39}Ar$ age (Ma)	MSWD	Plagioclase composition	$\delta^{18}O$feldspar (‰)
Steer Basin Member	0.52	N	5.91, 5.04 (49)	4.85 (21)	10.63±0.08	0.59	Andesine	2.23±0.13
Brown's Bench 8	0.52	N	5.88, 5.14 (46)	4.90 (12)	10.60±0.12	0.99	Andesine	2.32±0.25
Jackpot 7	0.53	N	5.88, 5.15 (30)	5.06 (16)	10.63±0.10	0.65	Andesine	2.19±0.24
Big Bluff Member	0.38	N	Absent	2.39 (33)	10.98±0.07	1.02	Oligoclase	2.98±0.23
Brown's Bench 7	0.33	N	Absent	2.29 (85)	11.05±0.07[a]	–	Oligoclase	2.86 ±0.01
Jackpot 1-6	0.34	N	Absent	Altered	10.98±0.05	0.81	Oligoclase	2.81±0.04
Cougar Point XIII	0.30	N	Absent	2.52 (30)	10.96±0.06	–	Oligoclase	2.84[#] ±0.20
					10.94±0.06			3.22±0.27
					10.89±0.07[a]			
Cougar Point XI	0.30	R	4.23 (10)	3.94,1.85 (20)	11.36±0.07[a]	–	Oligoclase	2.6[#]±0.20
Brown's Bench 5	0.38	R	4.26 (15)	3.88, 1.78 (13)	11.42±0.08	0.81	Oligoclase	2.72±0.06

Values for bulk TiO_2 (Bonnichsen et al. 2008; Ellis 2009), pigeonite, augite and $\delta^{18}O$ are averages

[a] Data from Bonnichsen et al. (2008)

[#] Data from Boroughs et al. (2005)

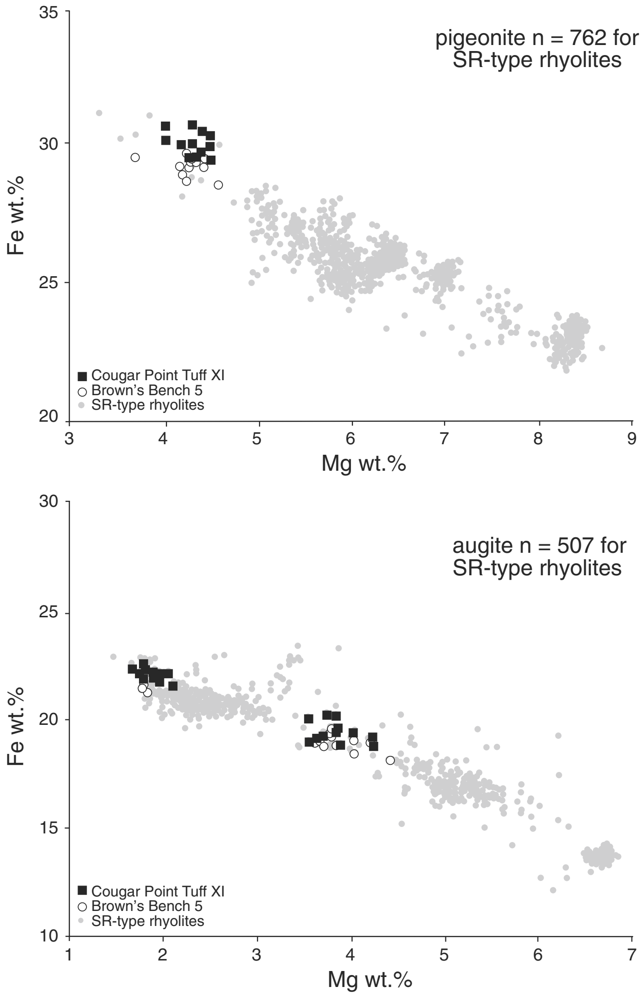


Fig. 4 Clinopyroxene compositions of Cougar Point Tuff XI and Brown's Bench 5 illustrating the good agreement between these units. Note the two distinct modes of augite in both units. Clinopyroxene compositions for the CSRP as a whole (more than 30 rhyolitic units analysed) are represented by the light grey circles with data from Ellis (2009) and Cathey and Nash (2004)

(Boroughs et al. 2005) and $\delta^{18}O$ 2.72±0.03‰ for Brown's Bench 5, within error of each other. A separate sample of Brown's Bench 5 was run independently at Washington State University, giving a $\delta^{18}O$ value of 2.68±0.20‰ and thus lending further support to the identical $\delta^{18}O$ values in these two units (Boroughs 2009, personal communication).

A published $^{40}Ar/^{39}Ar$ age of 11.36±0.07 Ma (2σ) is available for Cougar Point Tuff XI (Bonnichsen et al. 2008) and is indistinguishable from a new $^{40}Ar/^{39}Ar$ age of 11.42± 0.08 Ma (2σ, n=9) determined for the Brown's Bench 5 unit (Table 2 and Electronic supplementary material).

Despite the lack of similarity in the physical characteristics of these two units, we propose on the basis of the geochemical and geochronological data that Cougar Point Tuff XI and Brown's Bench 5 are correlative. Although the lack of similar physical characteristics is a concern, the general similarity of units to each other within the province limits the applicability of lithologic correlation. This general problem typifies some of the difficulties in correlation of CSRP units in that they do not exhibit sufficiently distinctive physical characteristics to distinguish them from other CSRP rhyolites.

Cougar Point Tuff XIII–Big Bluff Member–Jackpot 1–6–Brown's Bench 7 (N polarity)

Cougar Point Tuff XIII ranges from 40 to 80 m in thickness between the Bruneau and Jarbidge canyons and, in places, exhibits a step-like appearance due to differences in weathering characteristics of internal layers (Bonnichsen and Citron 1982). Near Murphy Hot Springs (M on Fig. 1), the base of the ignimbrite overlies approximately 1 m of parallel-bedded ash deposits that contain varying proportions of crystals and are interpreted as ashfall deposits. Throughout much of its exposure in the Bruneau–Jarbidge region, Cougar Point Tuff XIII contains a distinctive layer of lithophysae in the upper half of the unit (Fig. 2).

Some 75 km away from the Bruneau–Jarbidge canyons in the Cassia Mountains, the Big Bluff Member contains a series of well-sorted, parallel-bedded ashfall deposits overlain by an intensely welded, mostly lava-like ignimbrite (sensu Branney and Kokelaar 1992; Fig. 2). These units were previously correlated by Perkins et al. (1995) on the basis of whole rock compositions and geochronology. The Big Bluff Member is a cliff-forming ignimbrite which contains a zone of non-vesicular glass clasts near the base and has crude layering throughout. At the top, the ignimbrite is slightly rheomorphic with gently undulating open folds topped by a thin perlitic vitrophyre. Above the vitrophyre are lithophysae with green chalcedony fills and a pink to orange non-welded tuff containing abundant clasts of non-vesicular black rhyolitic glass (Fig. 2).

Between Cougar Point Tuff XIII and the Big Bluff Member, the Jackpot 1–6 sub-members of Andrews et al. (2008) in the Rogerson Graben are defined by differences in weathering attributes and the presence of lithophysal horizons within the Jackpot ignimbrite (Fig. 2). The majority of the thickness of Jackpot 1–6 is within Jackpot 5, which is rheomorphic near the top and has a thin perlitic vitrophyre with chalcedony-filled lithophysae. Jackpot 6 is a non-welded tuff exhibiting local cross-stratification and containing abundant accretionary lapilli (Fig. 5b).

And finally, between Jackpot 1–6 outcrops and Cougar Point Tuff XIII is Brown's Bench 7 located on the Brown's Bench escarpment (Bonnichsen et al. 2008). This unit has a poorly exposed base and is composed of multiple sub-units with the uppermost unit rheomorphic (Fig. 2).

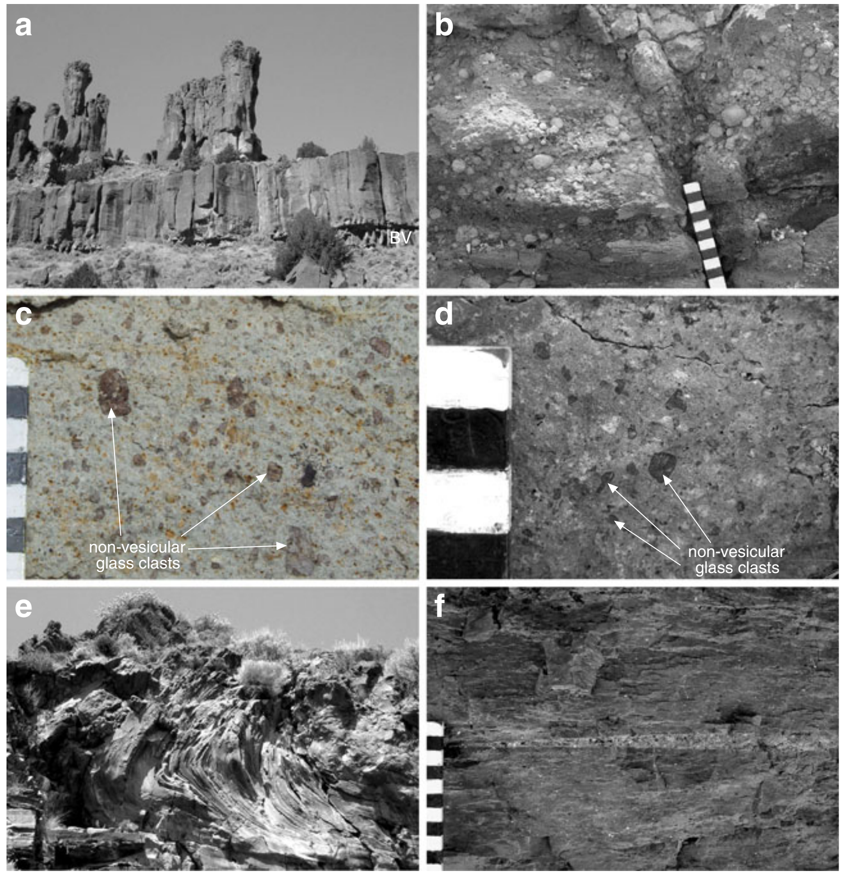


Fig. 5 Field appearance of the ignimbrites correlated in this study. **a** Cougar Point Tuff XI near Jarbidge, Nevada, with prominent erosional columns at the top and basal vitrophyre (*BV*). **b** Accretionary lapilli in partially welded tuff from the Jackpot 6, south of the town of Jackpot, Nevada. **c** Dense non-vesicular rhyolitic glass clasts in Jackpot 3. **d** Dense non-vesicular rhyolitic glass clasts in the base of the Big Bluff Member in Rock Creek, Idaho. **e**. Highly rheomorphic upper section of the Steer Basin Member in Rock Creek. **f** Crystal-rich fiammé in the base of Jackpot 7 of Andrews et al. (2008). *Scale* represents centimetres in all instances

The four units share the distinctive petrographic feature of euhedral to subhedral sanidine crystals mantled by irregular quartz and sanidine intergrowths. This feature which is found in the upper part of the Big Bluff Member (Ellis et al. 2010) is also reported from Jackpot 1–6 (Andrews et al. 2008) and Cougar Point Tuff XIII (Bonnichsen and Citron 1982). All four of the ignimbrites are characterised by a lack of pigeonite (otherwise common to CSRP rhyolites) and possession of only a single augite composition (Fig. 6), although clinopyroxenes in Jackpot 1–6 are too altered to be certain of composition (e.g. Andrews et al. 2008). Plagioclase in all the units is oligoclase $An_{25–30}$ (Fig. 7).

Oxygen isotopes ($\delta^{18}O$) as determined on plagioclase are: Big Bluff Member, 2.98±0.22‰; Jackpot 1–6, 2.81±0.04‰; Brown's Bench 7, 2.86±0.01‰; and Cougar Point Tuff XIII is slightly higher with an average value of 3.22±0.27‰ (although a different sample yielded 2.84±0.20‰, Boroughs 2009, personal communication). Such a range in the O isotope data does not negate a potential correlation between these units; a greater total range of feldspar $\delta^{18}O$ has been recorded in individual rhyolite units further east in the Snake River Plain (Bindeman et al. 2007).

$^{40}Ar/^{39}Ar$ ages of 10.98±0.07 Ma (2σ, n=14) for the Big Bluff Member and 10.97±0.05 Ma (2σ, n=21) for Jackpot 1–6 were determined (Table 2 and Electronic supplementary material), and they agree well with published ages of 11.05±0.07 Ma (2σ) for Brown's Bench 7 (Bonnichsen et al. 2008) and 10.93±0.06 Ma (2σ) for Cougar Point Tuff XIII (average of three separate determinations; Bonnichsen et al. 2008).

The similarities in plagioclase and augite compositions and the absence of pigeonite in the Cougar Point Tuff XIII, Big Bluff Member, Jackpot 1–6 and Brown's Bench 7 units suggest that all these units are the product of one eruption. The precise geochronology further supports such a proposal. The oxygen isotope compositions of the units are in broad agreement albeit with the values from Cougar Point Tuff XIII slightly higher in one determination.

Steer Basin Member–Jackpot 7–Brown's Bench 8 (N polarity)

The Steer Basin Member is an intensely welded and lava-like ignimbrite located in the Cassia Mountains, south of Twin Falls (Fig. 1). Beneath the ignimbrite, a distinctive layer of aphyric, black obsidian represents a crystal-free ashfall deposit (possibly of co-ignimbrite origin) that was fused to glass by heat conducted downwards upon emplacement of the ignimbrite. The ignimbrite contains ~10–15%

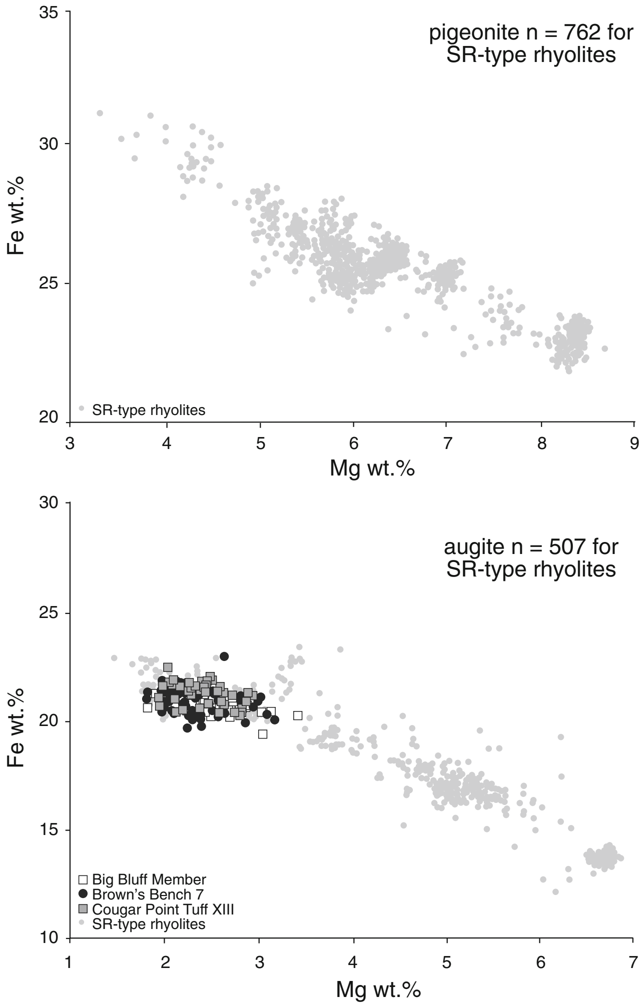


Fig. 6 Clinopyroxene compositions of Cougar Point Tuff XIII, Big Bluff Member and Brown's Bench 7 illustrating the good agreement between these units. The absence of pigeonite is distinctive for this correlation, as it is generally present in central Snake River Plain ignimbrites (e.g. Cathey and Nash 2004; Ellis et al. 2010)

crystals, and above the basal vitrophyre in the lower couple of metres of the unit fiammé of grey, crystal-rich vesicular tuffs are present (Ellis 2009). The upper third of the ignimbrite is intensely rheomorphic and deformed into open folds that may be up to 1 m in amplitude. A thin perlitic vitrophyre occurs above the rheomorphic zone, and non-welded tuff is rarely preserved within the synforms at the top of the unit (Fig. 2).

Located in the Rogerson Graben (RG on Fig. 1), Jackpot 7 also contains crystal-rich fiammé in the base of the unit (Andrews et al. 2008). Although not reported by Andrews et al. (2008), a basal vitrophyre in Jackpot 7 is underlain by a distinctive layer of obsidian (Fig. 2).

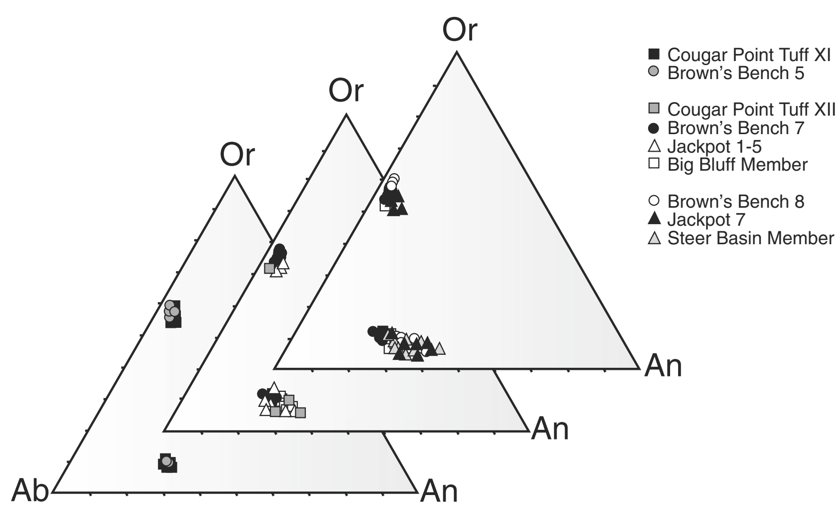
Brown's Bench 8 is a ≥40-m-thick intensely welded, lava-like rhyolite unit that has a rheomorphic upper third with open folds (Fig. 2). The base of the unit is not well exposed.

All three units possess two populations of pigeonite that have distinctive compositions when compared to the other units in this study (Fig. 8). Augite compositions in the three units overlap, albeit over a broader range than the pigeonite compositions (Fig. 8). We know of no other rhyolite in the CSRP which contains the same combination of pigeonite and augite compositions. Plagioclase in all three of these ignimbrites is andesine $An_{33–40}$, in contrast to the oligoclase recorded in the older Cougar Point Tuff XIII and Cougar Point Tuff XI ignimbrites.

An oxygen isotope composition ($\delta^{18}O$) for the Steer Basin Member is 2.24±0.13‰, which is in close agreement with that of 2.19±0.24‰ for Jackpot 7 and 2.44±0.25‰ for Brown's Bench 8.

$^{40}Ar/^{39}Ar$ geochronology for these three units provided ages of 10.63±0.08 Ma for the Steer Basin Member, 10.63±0.1 Ma for Jackpot 7, and 10.66±0.09 Ma for Brown's Bench 8 (Table 2; Fig. 9).

Fig. 7 Feldspar compositions of all the units within the three correlations in this study. Jackpot 1–6 and Jackpot 7 compositions from Andrews et al. (2008). The youngest units in this work contain plagioclase with a different composition to Cougar Point Tuff XI and XIII



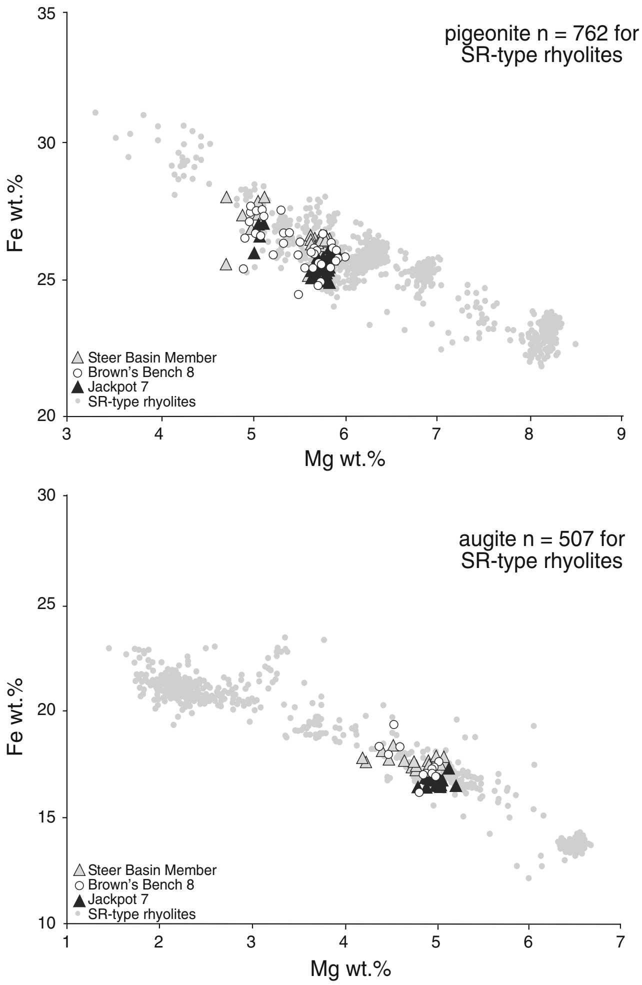


Fig. 8 Clinopyroxene compositions of the Steer Basin Member, Jackpot 7 and Brown's Bench 8 illustrating the good agreement between these units. The difference in composition between this correlation and the others considered here may be seen by comparison with Figs. 4 and 6

The similarities seen in these units in the field (e.g. basal layer of obsidian, fiammé near the base of the ignimbrite) are supported by multiple lines of geochemical evidence, with pigeonite, augite and feldspar compositions identical. The similarity in oxygen isotopic compositions and the $^{40}Ar/^{39}Ar$ geochronology serve to further support the correlation with the newly defined unit termed the Steer Basin Tuff.

Discussion

Estimated eruption volumes

On the basis of the evidence presented here, we propose that the nine units described above are three, albeit large, ignimbrites which are subsequently termed Cougar Point Tuff XI, Cougar Point Tuff XIII and the Steer Basin Tuff in order of decreasing age. Whilst this reduces the total number of ignimbrites in the CSRP, we can revise the estimated volumes of these individual ignimbrites. The estimation of eruption volumes is difficult because no widely accepted method of doing so exists. Here, we provide three methods for estimating the volumes of Cougar Point Tuff XI, Cougar Point Tuff XIII and the Steer Basin Tuff; each method results in different final volume estimations.

Method 1

The volumes of ignimbrites are calculated by applying the average thickness of the unit to the known areal distribution of the unit. Examples of volume estimates that utilise this method include the Kneeling Nun Tuff (Elston et al. 1975) and the Bishop Tuff (Bailey 1976). For the three ignimbrites, in this study, this results in volumes of ~180 km^3 (2,773 $km^2 \times 65$ m thick) for Cougar Point Tuff XI, ~500 km^3 (6,719 $km^2 \times 75$ m thick) for Cougar Point Tuff XIII and ~177 km^3 (3,221 $km^2 \times 55$ m thick) for the Steer Basin Tuff (Fig. 10).

Method 2

In this method, the outflow volumes as calculated above are inferred to be equal to the volumes of intracaldera ignimbrite, thus doubling the estimated volumes to ~360 km^3 for Cougar Point Tuff XI, ~1,000 km^3 for Cougar Point Tuff XIII and ~354 km^3 for the Steer Basin Tuff. As previously mentioned, no calderas in the central Snake River Plain are currently exposed, so their size is consequently unknown;

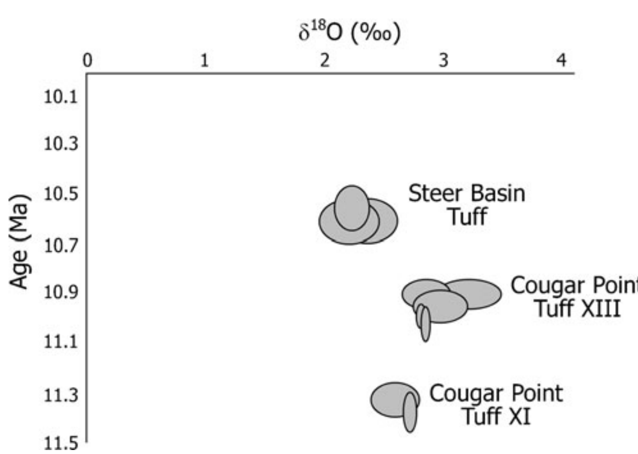


Fig. 9 Oxygen isotopic compositions of the units in the three correlations, determined from the average of two or more determinations with additional data from Boroughs et al. (2005) and Bonnichsen et al. (2008). Oxygen isotopic compositions are plotted against $^{40}Ar/^{39}Ar$ geochronology with the size of the ellipse representing the error on each measurement

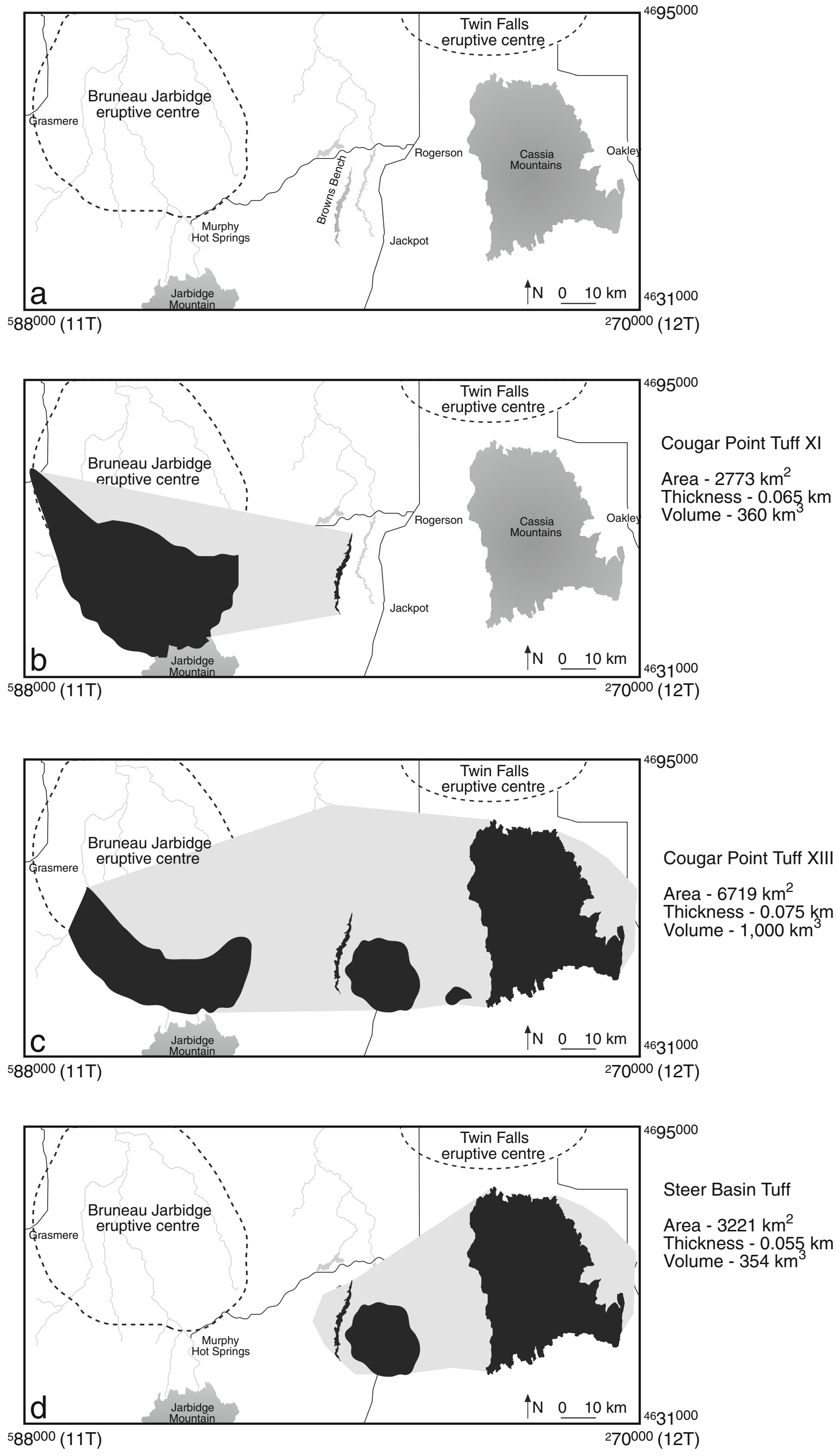


Fig. 10 Simplified maps showing the outcrop of the units in these correlations, areas covered and estimated volumes. **a** Overview map of the area. **b** Outcrop and volume of Cougar Point Tuff XI. **c** Outcrop and volume of Cougar Point Tuff XIII. **d** Outcrop and volume of the Steer Basin Tuff

however, the addition of inferred intracaldera ignimbrite to outflow volumes is a widespread practice (e.g. Lipman 1997; Maughan et al. 2002; Morgan and McIntosh 2005). The volumes of intracaldera deposits are strongly dependent upon the style of caldera collapse and caldera morphology (e.g. Lipman 1997), and therefore, any inclusion of an intracaldera component is an inference.

Method 3

This method assumes that the volumes of intracaldera ignimbrite, outflow sheet and associated ashfall are equal, in essence tripling the volumes proposed in "Method 1", resulting in estimated volumes of 540 km^3 for Cougar Point Tuff XI, 1,500 km^3 for Cougar Point Tuff

XIII and 531 km^3 for the Steer Basin Tuff. This method has been used to estimate the volume of a number of voluminous deposits (e.g. Cerro Galan, Sparks et al. 1985; Toba, Rose and Chesner 1987). Ashfall deposits associated with the CSRP eruptions are known to exist in intermontane basins across the northwestern USA and on the plains of Nebraska and Kansas (Perkins and Nash 2002; Rose et al. 2003; Anders et al. 2009). For example, one ashfall deposit located at Aldrich Station in southwestern Nevada and South Willow Canyon, central Utah, has been correlated to Cougar Point Tuff XIII, some 500 km away (Perkins et al. 1998; Perkins and Nash 2002). Similarly, ashfall in southern Nevada has been correlated to Cougar Point Tuff XI (Perkins et al. 1998). Ashfall deposits are rarely exposed underneath the ignimbrites in the CSRP, and locations are too scattered to allow any reasonable reconstructions of volumes. Moreover, ash in some places has been significantly reworked, e.g. at Trapper Creek, Idaho (Perkins et al. 1995) and in the Ogallala Group of Nebraska where there is evidence of significant thickening of deposits into topography and of minor ripple cross lamination (Rose et al. 2003). Cumulatively, this leads to a great deal of uncertainty when attempting to estimate the volume of ashfall in the CSRP.

Preferred volume estimates

In this work, we consider the volumes produced using "Method 2" to be the most realistic. Although no calderas are currently exposed, we do not know of any eruptions forming ignimbrite outflow sheets >50 km^3 that did not produce a caldera. Commonly, the volume of the intracaldera ignimbrite is assumed to be of equivalent volume to the extracaldera deposit (e.g. Lipman 1984) and where detailed studies have been made, this assumption has been found to be legitimate (e.g. Rose and Chesner 1987; Wilson 2001). A number of other studies have shown that the intracaldera volume may be larger than the outflow ignimbrite (e.g. Bishop Tuff, Hildreth and Wilson 2007; Bandelier Tuff, Self 2010). In some cases, the intracaldera volumes have been found to be significantly larger than the outflow sheet (e.g. approximately 75% total volume for the McDermitt Tuff, northern Nevada, authors' unpublished data; 66% total volume for the Atana ignimbrite, Lindsay et al. 2001; 83% total volume for Vilama caldera, Soler et al. 2007). Similar order of magnitude assumptions have also been made for the volume of intrusive to extrusive products in volcanic fields (e.g. de Silva and Gosnold 2007). Therefore, we consider assuming an equivalent volume of intracaldera ignimbrite to be reasonable.

Although likely a significant component of the total volume, an ashfall component cannot be reasonably estimated for these eruptions and therefore is not included within the volume estimates. Moreover, an ashfall component is not included in the volume calculations of the ignimbrites from the younger Heise and Yellowstone eruptive centres, so exclusion from our estimates makes for direct comparison. For these reasons, we propose volumes of ~350 km^3 dense rock equivalent (DRE; see later) for Cougar Point Tuff XI and the Steer Basin Tuff, and ~1,000 km^3 DRE for Cougar Point Tuff XIII. We emphasise that we consider these to be minimum estimates.

Comparison with Yellowstone track volumes

The bulk deposit volumes of the ignimbrites in this study are comparable to those from other parts of the Yellowstone track. Cougar Point Tuff XI and the Steer Basin Tuff have slightly larger volumes than the Mesa Falls Tuff, although the latter has a slightly larger area (2,700 km^2, Christiansen 2001; Fig. 11a). Cougar Point Tuff XIII has a similar estimated volume to Lava Creek Tuff (~1,000 km^3) though the latter has the greater areal distribution (7,300 km^2). However, the characteristics of the deposits are markedly different between the ignimbrites of the central Snake River Plain which are intensely welded (e.g. Branney et al. 2008) and those of other parts of the hotspot track which are less welded and contain pumice (e.g. Christiansen 2001). Clearly comparing the bulk volume of a lava-like ignimbrite with one which contains abundant vesicles within pumice clasts does not provide reasonable results. To circumvent this, Mason et al. (2004) provide a method of determining the magnitude of an eruption based on erupted mass. To use the classification of Mason et al. (2004), the density of the rock is required which was measured directly (see Electronic supplementary material for details) and estimated using the MAGMA programme (Wohletz 1999). Measured densities ranged between 2,330 and 2,285 kg m^{-3} and calculated densities were between 2,365 and 2,341 kg m^{-3}. The magnitude scale favours the densely welded CSRP ignimbrites so making Cougar Point Tuff XIII slightly larger magnitude than the Lava Creek Tuff; relative magnitudes of hotspot track deposits are illustrated in Fig. 11b.

Eruption frequency

In an attempt to assess the frequency of explosive eruptions in the CSRP, we have constructed a plot of the eruption frequency based on the ignimbrite record (Fig. 12). Previous attempts at producing such plots for the Yellowstone track have been based on well-studied ashfall stratigraphies (Perkins et al. 1995; Rose et al. 2003; Perkins and Nash 2002; Nash et al. 2006; Anders et al. 2009). Within these studies of the ashfall record, there have been discrepancies over the frequency and distribution of eruptions. For example, some studies have shown a

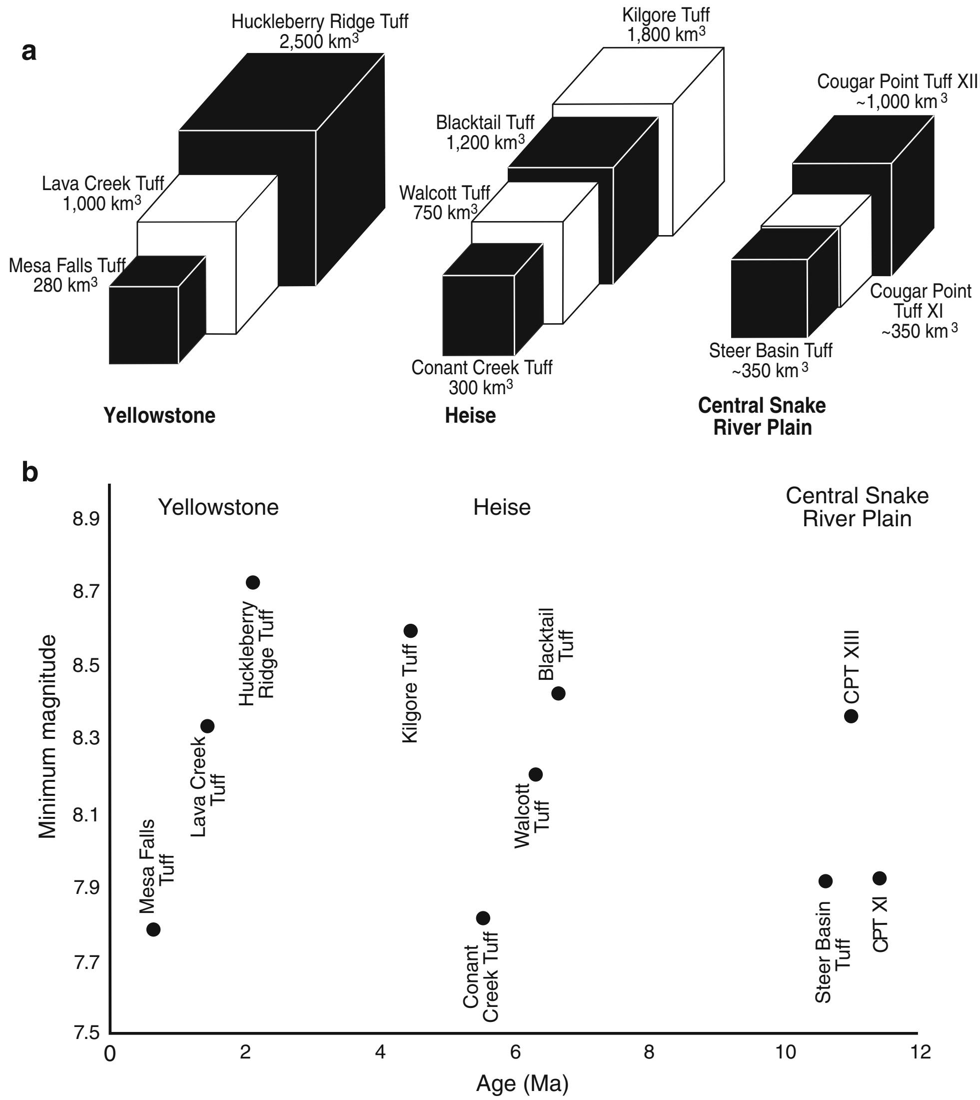


Fig. 11 Volumes of the three correlations defined in this study compared to other eruption volumes estimated from the Yellowstone hotspot with magnitudes calculated after Mason et al. (2004)

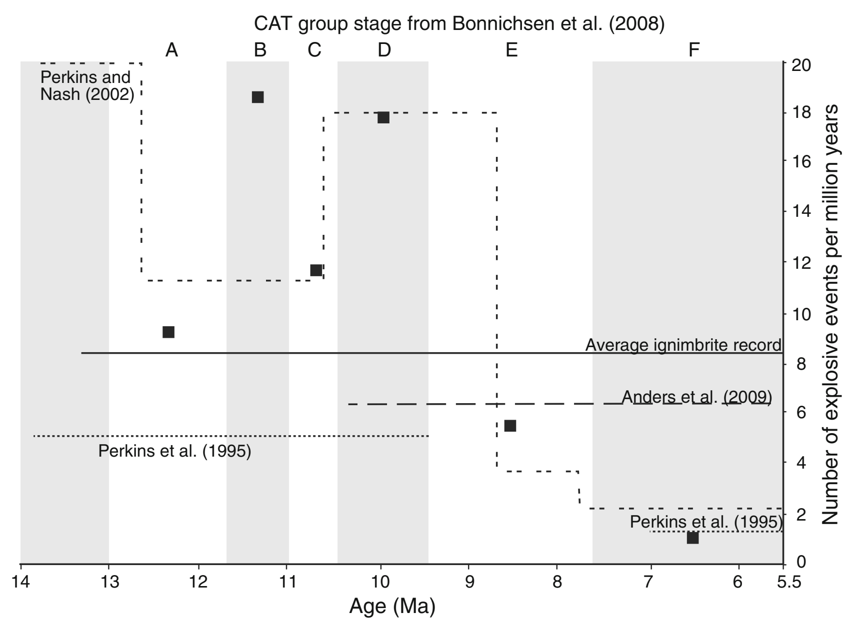


Fig. 12 Comparison of eruption frequency from the Yellowstone hotspot as defined from the ignimbrite record and the ashfall record. *Black squares* represent ignimbrite record using averages for the periods **a**–**f** in Bonnichsen et al. (2008) and taking into account the correlations made in this work

significant decrease in eruptive frequency after ~9 Ma (Perkins et al. 1995; Perkins and Nash 2002), whereas Anders et al. (2009) found eruption frequencies three times greater than did earlier workers.

The eruptive frequency as recorded by the ignimbrite record is shown in Fig. 12. The CAT groups of Bonnichsen et al. (2008) are themselves grouped into periods A–F, and the ignimbrite record is based on averaging the number of ignimbrites found within any of these periods. This record also contains a number of units of equivocal origin, and in these cases, the numbers were split evenly between lava and ignimbrites (this is conservative as in the record of units of known origin ignimbrites are almost three times as common as lavas). Following the correlations made in this study, the number of ignimbrites is reduced by 6. This change results in a decrease of eruptive frequency from 20 to 11.6 explosive eruptions per million years and moves the ignimbrite record closer to the values suggested by the ashfall records.

Agreement between the ashfall and ignimbrite records through the CSRP is generally good, except for period 'B' of Bonnichsen et al. (2008). At period 'B', there appears to be a significant over-estimation of eruptions in the ignimbrite record compared to the ashfall record. This suggests that there may be ignimbrites present in the outflow succession of the Snake River Plain that have correlative units yet to be recognised. Although there is good agreement between the ignimbrite and ashfall record in period D, during this period, the ashfall record is thought to be over-estimated (Perkins and Nash 2002). Therefore, the eruptive frequency of the ignimbrite record may also be over-estimated and a number of ignimbrites in this period may be correlatives.

Further potential correlations

Steer Basin Tuff and Cougar Point Tuff XV?

It is not known whether the Steer Basin Tuff (Fig. 2) correlates to any of the units in the Bruneau–Jarbidge area. Physically, the Steer Basin Tuff and Cougar Point Tuff XV share a number of similar characteristics, including the presence of crystal aggregates of augite, pigeonite, opaque oxides and plagioclase (as reported in the Steer Basin Member, Ellis et al. 2010). Additionally, numerous small fiammé (Bonnichsen and Citron 1982) are present in both units (e.g. Fig. 5f). Bonnichsen and Citron (1982) and Bonnichsen et al. (2008) refer to the uppermost ignimbrite in Bruneau and Jarbidge canyons as Cougar Point Tuff XV, whereas Perkins et al. (1995) found that these units in Bruneau and Jarbidge canyon have different whole rock and glass compositions; they refer to them as CPT XVb (canyon of the Bruneau river) and CPT XVj (canyon of the Jarbidge river). Cathey and Nash (2004) confirmed the work of Perkins et al. (1995) by showing that CPT XVj and CPT XVb have different clinopyroxene compositions. On the basis of whole rock composition, Perkins et al. (1995) suggested that CPT XVb might be a correlative of the Steer Basin Tuff. The clinopyroxene compositions of CPT XVb unit agree well with those of the Steer Basin Tuff, whereas augite compositions in CPT XVj are distinctly different and pigeonite is absent in this unit (Fig. 13). The age of Cougar Point Tuff XV has not been directly determined, but an inferred age of 10.5 Ma (based on interpolation between units of known age) is widely accepted (Perkins et al. 1995, 1998; Cathey and Nash 2004; Bonnichsen et al. 2008). Such an age correlates well with age data for the Steer Basin Tuff (see above). The agreement between the units in terms of

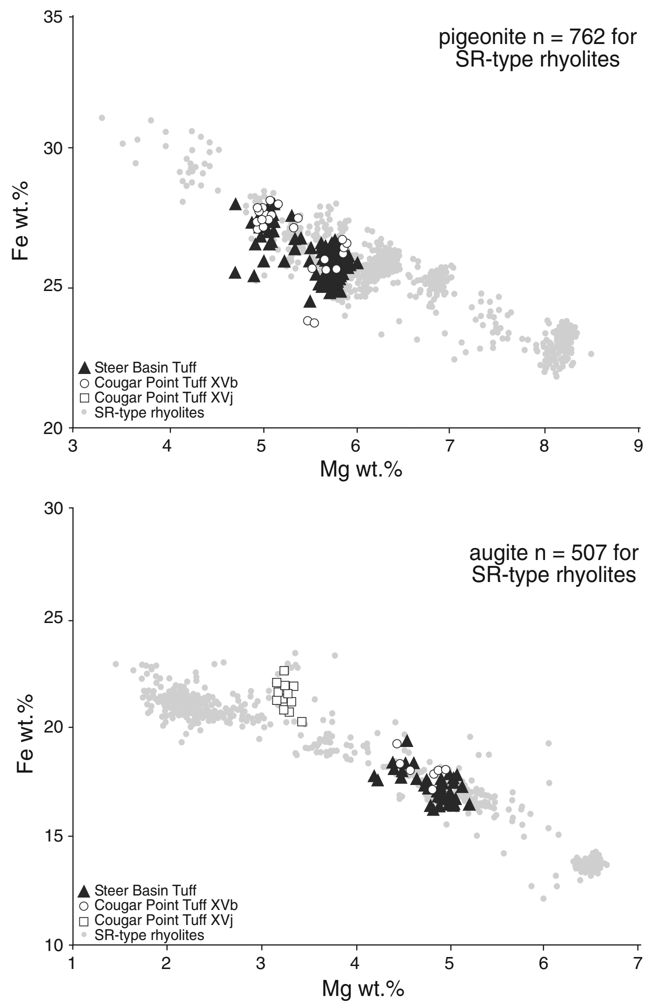


Fig. 13 Clinopyroxene compositions for the newly correlated Steer Basin Tuff compared to the compositions of Cougar Point Tuff XV in the canyons of the Bruneau (CPT XVb) and Jarbidge (CPT XVj) rivers (Cathey and Nash 2004) illustrating the possibility of correlation between the Steer Basin Tuff and Cougar Point Tuff XVj

physical characteristics, whole rock composition and clinopyroxene compositions clearly portends that the Steer Basin Tuff and Cougar Point Tuff XVb are correlatives; however, without precise geochronology, we cannot confirm such a correlation. If the correlation can be confirmed, then the area covered by the Steer Basin Tuff would be slightly smaller than that covered by Cougar Point Tuff XIII and with thicknesses between 30–100 m would result in a volume estimate≈600 km^3.

Cougar Point Tuff XI and tuff of Fir Grove?

The deposits of Cougar Point Tuff XI extend from the Bruneau–Jarbidge region, east to Brown's Bench (Fig. 10) where the displacement on the Brown's Bench Fault leaves it stratigraphically too low to be exposed in the Rogerson Graben (Andrews et al. 2008). To the north of the plain in the East Bennett Hills, the reverse polarity tuff of Fir Grove has whole rock compositions (TiO_2 0.28–0.40 wt.%) and a low crystal content, similar to Cougar Point Tuff XI. The age of the tuff of Fir Grove has been determined by $^{40}Ar/^{39}Ar$ as 11.17±0.08 Ma (Oakley and Link 2006), close to but not within error of the 11.36± 0.07 Ma age for Cougar Point Tuff XI (Bonnichsen et al. 2008). However, the age of the tuff of Fir Grove was generated by step heating of multiple sanidines rather than single crystal work, and the full dataset (including monitors) is unavailable, so further work is required to test the currently accepted age. Detailed work to test this correlation using other isotopic compositions of the units (O, Sr and Pb isotopes) and using clinopyroxene chemistry is ongoing. Should Cougar Point Tuff XI stretch from the southern margin of the Bruneau–Jarbidge eruptive centre to the East Bennett Hills, then the volume of the resultant unit could rank alongside that of the Huckleberry Ridge Tuff, the largest known rhyolitic unit from the Yellowstone hotspot.

Conclusions

The results of this study have implications for the central Snake River Plain and Yellowstone hotspot track in terms of eruptive size, frequency and style. More broadly, the production of ~1,700 km^3 of rhyolitic magma, all of which is low $\delta^{18}O$ (2.3-2.9‰), may allow constraints to be placed upon models of magma genesis for such large-scale eruptions. The main conclusions of our study are listed below.

1. Despite the lack of distinctive physical features in the CSRP ignimbrites, correlation between regions, some 50 km apart, is possible.
2. Correlations have been proposed on the basis of field evidence (e.g. relative stratigraphic positions) and detailed geochemistry. The combination of multiple techniques, particularly the use of pigeonite and augite compositions and high-precision geochronology, provides a powerful means of correlation.
3. The volumes of three newly defined ignimbrites have been conservatively estimated ~350 km^3 for Cougar Point Tuff XI and the Steer Basin Tuff and ~1,000 km^3 for Cougar Point Tuff XIII.
4. Given the distribution of the units as currently known, it appears likely that further correlations may be possible. Large-scale ignimbrites are most commonly distributed in a radial or semi-radial distribution. There is no reason to suggest that such a distribution should not ultimately be found for ignimbrites in the central Snake River Plain.
5. Correlating necessarily reduces the number and frequency of the eruptions recorded from the CSRP but gives better agreement with ashfall deposits.

Acknowledgments This work represents part of the PhD of BE funded by NERC (NER/S/A/2004/12340). O isotope analyses at the U of Oregon were supported by the EAR-CAREER-0844772, and additional funding from NSF (EAR-0911457) is gratefully acknowledged. We are grateful to Scott Boroughs for providing unpublished oxygen isotope data and Henrietta Cathey and Shan de Silva for comments on an earlier draft. Thorough reviews from Barbara Nash and Jamie Gardner improved the final version, and editorial assistance from Michael Clynne is also appreciated.

References

Anders M, Saltzman J, Hemming SJ (2009) Neogene tephra correlations in eastern Idaho and Wyoming: implications for Yellowstone hotspot-related volcanism and tectonic activity. Geol Soc Am Bull 121:837–856. doi:10.1130/B26300.1

Andrews GDM, Branney MJ (2011) Emplacement and rheomorphic deformation of a large, lava-like rhyolitic ignimbrite: Grey's Landing, southern Idaho. Geol Soc Am Bull 123:725–743. doi:10.1130/B30167.1

Andrews GDM, Branney MJ, Bonnichsen B, McCurry M (2008) Rhyolitic ignimbrites in the Rogerson Graben, southern Snake River Plain volcanic province: volcanic stratigraphy, eruption history and basin evolution. Bull Volcanol 70:269–291. doi:10.1007/s00445-007-0139-0

Bachmann O, Bergantz G (2008) The magma reservoirs that feed supereruptions. Elements 4:17–21

Bachmann O, Dungan M, Lipman P (2002) The Fish Canyon magma body, San Juan Volcanic Field, Colorado: rejuvenation and eruption of an upper-crustal batholith. J Petrol 43:1469–1503

Bailey RA (1976) Volcanism, structure, and geochronology of Long Valley caldera, Mono County, California. J Geophys Res 81:725–744

Baines PG, Sparks RSJ (2005) Dynamics of giant volcanic ash clouds from supervolcanic eruptions. Geophys Res Lett 32:L24808. doi:10.1029/2005GL024597

Bindeman IN, Watts KE, Schmitt AK, Morgan LA, Shanks PWC (2007) Voluminous low $\delta^{18}O$ magmas in the late Miocene Heise Volcanic Field, Idaho: implications for the fate of Yellowstone hotspot calderas. Geology 35:1019–1022. doi:10.1130/G24141A.1

Bonnichsen B (1982) The Bruneau-Jarbidge eruptive center, Southwestern Idaho. In: Bonnichsen B, Breckenridge RM (eds) Cenozoic geology of Idaho. Idaho Bur Min Geol Bull 26:237–254

Bonnichsen B, Citron GP (1982) The Cougar Point Tuff, southwestern Idaho. In: Bonnichsen B, Breckenridge RM (eds) Cenozoic geology of Idaho. Idaho Bur Mines Geol Bull 26:255–281

Bonnichsen B, Godchaux MM (2002) Late Miocene, Pliocene, and Pleistocene geology of southwestern Idaho with emphasis on basalts in the Bruneau-Jarbidge, Twin Falls, and western Snake River Plain regions. In: Bonnichsen B, White CM, McCurry M (eds) Tectonic and magmatic evolution of the Snake River Plain Volcanic Province. Idaho Geol Surv Bull 30:233–312

Bonnichsen B, Leeman WP, Honjo N, McIntosh WC, Godchaux MM (2008) Miocene silicic volcanism in southwestern Idaho: geochronology, geochemistry, and evolution of the central Snake River Plain. Bull Volcanol 70:315–342. doi:10.1007/s00445-007-0141-6

Boroughs S, Wolff J, Bonnichsen B, Godchaux M, Larson P (2005) Large-volume, low-$\delta^{18}O$ rhyolites of the central Snake River Plain, Idaho, USA. Geology 33:821–824. doi:10.1130/G21723.1

Branney MJ, Kokelaar BP (1992) A reappraisal of ignimbrite emplacement: progressive aggradation and changes from particulate to non-particulate flow during emplacement of high-grade ignimbrite. Bull Volcanol 54:504–520

Branney MJ, Bonnichsen B, Andrews GDM, Ellis B, Barry TL, McCurry M (2008) 'Snake River (SR) -type' volcanism at the Yellowstone hotspot track: distinctive products from unusual, high-temperature silicic super-eruptions. Bull Volcanol 70:293–314. doi:10.1007/s00445-007-0140-7

Brueseke ME, Hart WK (2008) Geology and petrology of the mid-Miocene Santa Rosa-Calico volcanic field, northern Nevada. Nevada Bureau of Mines and Geology 113, 44p

Camp VE (1995) Mid-Miocene propagation of the Yellowstone mantle plume head beneath the Columbia River basalt source region. Geology 23:435–438

Camp VE, Hanan BB (2008) A plume-triggered delamination origin for the Columbia River basalt group. Geosph 4:480–495

Camp VE, Ross ME (2004) Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific Northwest. J Geophys Res 109:B08204. doi:10.1029/2003JB002838

Cathey HE, Nash BP (2004) The Cougar Point Tuff: implications for thermochemical zonation and longevity of high-temperature, large-volume silicic magmas of the Miocene Yellowstone hotspot. J Petrol 45:27–58. doi:10.1093/petrology/egg081

Christiansen RL (2001) The Quaternary and Pliocene Yellowstone Plateau Volcanic Field of Wyoming, Idaho, and Montana. US Geol Sur Prof Paper 729-G:145

Christiansen RL, Foulger GR, Evans JR (2002) Upper mantle origin of the Yellowstone hotspot. Geol Soc Am Bull 114:1245–1256

Coble MA, Mahood GA (2008) New geologic evidence for additional 16.5–15.5 Ma silicic calderas in northwest Nevada related to initial impingement of the Yellowstone hot spot. IOP Conf Series: Earth and Env Sci 3:012002

de Silva SL, Gosnold WD (2007) Episodic construction of batholiths: insights from the spatiotemporal development of an ignimbrite flare-up. J Volcanol Geotherm Res 167:320–335

Ellis BS (2009) Rhyolitic explosive eruptions of the central Snake River Plain, Idaho: investigations of the lower Cassia Mountains succession and surrounding areas. Unpublished PhD thesis, University of Leicester, 169 p

Ellis B, Branney MJ (2010) Silicic phreatomagmatism in the Snake River Plain: the Deadeye Member. Bull Volcanol 72:1241–1257. doi:10.1007/s00445-010-0400-9

Ellis BS, Barry TL, Branney MJ, Wolff JA, Bindeman I, Wilson R, Bonnichsen B (2010) Petrologic constraints on the development of a large-volume, high temperature, silicic magma system: the Twin Falls eruptive centre, central Snake River Plain. Lithos 120:475–489. doi:10.1016/j.lithos.2010.09.008

Elston WE, Seager WR, Clemons RE (1975) Emory cauldron, Black Range, New Mexico, source of the Kneeling Nun Tuff. Field Conf Guide NM Geol Soc 26:283–292

Evans JG (1992) Geologic map of the Dooley Mountain Quadrangle, Baker County, Oregon. US Geol Survey Geology Quad GQ-1694, scale 1:24000

Gardner JE, Layer PW, Rutherford MJ (2002) Phenocrysts versus xenocrysts in the youngest Toba Tuff: implications for the petrogenesis of 2800 km^3 of magma. Geology 30:347–350

Godchaux MM, Bonnichsen B (2002) Syneruptive magma-water and posteruptive lava–water interactions in the Western Snake River Plain, Idaho, during the past 12 million years. In: Bonnichsen B, White CM, McCurry M (eds) Tectonic and magmatic evolution of the Snake River Plain Volcanic Province. Idaho Geol Surv Bull 30:387–434

Henry CD, Price JG, Rubin JN, Parker DF, Wolff JA, Self S, Franklin R, Barker DS (1988) Widespread, lava-like silicic volcanic rocks of Trans-Pecos Texas. Geology 16:509–512

Henry CD, Castor SB, McIntosh WC, Heizler MT, Cuney M, Chemillac R (2006) Timing of oldest Steens basalt magmatism from precise dating of silicic volcanic rocks, McDermitt caldera and northwest Nevada Volcanic Field. Eos Transactions AGU 87 (52)

Hildreth W, Wilson CJN (2007) Compositional zoning of the Bishop Tuff. J Petrol 48:951–999. doi:10.1093/petrology/egm007

Honjo N, Bonnichsen B, Leeman WP, Stormer JC (1992) Mineralogy and geothermometry of high-temperature rhyolites from the central and western Snake River Plain. Bull Volcanol 54:220–237

Hooper PR, Camp VE, Reidel SP, Ross ME (2007) The origin of the Columbia River Flood Basalt province: plume versus non-plume models. In: Foulger G, Jurdy D (eds) Plates, plumes and planetary processes. Geol Soc Am Spec Pap 430:635–668

Jellinek AM, De Paolo DJ (2003) A model for the origin of large silicic magma chambers: precursors of caldera-forming eruptions. Bull Volcanol 65:363–381

Jones GS, Gregory JM, Stott PA, Tett SFB, Thorpe RB (2005) An AOGCM simulation of the climate response to a volcanic super-eruption. Clim Dyn 25:725–738

Jordan BT, Grunder AL, Duncan RA, Deino AL (2004) Geochronology of age-progressive volcanism of the Oregon High Plains: implications for the plume interpretation of Yellowstone. J Geophys Res 109:B10202–B10221

Kuiper KF, Deino A, Hilgen FJ, Krijgsman W, Renne PR, Wijbrans JR (2008) Synchronizing rock clocks of Earth history. Science 320:500–504. doi:10.1126/science.1154339

Lanphere MA, Champion DE, Christiansen RL, Izett GA, Obradovich JD (2002) Revised ages for tuffs of the Yellowstone plateau volcanic field: assignment of the Huckleberry Ridge Tuff to a new geomagnetic polarity event. Geol Soc Am Bull 114:559–568. doi:10.1130/0016-7606(2002)114<0559:RAFTOT>2.0.CO;2

Leeman WP, Annen C, Dufek J (2008) Snake River Plain–Yellowstone silicic volcanism: implications for magma genesis and magma fluxes. Geol Soc Lond Spec Publ 304:235–259. doi:10.1144/SP304.12

Leeman WP, Schutt DL, Hughes SS (2009) Thermal structure beneath the Snake River Plain: implications for the Yellowstone hotspot. J Volcanol Geotherm Res 188:57–67. doi:10.1016/j.jvolgeores.2009.01.034

Lindsay JM, de Silva S, Trumbull R, Emmermann R, Wemmer K (2001) La Pacana caldera, N. Chile: a re-evaluation of the stratigraphy and volcanology of one of the world's largest resurgent calderas. J Volcanol Geotherm Res 106:145–173. doi:10.1093/petrology/42.3.459

Lipman PW (1984) The roots of ash-flow calderas in North America: windows into the tops of granitic batholiths. J Geophys Res 89:8801–8841

Lipman PW (1997) Subsidence of ash-flow calderas: relation to caldera size and magma-chamber geometry. Bull Volcanol 59:198–218

Ludwig KR (2003) Isoplot 3.00. Berkeley Geochronology Center, Spec Pub 4, 70 p

Manea VC, Manea M, Leeman WP, Schutt DL (2009) The influence of plume head–lithosphere interaction on magmatism associated with the Yellowstone hotspot track. J Volcanol Geotherm Res 188:68–85. doi:10.1016/j.jvolgeores.2008.12.012

Mark DF, Barfod D, Stuart FM, Imlach J (2009) The ARGUS multicollector noble gas mass spectrometer: performance for $^{40}Ar/^{39}Ar$ geochronology. Geochem Geophys Geosyst 10(2). doi:10.1029/2009GC002643

Mason BG, Pyle DM, Oppenheimer C (2004) The size and frequency of the largest explosive eruptions on Earth. Bull Volcanol 66:735–768. doi:10.1007/s00445-004-0355-9

Maughan LL, Christiansen EH, Best MG, Gromm CS, Deino AL, Tingey DG (2002) The Oligocene Lund Tuff, Great Basin, USA: a very large volume monotonous intermediate. J Volcanol Geotherm Res 113:129–157. doi:10.1016/S0377-0273(01)00256-6

Morgan LA, McIntosh WC (2005) Timing and development of the Heise volcanic field, Snake River Plain, Idaho, western USA. Geol Soc Am Bull 117:288–306. doi:10.1130/B25519.1

Nash BP, Perkins ME, Christensen JN, Lee DC, Halliday AN (2006) The Yellowstone hotspot in space and time: Nd and Hf isotopes in silicic magmas. Earth Plan Sci Lett 247:143–156. doi:10.1016/j.epsl.2006.04.030

Oakley WL, Link PK (2006) Geologic map of the Davis Mountain Quadrangle, Gooding and Camas Counties, Idaho. Idaho Geol Surv Technical Report T-06-6

Perkins ME, Nash BP (2002) Explosive silicic volcanism of the Yellowstone hotspot: the ash fall tuff record. Geol Soc Am Bull 114:367–381

Perkins ME, Nash WP, Brown FH, Fleck RJ (1995) Fallout tuffs of Trapper Creek Idaho—a record of Miocene explosive volcanism in the Snake River Plain volcanic province. Geol Soc Am Bull 107:1484–1506

Perkins ME, Williams SK, Brown FH, Nash WP, McIntosh W (1998) Sequence, age, and source of silicic fallout tuffs in middle to late Miocene basins of the northern Basin and Range Province. Geol Soc Am Bull 110:344–360. doi:10.1130/00167606(2002)114<0367:ESVOTY>2.0.CO;2

Pierce KL, Morgan LA (1992) The track of the Yellowstone hotspot: volcanism, faulting and uplift. In: Link PK, Kuntz MA, Platt LB (eds) Regional geology of Eastern Idaho and Western Wyoming. Geol Soc Am Mem 179:1–53

Rampino MR (2002) Supereruptions as a threat to civilizations on Earth-like planets. Icarus 156:562–569

Rampino MR, Self S (1992) Volcanic winter and accelerated glaciation following the Toba super-eruption. Nature 359:50–52

Rose WI, Chesner CA (1987) Dispersal of ash in the great Toba eruption, 75 ka. Geology 15:913–917

Rose WI, Riley CM, Darteville S (2003) Sizes and shapes of 10 Ma distal fall pyroclasts in the Ogallala Group, Nebraska. J Geol 111:115–124

Rytuba JJ, McKee EH (1984) Peralkaline ash flow tuffs and calderas of the McDermitt volcanic field, southeast Oregon and north central Nevada. J Geophys Res 89(B10):8616–8628

Self S (2010) A new look at the deposits and eruption sequence of the Otowi Member, Bandelier Tuff Formation, Jemez Mountains, New Mexico. Geol Soc Am 42(5):5, Abstracts with Programs

Shervais JW, Hanan BB (2008) Lithospheric topography, tilted plumes, and the track of the Snake River–Yellowstone hot spot. Tectonics 27:TC5004

Shervais JW, Vetter SK, Hanan BB (2006) Layered mafic sill complex beneath the eastern Snake River Plain: evidence from cyclical geochemical variations in basalt. Geology 34:365–368. doi:10.1130/G22226.1

Soler MM, Caffe PJ, Coira BL, Onoe AT, Kay SM (2007) Geology of the Vilama caldera: a new interpretation of a large-scale explosive event in the Central Andean plateau during the Upper Miocene. J Volcanol Geotherm Res 164:27–53. doi:10.1016/j.jvolgeores.2007.04.002

Sparks RSJ, Francis PW, Hamer RD, Pankhurst RJ, O'Callaghan LO, Thorpe RS, Page R (1985) Ignimbrites of the Cerro Galan caldera, NW Argentina. J Volcanol Geotherm Res 24:205–248

Williams PL, Mytton JW, Covington HR (1990) Geologic map of the Stricker 1 quadrangle, Cassia, Twin Falls, and Jerome Counties, Idaho. US Geol Surv Misc Inv Series Map I-2078 scale 1:48,000

Wilson CJN (2001) The 26.5 ka Oruanui eruption, New Zealand: an introduction and overview. J Volcanol Geotherm Res 112:133–174

Wohletz KH (1999) MAGMA: calculates IUGS volcanic rock classification, densities, and viscosities. Los Alamos National Laboratory computer code LA-CC 99-28, Los Alamos

Wolff JA, Ramos FC, Hart GL, Patterson JD, Brandon AD (2008) Columbia River flood basalts from a centralized crustal magmatic system. Nat Geosci 1:177–180. doi:10.1038/ngeo124