Bull Volcanol (2008) 70:269–291
DOI 10.1007/s00445-007-0139-0

RESEARCH ARTICLE

Rhyolitic ignimbrites in the Rogerson Graben, southern Snake River Plain volcanic province: volcanic stratigraphy, eruption history and basin evolution

Graham D. M. Andrews · Michael J. Branney ·
Bill Bonnichsen · Michael McCurry

Received: 10 February 2005 / Accepted: 8 March 2007 / Published online: 20 June 2007

Abstract The 80 km long NNE-trending Rogerson Graben on the southern margin of the central Snake River Plain, Idaho, USA, hosts a rhyolitic pyroclastic succession, 200 m thick, that records a period of successive, late-Miocene, large-volume explosive eruptions from the Yellowstone–Snake River Plain volcanic province, and contemporaneous extension. The succession, here termed the Rogerson Formation, comprises seven members (defined herein) and records at least eight large explosive eruptions with numerous repose periods. Five high-grade and extremely high-grade ignimbrites are intercalated with three non-welded ignimbrites and two volcaniclastic deposits, with numerous repose periods (palaeosols) throughout. Two of the ignimbrites are dominantly rheomorphic and lava-like but contain subordinate non-welded pyroclastic layers. The ignimbrites are typical Snake River Plain high-silica rhyolites, with anhydrous crystal assemblages and high inferred magmatic temperatures (≤ 1,025°C). We tentatively infer that the Jackpot and Rabbit Springs Members may have been emplaced from the Bruneau–Jarbidge eruptive centre on the basis of: (1) flow lineation trends, (2) crystal assemblage, and (3) radiometric age. We infer that the overlying Brown's View, Grey's Landing, and Sand Springs Members may have been emplaced from the Twin Falls eruptive centre on the basis of: (1) kinematic indicators (from the east), and (2) crystal assemblage. Furthermore, we have established the contemporaneous evolution of the Rogerson Graben from the emplacement of the Jackpot Member onwards, and infer that it is similar to younger half-graben along the southern margin of the Snake River Plain, formed by local reactivation of Basin and Range structures by the northeastwardly migration of the Yellowstone hot-spot.

Keywords Snake River Plain volcanic province · Rheomorphic ignimbrite · Volcanic stratigraphy · Geothermometry · Rhyolite · Basin and range · Yellowstone hot-spot

---

This paper constitutes part of a special issue dedicated to Bill Bonnichsen on the petrogenesis and volcanology of anorogenic rhyolites.

Editorial responsibility: M McCurry

Electronic supplementary material The online version of this article (doi:10.1007/s00445-007-0139-0) contains supplementary material, which is available to authorized users.

G. D. M. Andrews · M. J. Branney
Department of Geology, University of Leicester,
Leicester LE1 7RH, UK

G. D. M. Andrews (✉)
Department of Earth and Ocean Sciences,
University of British Columbia,
Vancouver, BC V6T 1Z4, Canada
e-mail: gandrews@eos.ubc.ca

B. Bonnichsen
927 East 7th Street,
Moscow, ID 83843, USA

M. McCurry
Department of Geosciences, Idaho State University,
Pocatello, ID 83209-8072, USA

Introduction

This paper documents and interprets a rhyolitic volcanic succession in the Rogerson Graben of southern Idaho. It presents a detailed lithostratigraphy through eight previously undescribed ignimbrites and associated ash-fall tuffs and other volcaniclastic deposits. We provide geochemical data and estimates of pre-eruptive magmatic temperatures for the units to allow correlation with existing and future stratigraphic sections in the Yellowstone-Snake River Plain volcanic province. The succession occupies an important geographical and tectonic position for two reasons: (1) it is equidistant between the Bruneau–Jarbidge and Twin Falls eruptive centres (Pierce and Morgan 1992), and is a potentially good area to correlate between successions from each eruptive centre; and (2) it is the most westerly (and possibly oldest) of nine major basins along the southern and south-eastern margins of the Snake River Plain (Rodgers et al. 2002).

An intriguing aspect of the Rogerson Graben succession is the preponderance of intensely welded, high-grade ignimbrites (five members) including two that are rheomorphic and lava-like (*sensu* Branney and Kokelaar 1992). The Yellowstone-Snake River Plain volcanic province is host to some of the youngest and best-exposed rheomorphic and lava-like ignimbrites known, and has been the site of several key studies (e.g., Bonnichsen and Citron 1982; Ekren et al. 1984). Extremely high-grade ignimbrites are common components of many volcanic provinces in a diverse range of tectonic settings (e.g., Gran Canaria, Schmincke 1974; Wall Mountain Tuff, Colorado, Chapin and Lowell 1979; Keweenawan rift, Minnesota, Green and Fitz 1993). Their structural characteristics (e.g., flow-banding, flow folds, etc.) and emplacement mechanisms remain poorly understood. Recent studies have concentrated on the timing and rate of welding (e.g., Freundt 1998), the timing of rheomorphic flow relative to deposition, welding and eventual cooling (e.g., Andrews 2006), and the styles of rheomorphic deformation (e.g., Branney et al. 2004; Andrews 2006). Many rheomorphic ignimbrites elsewhere are peralkaline (e.g., Gran Canaria, Pantelleria), and therefore, had unusually low viscosities when deposited. In contrast, those in the Yellowstone–Snake River Plain volcanic province in general, and the Rogerson Graben in particular, are as intensely welded and rheomorphic as ignimbrites from elsewhere but, they are characteristically metaluminous and have very high eruption temperatures (900–1,000°C; Honjo et al. 1992).

Geological setting

Voluminous bimodal volcanism has dominated the interior northwestern United States since the mid Miocene, following the initiation of Yellowstone hot-spot magmatism at ~16.8 Ma (Camp and Ross 2004). The Yellowstone–Columbia River volcanic mega-province is adjacent to and contemporaneous with crustal extension and magmatism in the Basin and Range province, leading to complex basin evolution along the margins of the Snake River Plain (e.g., Rodgers et al. 2002), and the location of present-day seismicity around the Yellowstone ‘seismic parabola’ (Anders et al. 1989).

Rhyolites of the Yellowstone–Snake River Plain volcanic province are time-transgressive, and successive volcanic centres young northeastwards towards the Yellowstone centre (Fig. 1 inset). Most of the eruptive centres are buried and their stratigraphies are known primarily from outflow sheets at the southern and northern margins of the Snake River Plain. However, there are significant gaps in stratigraphic coverage, both temporally and spatially, that hinder better understanding of the temporal evolution of the province.

Between 12 and 8 Ma, rhyolite volcanism was concentrated around the Bruneau–Jarbidge and Twin Falls areas and the margins of the contemporaneously extending West Snake River Plain graben (Pierce and Morgan 1992; Perkins and Nash 2002; Fig. 1 inset). The period 11.7–10.0 Ma is described by some workers as an ‘ignimbrite flare-up’ period because of the huge volume of ignimbrites erupted (Bonnichsen 2004; Bonnichsen et al. 2007). Younger basalts largely bury these volcanic centres so their nature and structure is poorly constrained (see Branney et al. 2007). Eruptions during this time produced numerous large-volume, rhyolitic ignimbrite outflow sheets (the ‘Idavada Volcanic Group’ of Malde and Powers 1962; including the ‘Cougar Point Tuff Formation’ of Bonnichsen and Citron 1982) exposed along the northern and southern margins of the central Snake River Plain. At the Bruneau–Jarbidge and Twin Falls eruptive centres, and on the Yellowstone Plateau, the ignimbrite-forming eruptions were typically followed by voluminous rhyolite lavas (e.g., the Sheep Creek Rhyolite, Bonnichsen 1982b).

Analytical methods

Whole-rock analyses were undertaken with a Phillips PW1400 X-ray fluorescence spectrometer (XRF) at the University of Leicester. Glass and crystal compositions (re-calculated to 100 wt.%) were analysed on a JEOL 8600 S electron microprobe (EMP) at the University of Leicester, using a 15 kV accelerating potential, 30 nA incident current, and 5 and 10 μm spot size respectively.

Stratigraphy—the Rogerson Formation

The Rogerson Formation (Fig. 2) is exposed throughout its type locality, the Rogerson graben (Fig. 1), where it consists of five extensive and gently (≤10°) dipping rhyolite sheets, separated by four non-welded volcaniclastic units. The base of the formation is not seen and attempts to establish the regional-scale stratigraphic relations are ongoing. It is probable that the formation

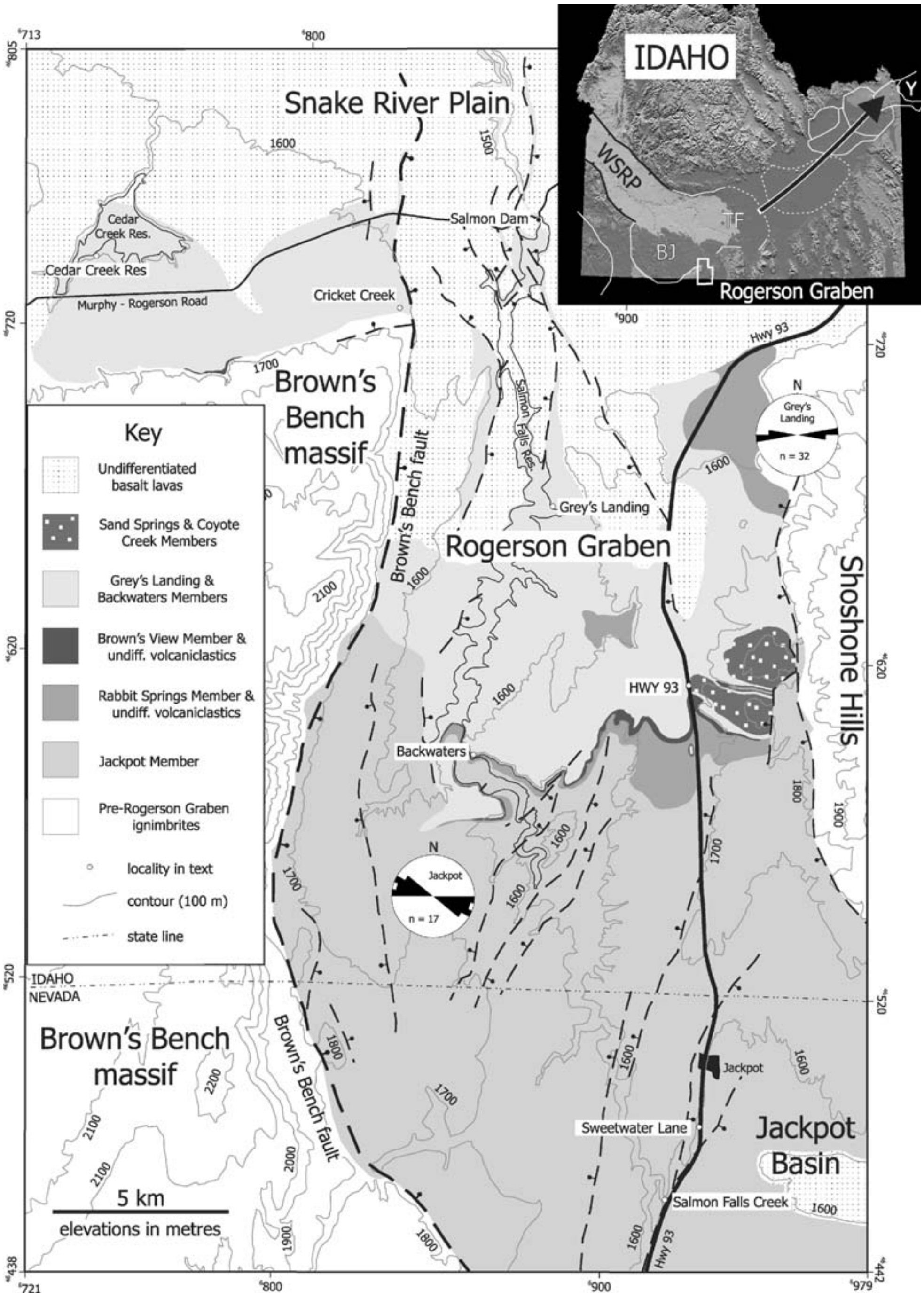


Fig. 1 Geological map of the Rogerson Graben and surrounding areas (Twin Falls County, Idaho and Elko County, Nevada), showing the present distribution of the Rogerson Formation, at localities named in the text. Selected UTM coordinates for zone 11T shown. Inset: Location of the Rogerson Graben in relation to southern Idaho and inferred, successive eruptive centres (Bruneau–Jarbidge—B–J; Twin Falls—TF; Yellowstone—Y) that young to the NNE

overlies rhyolite ignimbrites of the Cougar Point Tuff Formation (12.7–10.5 Ma; Cathey and Nash 2004), and possibly, inliers of upper Palaeozoic, Mesozoic, and Palaeogene sedimentary and volcanic rocks as reported from the base of Cassia Mountains succession (Williams et al. 1999). The top of the formation is being denuded as part of the present-day topographic surface, other than where it has been buried by basalt lavas (~ 6.8 Ma; Bonnichsen and Godchaux 2002) at the northern end of the graben (Fig. 1).

Jackpot Member

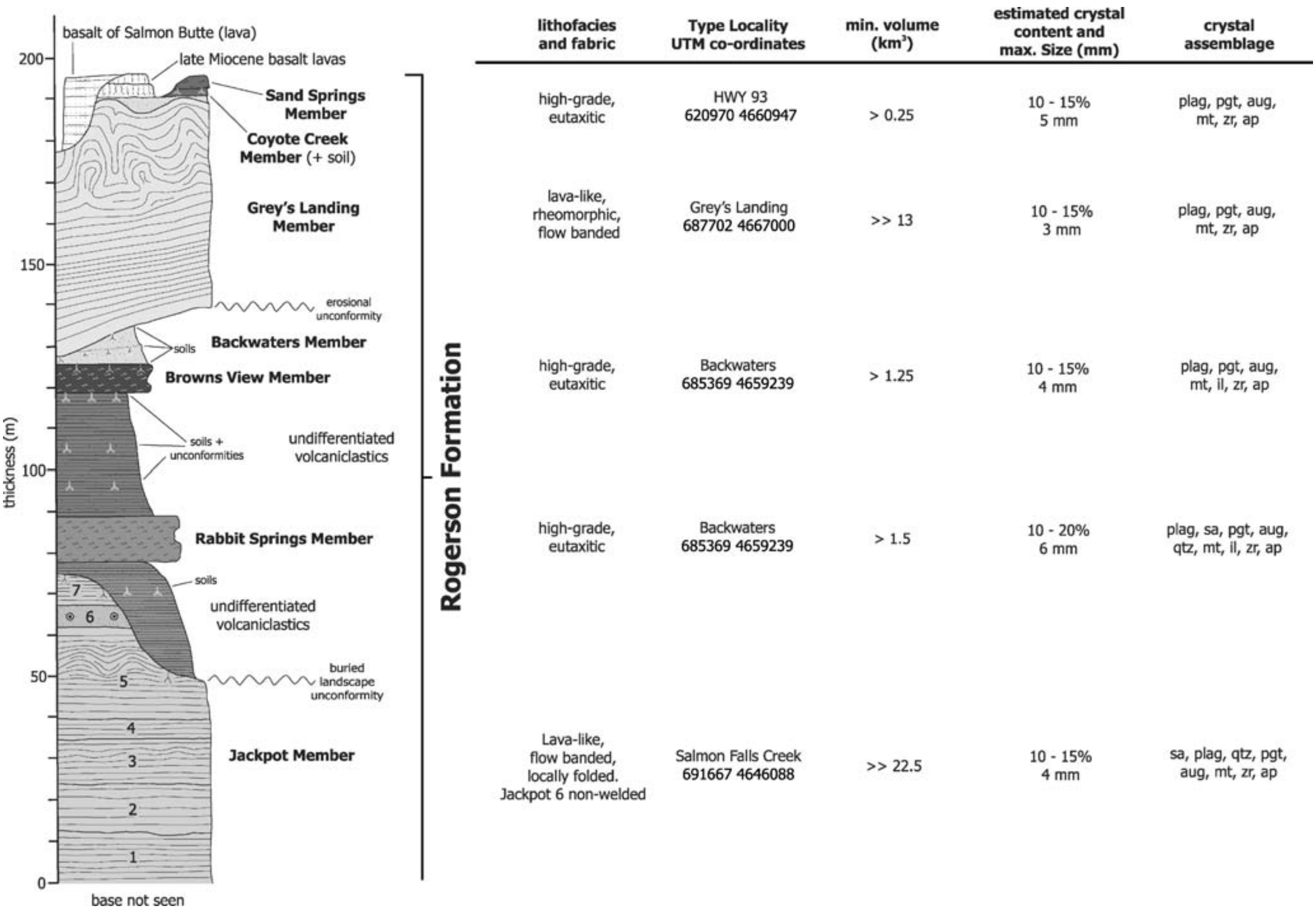
At its type locality at Salmon Falls Creek, 4.5 km south of Jackpot, Nevada (Figs. 1 and 3) the Jackpot Member is ≥75 m thick, although its base is not exposed. It outcrops extensively (>300 km^2) in the south of the Rogerson Graben, where it is unconformably overlain by a thick, bedded volcaniclastic deposit and the Rabbit Springs Member. It is readily distinguished from other members by its stratigraphic position, considerable thickness, lava-like appearance, internal stratigraphy, and the unique occurrence of myrmekitic intergrowths around sanidine crystals in thin section (Fig. 4a).

We subdivide the Jackpot Member into seven informal sub-units (‘Jackpot 1 to 7’, Fig. 3) that form prominent cliffs, based on different columnar joint patterns, lithophysae-rich layers, and topographic benches between each cliff. ‘Jackpot 1 to 4’ (Fig. 4b) are welded, generally devitrified (lithoidal), lava-like, and lack eutaxitic fabrics. ‘Jackpot 1 and 2’ have well developed, closely spaced, subhorizontal joints (sheet-joints of Bonnichsen 1982b), columnar joints and prominent upper lithophysae-rich layers that lack joints. ‘Jackpot 3’ lacks columnar joints and lithophysae, and sheet-joint surfaces have a linear fabric defined by orientated prolate vesicles and are deformed by open, upright folds. ‘Jackpot 4’ is a lava-like, sheet-jointed rhyolite similar to ‘Jackpot 1,’ with some poorly developed columnar joints, and isolated lithophysae throughout its upper half especially concentrated in a 2 m-thick zone at the top.

‘Jackpot 5’ is 26–30 m thick, lava-like and flow-folded, with well developed columnar jointing, and well developed sheet-jointing in lower and central parts (Fig. 4b, c). The top 15 m show N or NE-trending upright, open folds on a scale of 1 m–10 m with NW–SE elongation lineations (stretched vesicle; Fig. 1). Prolate vesicles have axial ratios of ≤10:1 and trend parallel to the lineation. The uppermost 4 m are a perlitic vitrophyre with abundant lithophysae partly filled with pistachio-green chalcedony.

‘Jackpot 6’ (type locality: Sweetwater Lane, 2 km south of Jackpot, Fig. 1) is less intensely welded, more obviously pyroclastic than the other Jackpot sub-units and is characterized by the presence of abundant, equant obsidian lapilli (1–2 cm). It conformably overlies the upper vitrophyre of ‘Jackpot 5.’ A strongly welded 20 cm-thick base grades up into a layer of weakly welded obsidian lapilli-tuff (≤2 m). This layer is truncated by an erosion surface overlain by lenses of cross-bedded, non-welded lapilli-tuff of similar composition. This in turn grades up into a 1.5 m thick layer of obsidian-bearing lapilli-tuff containing lenses of accretionary lapilli. The top of this layer is not seen.

‘Jackpot 7’ is an 8 m thick columnar-jointed, flow-banded and dominantly lava-like sheet, similar to the non-lithophysal parts of ‘Jackpot 1’ (Fig. 3). It is exposed



lithofacies and fabric	Type Locality UTM co-ordinates	min. volume (km^3)	estimated crystal content and max. Size (mm)	crystal assemblage
high-grade, eutaxitic	HWY 93 620970 4660947	> 0.25	10 - 15% 5 mm	plag, pgt, aug, mt, zr, ap
lava-like, rheomorphic, flow banded	Grey's Landing 687702 4667000	>> 13	10 - 15% 3 mm	plag, pgt, aug, mt, zr, ap
high-grade, eutaxitic	Backwaters 685369 4659239	> 1.25	10 - 15% 4 mm	plag, pgt, aug, mt, il, zr, ap
high-grade, eutaxitic	Backwaters 685369 4659239	> 1.5	10 - 20% 6 mm	plag, sa, pgt, aug, qtz, mt, il, zr, ap
Lava-like, flow banded, locally folded. Jackpot 6 non-welded	Salmon Falls Creek 691667 4646088	>> 22.5	10 - 15% 4 mm	sa, plag, qtz, pgt, aug, mt, zr, ap

Fig. 2 General vertical section through the Rogerson Formation in the Rogerson Graben. Soils, erosion surfaces, and unconformities are marked. Details of lithofacies, welding grade, type locality, minimum volume, and crystal assemblage are given on the right. *plag* plagioclase, *sa* sanidine, *pgt* pigeonite, *aug* augite, *qtz* quartz, *mt* magnetite, *il* ilmentie, *zr* zircon, *ap* apatite

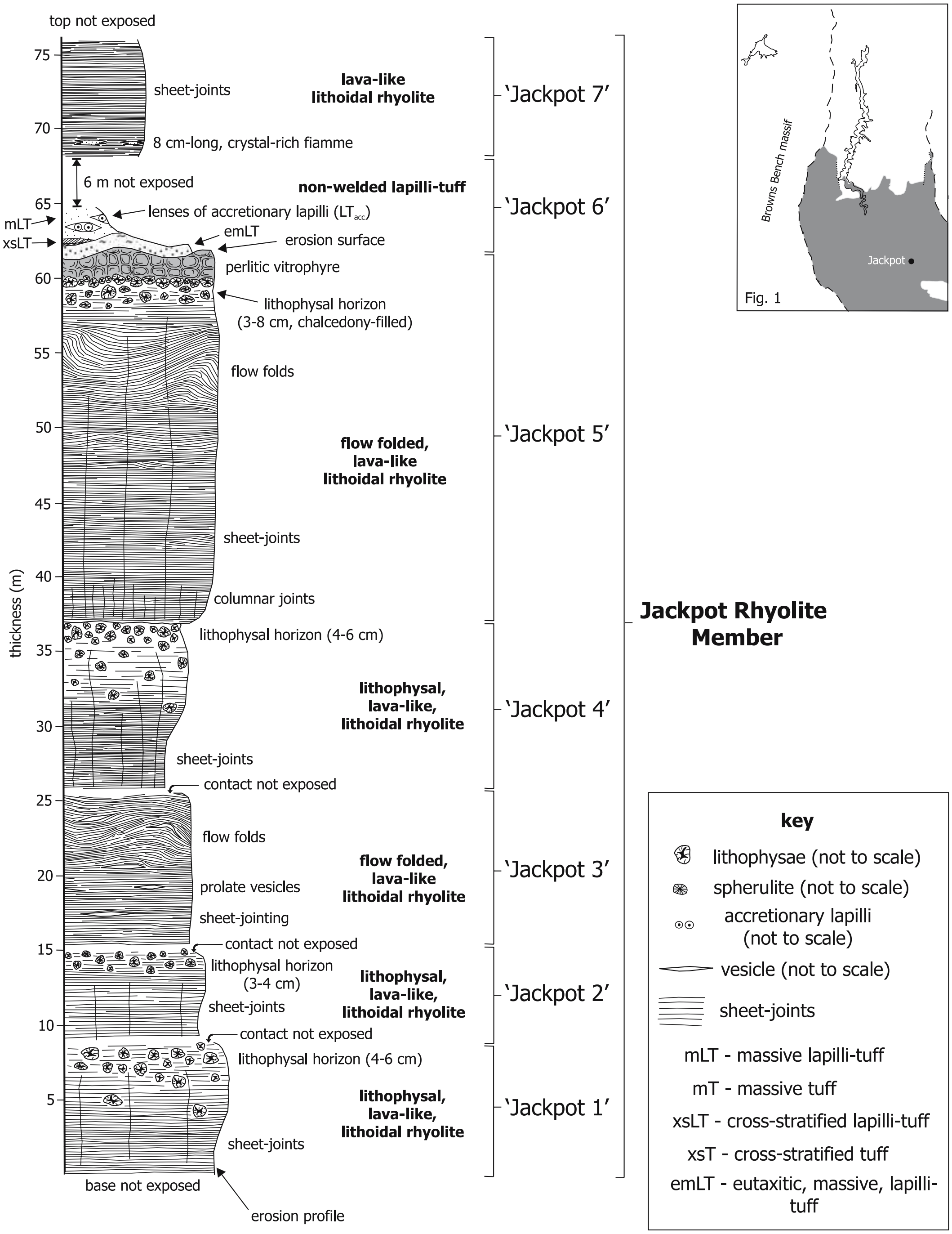


Fig. 3 Graphic log of the Jackpot Member, based upon sections at Salmon Falls Creek and Sweetwater Lane. Abbreviations on key follow Branney and Kokelaar 2002. *Inset* shows the outcrop of the member

widely across the southern Rogerson Graben, where it forms a prominent cap at the top of the Jackpot Member (Fig. 4c). It has well developed sheet-joints and is thoroughly de-vitrified. Folds and vitrophyres have not been seen. Ragged quartz and sanidine concentrations, possibly crystal-bearing fiamme (≤8 cm long), occur in a 75 cm thick layer, 1.5 m from the base.

Undifferentiated volcaniclastic units

Undifferentiated, bedded volcaniclastic deposits occur at two stratigraphic levels: (1) unconformably overlying the Jackpot Member; and (2) discordantly overlying the Rabbit Springs Member (Fig. 2). Both units consist of 2–10 cm thick layers of silt and sand-sized particles, with rare lenses

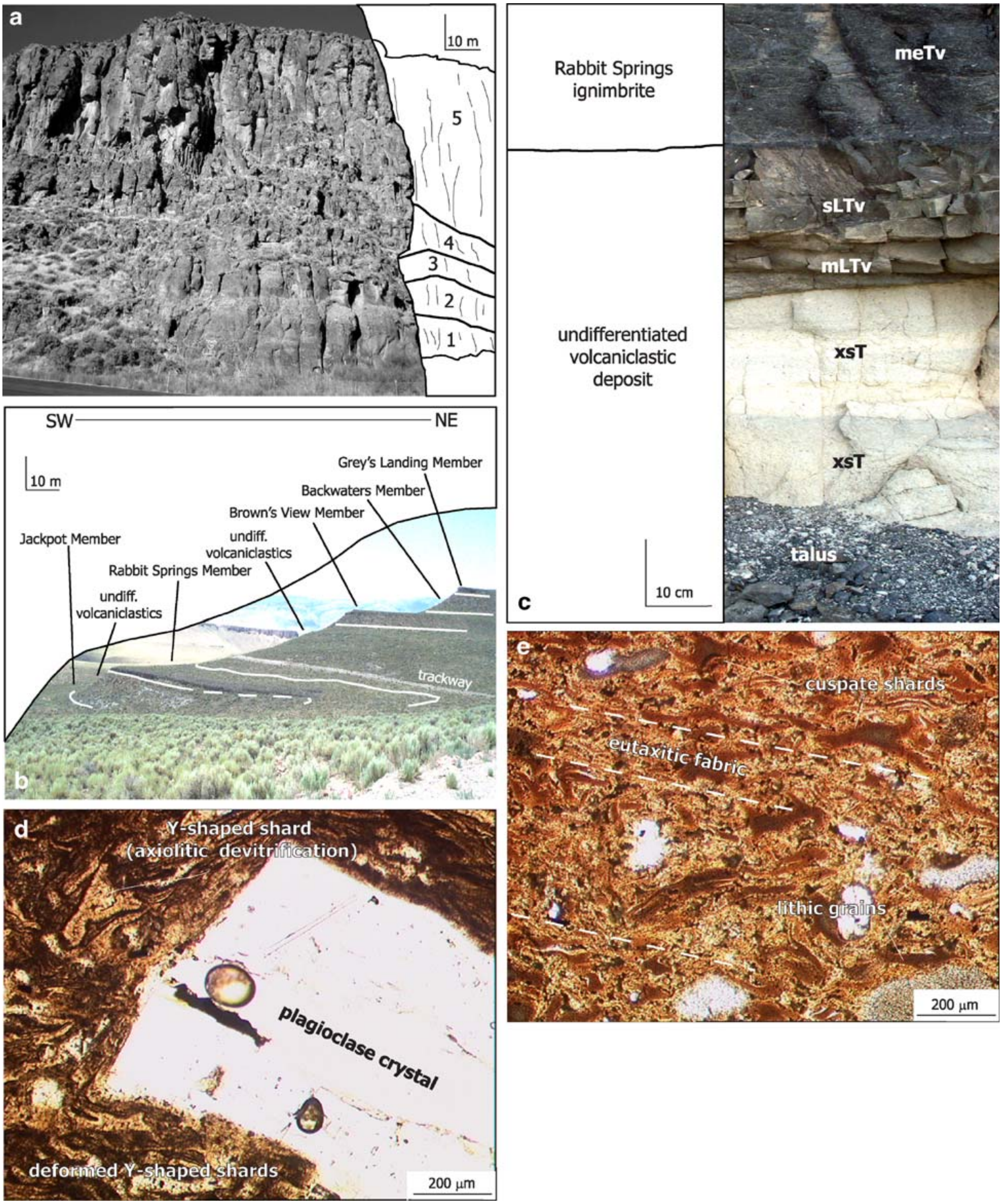


Fig. 4 **a** Lower part of the Jackpot Member at Salmon Falls Creek, showing subdivisions into 'Jackpot 1–5' by topographic benches and variations in columnar-jointing patterns. **b** Stratigraphy approximately 5 km east of Backwaters (Fig. 1), showing units dipping gently northwards. Note the thin and uniform nature of the welded Rabbit Springs, Brown's View and Grey's Landing Members, producing prominent topographic benches. **c** Base of Rabbit Springs Member at Backwaters, showing increasing fusing intensity in originally non-welded volcaniclastic deposits (*meTv* massive eutaxitic vitric tuff; *sLTv* stratified vitric lapilli-tuff; *mLTv* massive vitric lapilli-tuff; *xsT* cross-stratified tuff; Branney and Kokelaar 2002). **d** Photomicrograph (PPL) of the Rabbit Springs Ignimbrite basal vitrophyre showing welded Y-shaped shards, strongly flattened around the corner of a plagioclase crystal. Note the axiolitic devitrification textures developed in the largest shards. **e** Photomicrograph (PPL) of Brown's View Ignimbrite

of accretionary lapilli or ash-pellets, some rare rounded pumice lapilli, and intercalated thin palaeosols containing calcified rootlets. Individual layers are laterally continuous for ≥5 m; however, scour-structures, ripple laminations, low-angle cross-stratification (cross-set height ≤10 cm), normal graded bedding, and de-watering structures are common. Both units are typically buried by modern slopewash, and are locally bioturbated, making further examination difficult.

The lower bedded volcaniclastic unit unconformably overlies a buried landscape developed in Jackpot sub-units 5, 6, and 7 (Fig. 2), where the Jackpot Member has been extended on normal faults to produce several 25–30 m deep, NNE-trending, km-scale graben. This is best demonstrated immediately to the east of the Backwaters area (Figs. 1 and 4b). In turn, the lower bedded volcaniclastics are conformably overlain by the Rabbit Springs Member, and the topmost 1 m is fused against the basal vitrophyre of the later unit (Fig. 4b, c).

Rabbit Springs Member

The Rabbit Springs Member (Fig. 5) uncomformably overlies horsts developed in the Jackpot Member and conformably overlies undifferentiated volcaniclastic deposits (Figs. 2, 4b, c). It is an 8–12 m thick sheet with a minimum extent of 200 km^2, exposed across the central and eastern portion of the Rogerson Graben, where it is the lowest of several members that thin to a feather-edge and pinch out eastwards against the Shoshone Hills graben-margin (Fig. 1). In the Backwaters area it is disrupted by a pair of contemporaneous normal faults (the member thickening from 9 to 12 m) that deform the basal but not upper vitrophyre.

In the type locality of Backwaters, Idaho (Fig. 1) it is an 11 m thick tuff, with a lithoidal centre, and spherulitic and lithophysal upper and lower vitrophyres (Fig. 5). The basal vitrophyre is massive perlite, with a eutaxitic fabric of flattened Y-shaped ash shards, some of which wrap crystals (Fig. 4d). It is devoid of pumice lapilli and is characterized by an abundance of spherulites and lithophysae (≤8 cm across) some of which are filled with white chalcedony. The central lithoidal zone is thoroughly devitrified, with closely spaced sheet-joints, and relic pseudomorphs after spherulites within the matrix. This unit has yielded an ^{40}Ar–^{39}Ar date of 10.37 Ma±0.13 (Bonnichsen et al. 2007).

Undifferentiated volcaniclastic deposits

The upper bedded volcaniclastic unit discordantly overlies the Rabbit Springs Member and thins rapidly to the eastern margin of the graben; however, the contact is not exposed. The sedimentary characteristics of the unit are nearly identical to the lower volcaniclastics (see above); however, at least three thick (≥1 m) palaeosols (containing calcified rootlets) are developed within the unit. Internal angular unconformities are recorded by planar erosion surfaces cutting palaeosols, and subsequent discordant burial by later volcaniclastics. This is best demonstrated immediately to the south of the Backwaters area (Fig. 1). The upper bedded volcaniclastics are conformably overlain by the Brown's View Member, although the contact is not exposed (Fig. 2).

Brown's View Member

The Brown's View Member (type locality: Backwaters, Figs. 1 and 6) is a 4–8 m thick, ≥400 km^2 sheet that is exposed intermittently across the central Rogerson Graben, where it conformably overlies undifferentiated volcaniclastic deposits. It is the oldest member exposed outside the Graben to the northwest (Fig. 1), where it onlaps and oversteps older lava-like rhyolites of the Brown's Bench massif (10.22 Ma±0.09 (^{40}Ar–^{39}Ar); Bonnichsen and Godchaux 2002).

A massive, chocolate-brown lithoidal centre (~ 1.5 m thick) separates two sparsely spherulitic vitrophyres (≤3 m thick; Fig. 6). Both vitrophyres exhibit a ≤ mm-scale eutaxitic fabric (Fig. 4e), cuspate shards, and crystal and lithic fragments. There are no pumice lapilli or fiamme. The massive upper vitrophyre contains isolated lithophysae (5–8 cm diameter) and passes up into a thin orange palaeosol (~20 cm thick), with angular obsidian lapilli and small, calcified rootlets. In contrast to the Rabbit Springs Member, the Brown's View Member contains less lithophysae and spherulites, and it lacks sheet-joints.

Backwaters member

The Backwaters Member (type locality: Backwaters, Fig. 1) is 8–15 m thick. It likely conformably overlies the Browns View Member (contact not well-exposed) across the centre and north of Rogerson Graben (Fig. 1). It comprises at least two units (A and B on Fig. 7) separated by a palaeosol and erosion surface. Unit A is a ≥8 m thick layer of non-welded, massive tuff, containing lenses of sub-rounded to angular pumice lapilli and lithics supported by a tuff matrix, and is overlain by a 2 m thick palaeosol. The base of this unit is not exposed. Unit B is a 3–6 m thick, massive tuff containing lenses of sub-angular pumice lapilli and abundant calcified rootlets. It has an erosional base and the upper 4 m is host to a bioturbated palaeosol. Grass imprints are preserved on the upper surface of the palaeosol. The lower 2 m have been fused to black vitrophyre and the palaeosol baked, likely due to heat conducted downwards from the overlying Grey's Landing ignimbrite (Fig. 8a).

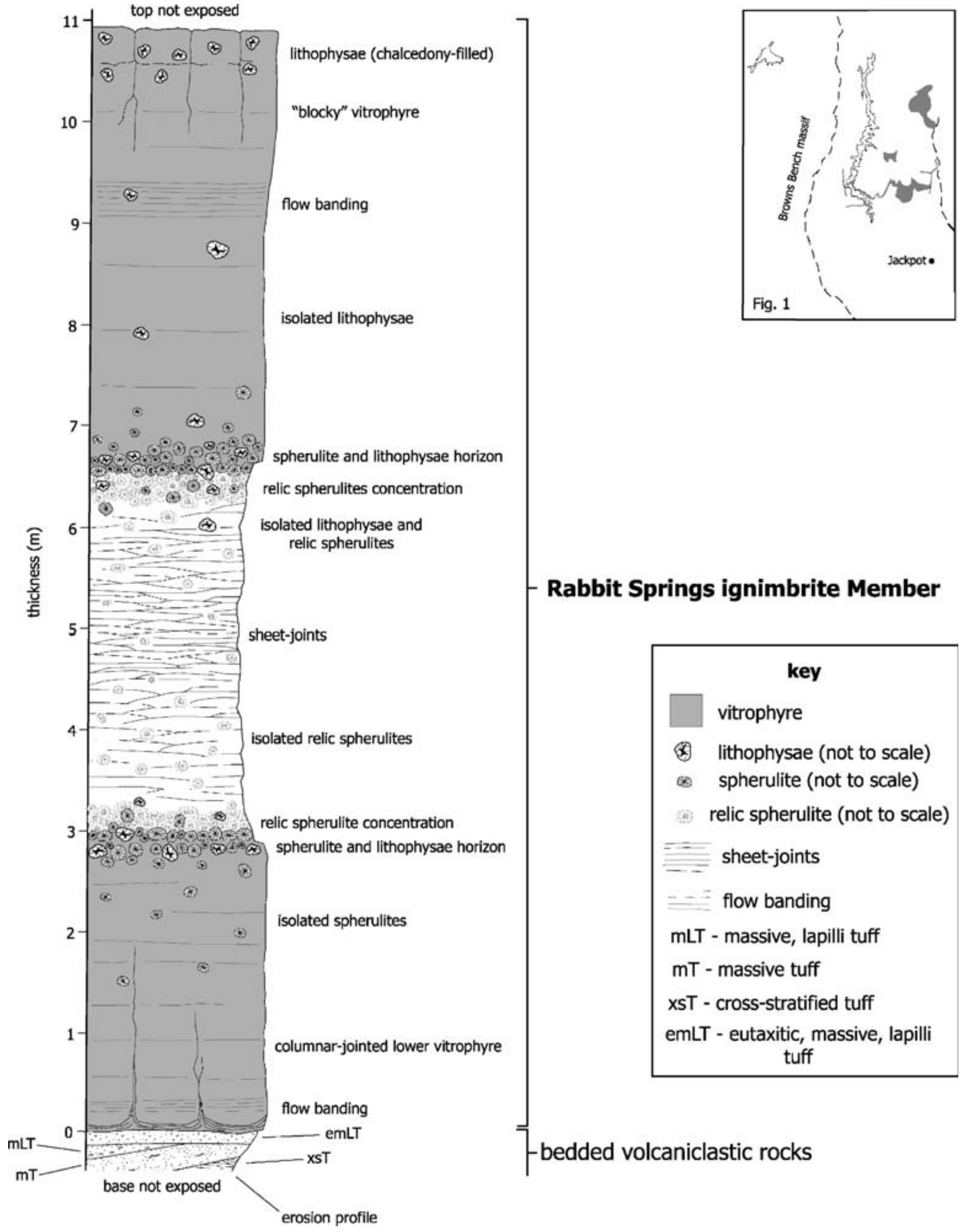


Fig. 5 Graphic log of the Rabbit Springs Member, from the Backwaters section. *Inset* shows the outcrop of the Member

Grey's Landing Member

The Grey's Landing Member (type locality: Grey's Landing, Idaho, Fig. 1) is a 5–65 m thick, rhyolitic sheet comprising a stratified ashfall deposit and a lava-like ignimbrite with a lower vitrophyre, a thick lithoidal centre, and a thin upper vitrophyre locally overlain by a non-welded top (Figs. 7 and 8b). The upper vitrophyre is eroded at the Type Section but is exposed elsewhere (e.g., Cedar Creek Reservoir, Fig. 1). In sections less than 5 m thick the entire member is vitric.

The Grey's Landing Member unconformably overlies the Backwaters Member both within and outside the Rogerson Graben, and its full areal extent is estimated to be ≥400 km^2 (Fig. 1). It has a wedge-shaped form within the Rogerson Graben that thins to a feather-edge towards the east (Fig. 8c) and south. Outside the graben it onlaps and oversteps older lava-like rhyolites of the Brown's Bench massif, and drapes the palaeo-fault scarp of the Brown's Bench Fault (Cricket Creek; Fig. 1). This unit has yielded an K–Ar date of 7.62 Ma±0.4 (Hart and Aronson 1983). It is overlain by late-Miocene and early-Pliocene basalt lavas in the north of the

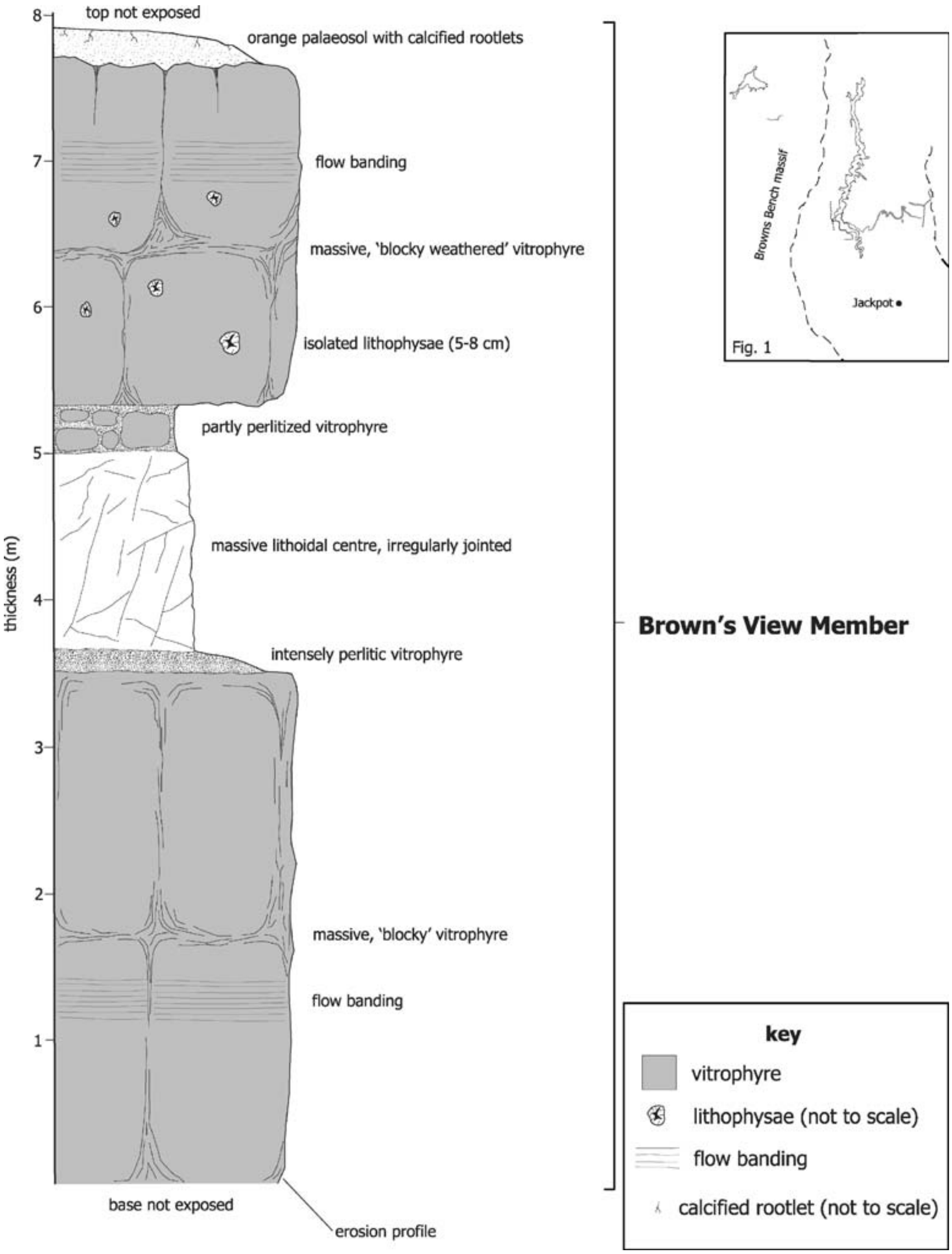


Fig. 6 Graphic log of the Brown's View Member from the Backwaters section. *Inset* shows outcrop of the Member

graben and in the adjoining Snake River Plain (Bonnichsen and Godchaux 2002, Fig. 2).

An equally extensive, parallel-stratified ash layer, ≤1.5 m thick, drapes the upper palaeosol of the Backwaters Member (Figs. 7, 8d, e). Along Highway 93, (Fig. 2) the stratified ash sits on a ~2 m thick bedded tephra succession in a local depression in the Backwaters Member. The stratified ash becomes progressively more fused and compacted under thicker ignimbrite (Fig. 8d, e).

The basal vitrophyre (Figs. 7, 8d, e) is 1–3 m thick, massive and spherulitic (2–4 cm diameter), and conformably overlies the underlying stratified ash. Extensive, horizontal sheets (>5 m long, ~6 cm thick) of devitrified rhyolite are found within the vitrophyre (Fig. 8d), with a lineation (~ E–W) developed on their surfaces (Fig. 1). Rare lithophysae (<8 cm diameter) are concentrated in graben-flank sections. Vitroclastic textures are preserved in strain-shadows around rotated crystals, in an otherwise flow-banded and flow-folded, glassy matrix (Fig. 9d).

A red–brown lithoidal central zone is pervasively flow-banded and flow-folded, with dm- to 10 m scale flow-folds (Fig. 10a–c), including sheath folds (e.g., Branney et al. 2004) of colour banding (Fig. 9b-d). Flow-folding scale and style define two deformation domains (Fig. 8c); a lower

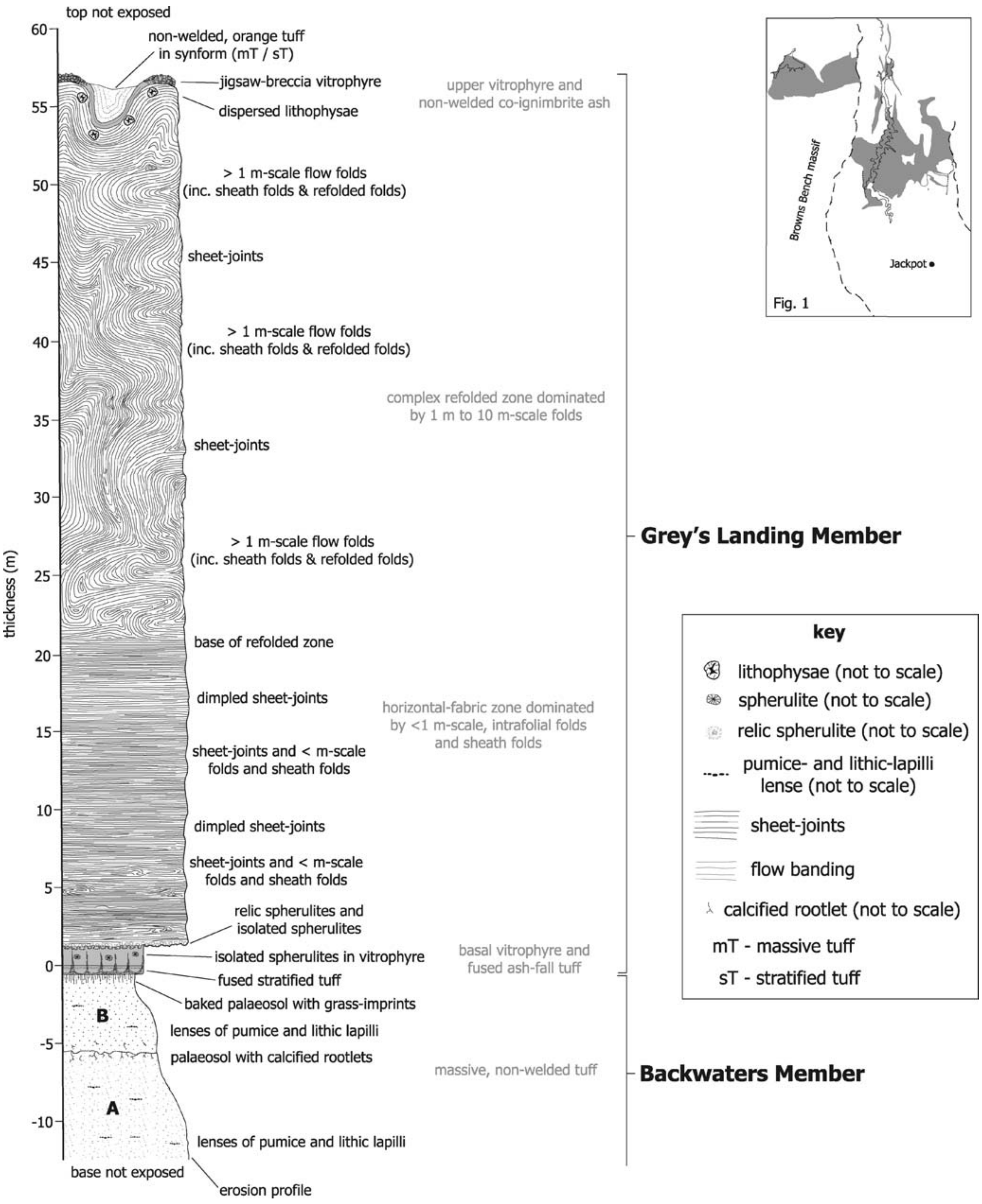


Fig. 7 Graphic log of the Backwaters and Grey's Landing Members based upon sections at Backwater, Grey's Landing and Salmon Dam. *Inset* shows outcrop of the Grey's Landing Member

‘flat’ domain of cm- to m-scale, recumbent isoclinal folds, and an upper ‘steep’ domain in which isoclinal folds are refolded by m- to 10 m scale upright folds. A penetrative lineation (Fig. 10a) is developed on some sheet-joint surfaces, especially in the less folded parts, and the orientation of lineations and parallel fold hinges varies with increasing height, as reported by Branney et al. (2004). ‘Dimple joints’ (Fig. 10b; Bonnichsen 1982b), dominate the lower 10 m where sheet joints and flow-folds are absent. Vesicles (0.2–20 cm diameter) occur in the upper 20 m of the lithoidal zone. Some have risen buoyantly, intruding and deforming the flow-banding (Fig. 10c).

A dark grey, upper vitrophyre is flow-banded and flow-folded. It is perlitic and locally spherulitic (≤3 cm diameter) and lithophysal (≤4 cm diameter). It is best exposed at Salmon Dam and Cedar Creek Reservoir (Fig. 1); however, it has been removed at the type locality. It locally shows autobrecciation, with jigsaw-fit blocks ≤0.5 m in diameter. At Salmon Dam and Cedar Creek Reservoir a massive to faintly stratified, aphyric, orange, sand-sized ash is preserved within 10 m scale synforms developed in the upper vitrophyre. Typically the contact between welded vitrophyre and non-welded tephra is a breccia in which angular clasts (≤10 cm diameter) of non-welded tephra are supported by a matrix of non-welded and partly fused orange ash, which is progressively more fused towards the vitrophyre.

Coyote Creek Member

The Coyote Creek Member (type locality: road-cut along Highway 93, 10 km south of Rogerson, Idaho, Fig. 1) is a 4–5 m thick, buff-brown, non-welded, massive, rhyolitic volcaniclastic layer that conformably overlies the Grey’s

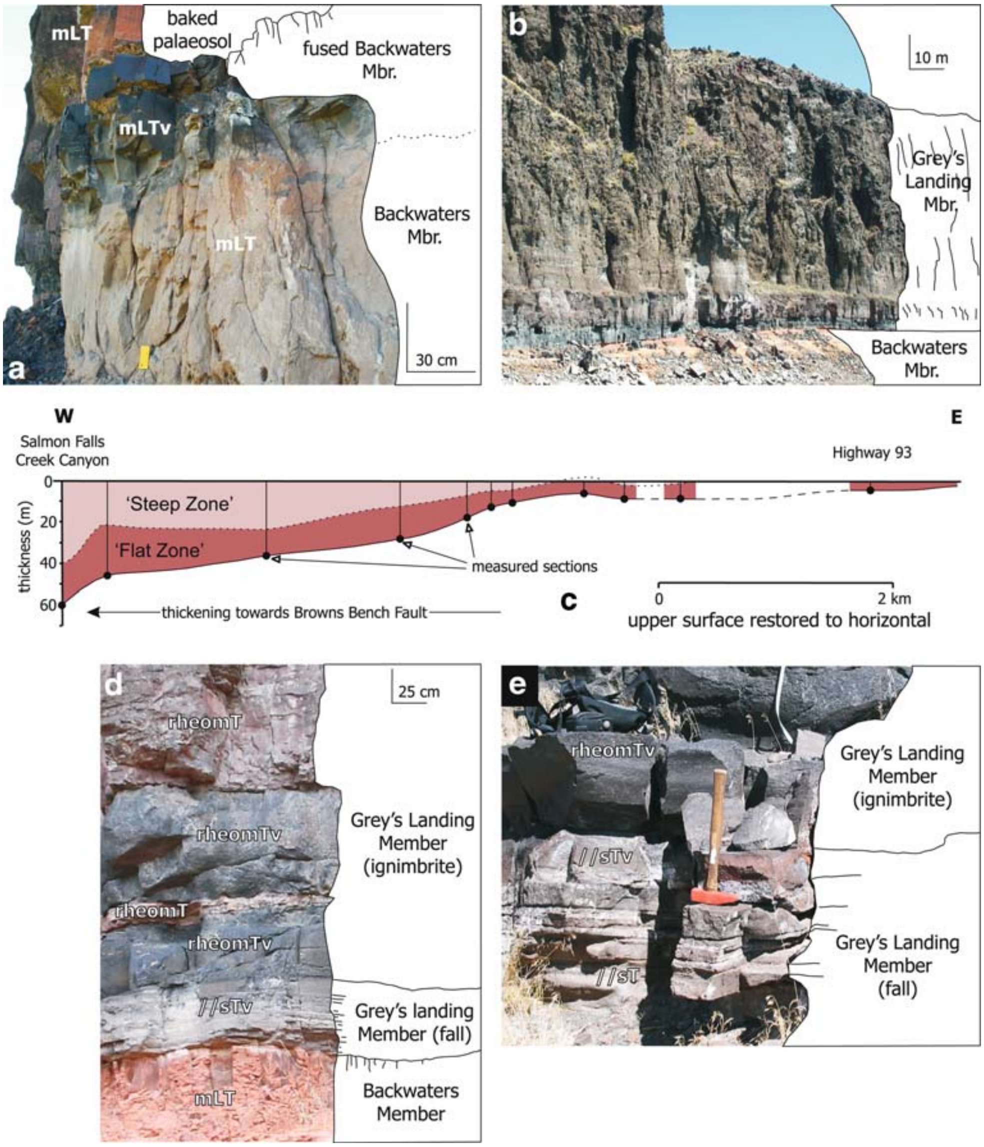


Fig. 8 Sections though the Grey’s Landing Member **a** Baking and fusing zonation with the Backwaters Member, Backwaters. **b** 55 m-thick Grey’s Landing Member dominated by massive, lithoidal centre, sitting on baked Backwaters Member palaeosol at Grey’s Landing. **c** Cross section through the Grey’s Landing ignimbrite from Salmon Falls Creek Canyon (*west*) to Highway 93 (*east*), showing wedge-shaped profile and relative thickness of the ‘steep’ and ‘flat’ zones. **d** Detail of the Grey’s Landing Member base where it is ~60 m-thick, showing the basal vitrophyre lying on fused and stratified, ashfall tuff, in turn lying on baked Backwaters Member palaeosol, Backwaters. **e** Detail of the base of the Grey’s Landing Member where it is ~12 m-thick, showing limited fusing of the underlying stratified tuff. Only the upper 30 cm of the stratified tuff are fused, Highway 93. *mLT* massive lapilli-tuff, *mLTv* massive vitric lapilli-tuff, *rheomT* rheomorphic tuff, *rheomTv* rheomorphic vitric tuff, *//sTv* parallel stratified vitric tuff (Branney and Kokelaar 2002)

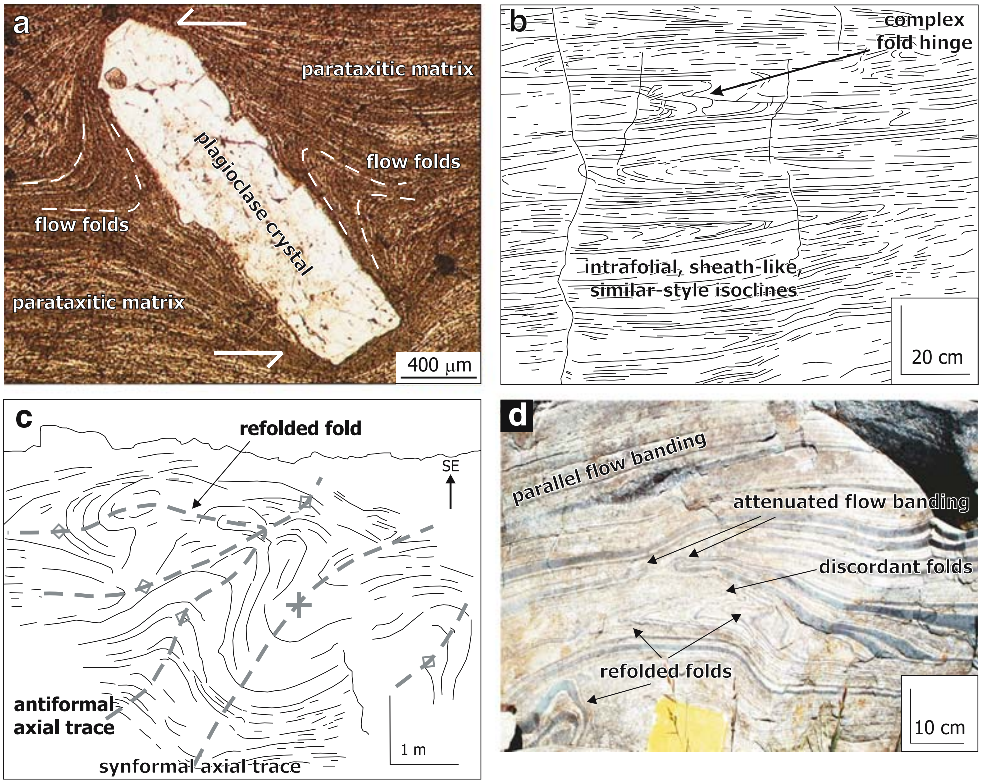


Fig. 9 Grey's Landing Member **a** rotated and mantled, euhedral plagioclase crystal and associated <mm-scale folds from the basal vitrophyre, Grey's Landing, section parallel to stretching direction (PPL). Note the flow banding and 'mylonitic appearance.' **b** Sketch of dm-scale, sheath-like, intrafolial, similar-style isoclinal folds, typical of the Grey's Landing ignimbrite 'flat zone'; Grey's Landing, viewed parallel to stretching direction. **c** Sketch of m-scale, complexly refolded folds in the 'steep zone,' Cedar Creek Reservoir, viewed perpendicular to transport direction. **d** Complex cm-scale folding, refolding and attenuation of flow banding, Salmon Dam, oblique to stretching direction

Landing Member (Fig. 2), although it is poorly exposed and has a limited areal extent (~4 km^2). It is composed of poorly sorted silt-and sand-grade material, mainly glass shards. The upper surface is a thick palaeosol (≤1.5 m), and the whole deposit is strongly bioturbated. Irregularly shaped ashy concretions (~5 cm diameter) are common.

Sand Springs Member

The Sand Springs Member (type locality: road-cut along Highway 93, 10 km south of Rogerson, Figs. 1 and 2) is a ≥8 m thick, dark-grey rhyolitic ignimbrite that conformably overlies the soil at the top of the Coyote Canyon

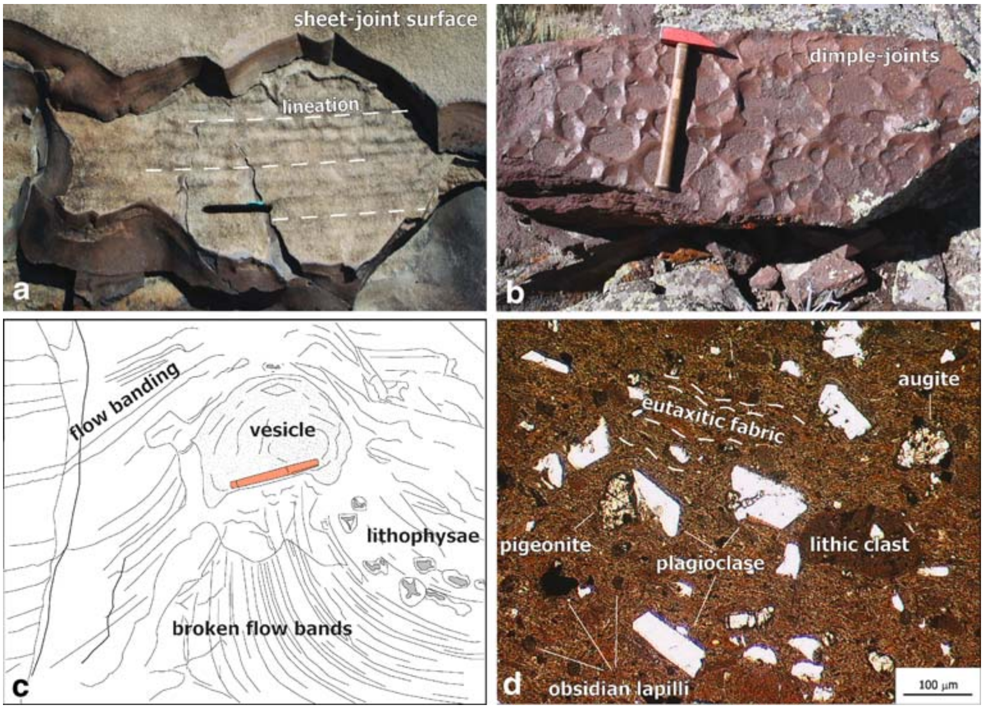


Fig. 10 **a** Lineation developed on sheet-joint surface, Grey's Landing ignimbrite Salmon Dam (pen 12 cm). **b** Dimple-joints on surface of a loose block, Grey's Landing ignimbrite Cedar Creek Reservoir (hammer shaft 40 cm). **c** Sketch of 15 cm diameter, spherical vesicle in banded, devitrified Grey's Landing ignimbrite, Cedar Creek Reservoir (pen 12 cm). Note how the vesicle has intruded upwards ('diapiric'), and broken through some banding. **d** Photomicrograph (PPL) of the Sand Springs Member showing eutaxitic, fine-tuff matrix surrounding abundant crystals and < mm-scale lithics

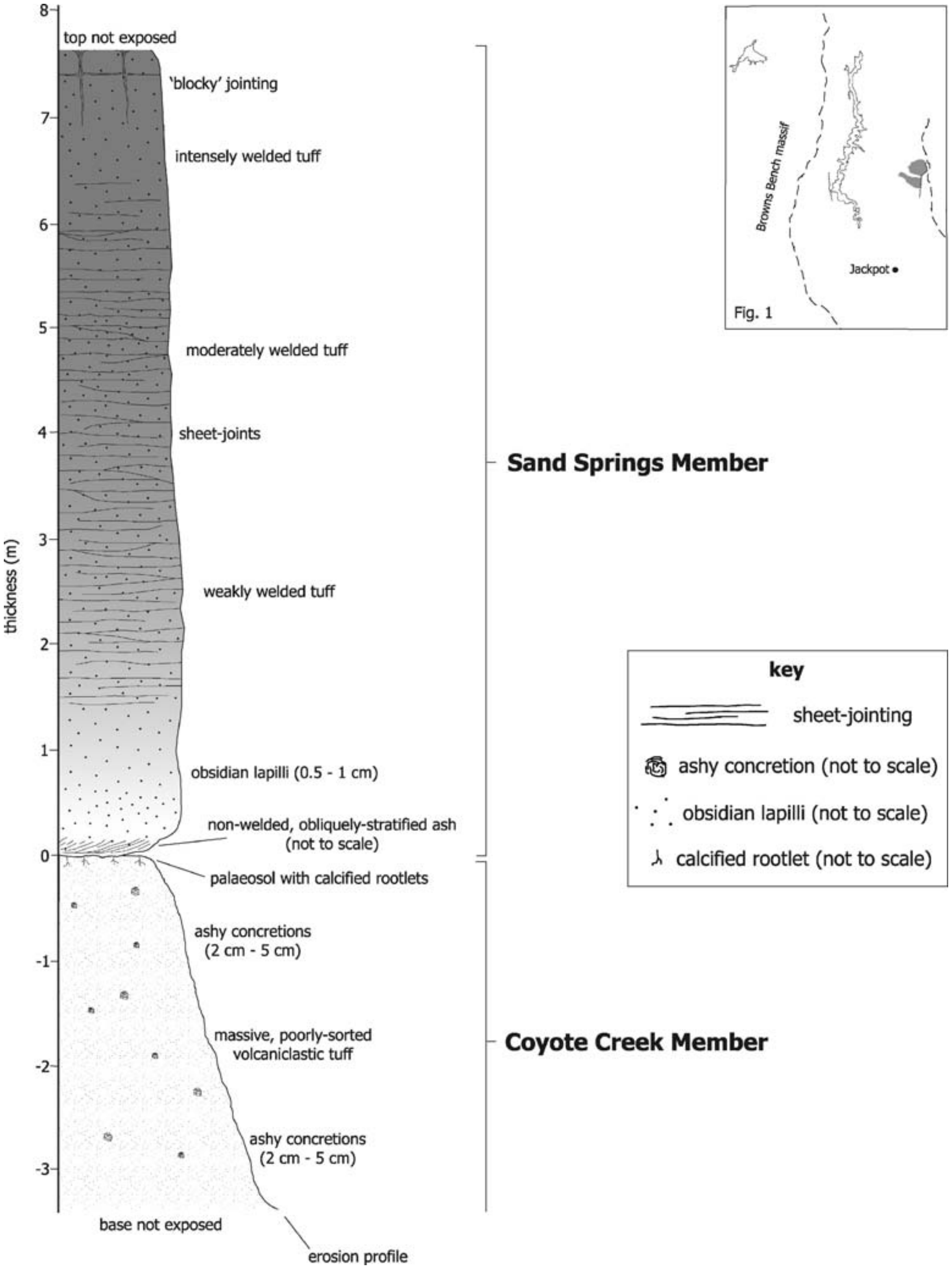


Fig. 11 Graphic log of the Sand Springs and Coyote Creek Members, from the Highway 93 road section. *Inset* shows the outcrop of the Sand Springs Member

Member (Fig. 11). It is restricted to the eastern margin of the Rogerson Graben, covering ~4 km^2. The basal 7 cm comprises a non-welded, low-angle cross-stratified tuff (cross-set height ≤10 cm). This grades up through massive, incipiently welded, moderately welded and then intensely welded, eutaxitic, vitric tuff. Vitroclastic textures (Fig. 10d) and small obsidian lapilli (0.5–1 cm diameter) are ubiquitous throughout the deposit, becoming progressively more flattened with increasing height. There are no pumice lapilli.

Geochemistry, petrology and geothermometry

We present whole-rock, glass and crystal chemical data from the Rogerson Formation, and estimate pre-eruptive temperatures. Our aim is to establish a geochemical dataset to characterise the members within the Rogerson Formation and to provide a basis for improving stratigraphic correlation with adjacent successions (e.g., the Cassia Mountain succession; McCurry et al. 1996) and distal fallout tephra deposits (e.g., Trapper Creek; Perkins et al. 1995).

Bulk-rock chemistry

The Rogerson Formation is composed of anhydrous, metaluminous rhyolites (68.25–75.7% SiO_2), with relatively high concentrations of TiO_2, MgO and Fe_2O_3, high Ga/Al ratios, high Fe_2O_3*/MgO ratios (Appendix Table 1).

Glass shard matrix chemistry

Electron microprobe spot analyses of glass shards and welded glass matrix from non-altered vitrophyres are presented in Appendix Table 2, however, glass analysis was not possible in lithoidal rhyolite; furthermore, the Jackpot Member lacks non-hydrated vitrophyre (sub-unit 5 perlitized upper vitrophyre) preventing any glass analysis. The Rabbit Springs, Brown's View, Grey's Landing, and Sand Springs Members have compositionally restricted shard populations (71–77.5 wt.% SiO_2; $CaO+Na_2O+K_2O$ ~10 wt.%), and there is no systematic variation between or within individual members.

Crystal chemistry

Plagioclase, pyroxene, titano-magnetite, and accessory apatite and zircon are ubiquitous throughout the Rogerson Formation (Fig. 12). They exist as single, often broken crystals (Fig. 9a) and as glomerocrysts of plagioclase, pyroxene, and titano-magnetite.

Plagioclase occurs in all units and exists in three textural forms: (1) euhedral crystals with sieve-texture (Fig. 9d); (2) subhedral to anhedral crystals associated with glomerocrysts; and (3) euhedral to subhedral, crystal fragments (Fig. 10d). All plagioclase found in Jackpot sub-units 3 and 5 is oligoclase (An 25–35; Figs. 12 and 13a), however, the plagioclase in 'Jackpot 7' and all other members in the Rogerson Formation is andesine (An 35–An 50; Figs. 12 and 13b). Sanidine crystals (Or 50–Or 57; Fig. 13a) occur only in the Jackpot and Rabbit Springs members. They have two forms: (1) anhedral crystals with myrmekite rims and (2) subhedral crystal fragments. The former are only found in the Jackpot Member, where they are much more abundant than the latter.

Pyroxene crystals occur in all members although those in the Jackpot Member are partly oxidized and hydrated, and altered to amphibole or clay. Non-zoned Ca-rich pyroxene (augite) and Ca-poor pyroxene (pigeonite) are found in equal abundances in all units apart from the Grey's Landing Member, in which augite is nearly absent from upper sections and minor quantities of hypersthene occurs at the base (Fig. 12). Pyroxene crystals occur in equal measure in two forms: (1) anhedral crystals associated with glomerocrysts and (2) crystal fragments. Pyroxene compositions are presented with tie lines joining analyses from co-existing crystals (Figs. 13c and d). Augites and pigeonites in the Rogerson Formation exhibit a range of compositions (Figs. 13c and d) which correspond to compositional trends described for the Cougar Point Tuff Formation (Cathey and Nash 2004).

Titano-magnetite and ilmenite are present in all units other than the Grey's Landing Member, in which ilmenite is absent (Fig. 12). Magnetite exists as both anhedral crystals within glomerocrysts, and as crystal fragments. Ilmenite occurs as discrete anhedral crystals only. Subhedral and anhedral quartz crystals are only found in the Jackpot and Rabbit Springs members (Fig. 12) where they exist as isolated, anhedral crystals. Anhedral apatite and zircon crystals are abundant in all units, commonly as inclusions in Fe–Ti oxides. Discrete apatites and zircons are only found associated with glomerocrysts.

Geothermometry

Electron microprobe analyses of crystal rim pairs were used to calculate mean crystal compositions ($n \geq 25$) for individual samples referenced for stratigraphic position within each ignimbrite. Mean crystal compositions were input to appropriate Fe–Ti oxide, two-pyroxene, and two-feldspar geothermometers, depending on the different crystal populations of respective members (Figs. 2 and 12). The use of geothermometry assumes that crystal rims were in equilibrium with the liquid, even if crystal cores may have not re-equilibrated.

Estimates of pre-eruptive temperature from Fe–Ti oxide (magnetite–ilmenite) thermometry and fO_2 were made using (1) the model of Ghiorso and Sack (1991), and (2) the QUILF 4.1 software package (Andersen et al. 1993) applying the model of Andersen et al. (1991) and technique of Manley and Bacon (2000). All Fe–Ti oxide pairs were tested for Mg/Mn equilibrium following the method of Bacon and Hirschmann (1988) before being applied to the two geothermometers, and only samples from the Browns View Member were found to be in equilibrium. Estimates of pre-eruptive temperature from two-pyroxene (augite-pigeonite pairs) thermometry were made in the Rabbit Springs, Browns View, Grey's Landing and Sand Springs Members, using a pressure constant of 5 kbar (e.g., Cathey and Nash 2004). First we used the model of Andersen et al. (1991) through the QUILF 4.1 software package (Andersen et al. 1993), and secondly we applied the graphical geothermometer of Lindsley (1983) plotted onto the pyroxene quadrilateral (Figs. 13c and d), where contours allow visual estimation of equilibrium temperature. Estimates of pre-eruptive temperature from two-feldspar

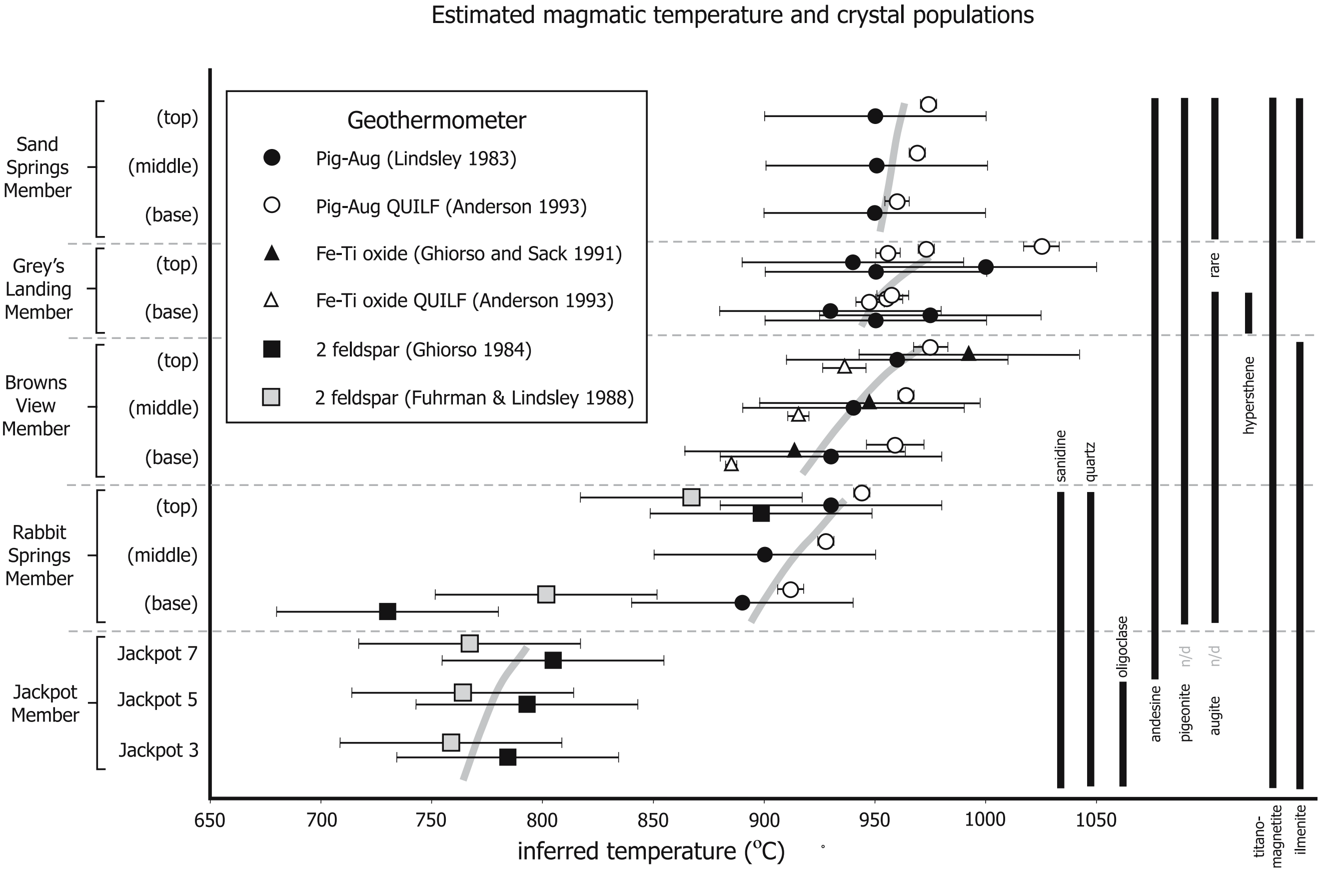


Fig. 12 Comparison of estimated magmatic temperature and crystal population with stratigraphic height in the Rogerson Formation. Magmatic temperatures are seen to increase with height in each member (*grey arrows*). Each data point represents the mean of 25 pairs of analyses. Error bars are ± 50°C for the models of Fuhrman and Lindsley (1988), Ghiorso (1984), Ghiorso and Sack (1991) and Lindsley (1983). *Errors bars* are 2s for the model of Andersen et al. (1993). *n/d* not determined

(plagioclase-sanidine pairs) thermometry were made in the Jackpot and Rabbit Springs Members. Using a pressure constant of 5 kbar, we applied the geothermometers of Ghiorso (1984) and Fuhrman and Lindsley (1988), using the SOLVCALC 1.0 software of Wen and Nekvasil (1994).

Pre-eruptive temperatures estimated from geothermometry are summarised in Fig. 12. Temperature estimates for the Rabbit Springs, Brown's View, Grey's Landing and Sand Springs Members are typically 850–1,000°C. Oxygen fugacity estimates of −11 to −13 log units are reported from the Brown's View Member. The pre-eruptive temperature of the Jackpot Member is significantly lower (≤800°C), however, previous workers applying two-feldspar thermometers to high-temperature rhyolites have urged caution, citing concerns regarding pressure uncertainties and post-emplacement alteration of crystals (e.g., Honjo et al. 1992; Cathey and Nash 2004). In the absence of suitable Fe–Ti oxide or pyroxene pairs we do not disregard these temperature estimates but echo previous workers' caution in their interpretation.

Discussion

Stratigraphy of the Rogerson Graben

Jackpot member

Jackpot Member sub-units 1–5 and 7, resemble lavas because they are massive, intensely flow-banded and jointed (Fig. 3), and are devoid of pumice and lithic lapilli, fiamme, and sedimentary structures. However, we interpret them to be ignimbrites because: (1) they exhibit laterally persistent internal stratigraphies; (2) they lack autobreccias, either at the base and top of the member, or between sub-units 1–5; and (3) they are too thin to be rhyolite lavas. Laterally persistent divisions between sub-units are defined by topographic breaks, changes in columnar joint size and spacing, the upper vitrophyre of Jackpot 5; and lithophysae-rich layers (Figs. 3 and 4a), which we interpret to record breaks in deposition, rapid cooling, and volatile de-gassing between emplacements. These divisions do not contain

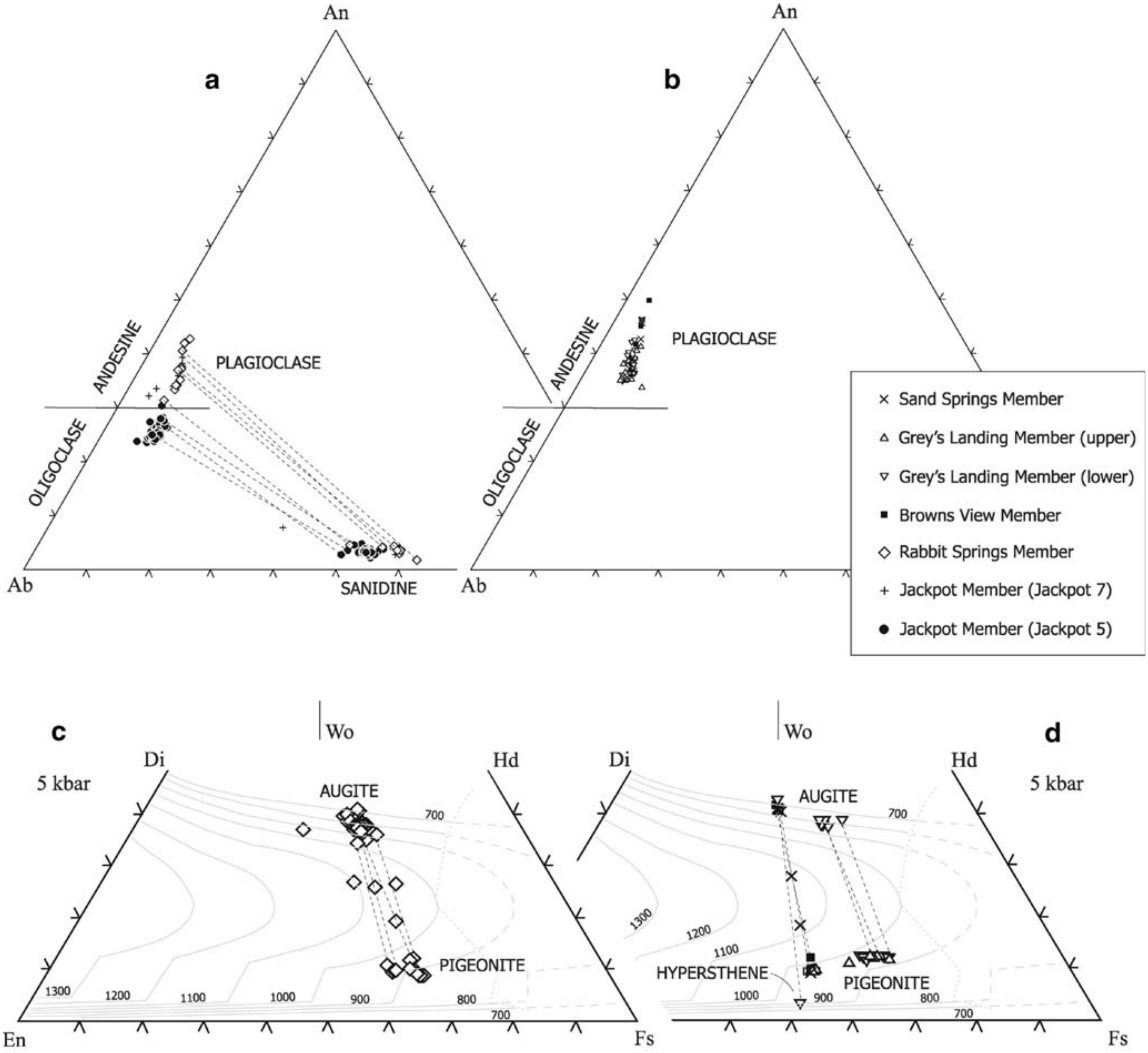


Fig. 13 Mineral compositions in the Rogerson Formation. **a** Ternary feldspar compositions for the Jackpot and Rabbit Springs Members. Tie-lines between co-existing plagioclase and sanidine crystals. **b** Ternary feldspar compositions for the Browns View, Grey's Landing and Sand Springs Members. Note the absence of sanidine. **c** Pyroxene composition quadrilateral for the Rabbit Springs Member. Jackpot Member pyroxenes were oxidized and not analysed. Tie-lines between co-existing clinopyroxene and pigeonite crystals. **d** Pyroxene composition quadrilateral for the Browns View, Grey's Landing and Sand Springs members. Note the absence of augite in the upper parts of the Grey's Landing Member. Tie-lines between co-existing clinopyroxene and pigeonite crystals. Thermal contours from Lindsley (1983) at 5 kbar

autobreccias, the presence of which is diagnostic of large-volume silicic lavas (Henry and Wolff 1992; Bonnichsen and Kauffman 1987; Sumner and Branney 2002), and we know of no silicic lavas in the Snake River Plain volcanic province that lack them. Furthermore, silicic lavas in the region tend to be thick (≥50 to ~300 m; Bonnichsen and Kauffman 1987), and tend not to form distal featheredges, as ignimbrites do (Branney et al. 2007). We tentavtively interpret NW–SE trending lineations to record emplacement from the Bruneau–Jarbidge area to the WNW (Fig. 1).

'Jackpot 6' is the least intensely welded sub-unit and its pyroclastic origin is clearly shown by the presence of cross-stratification, lensoidal bedding, ash shards, obsidian lapilli, and accretionary lapilli. We interpret this sub-unit to be an ignimbrite deposited from a pyroclastic density current that was cooler than those that emplaced sub-units 1–5 and 7. We suggest that the base of sub-unit 6 fused when it was deposited on top of the still hot sub-unit 5. The absence of weathered surfaces, soils, exotic tephra layers or sediments and vitrophyres between sub-units suggests that it represents a single eruptive unit of seven rapidly emplaced ignimbrites, which in turn, welded, cooled and devitrified together as a simple cooling unit (Smith 1960).

Undifferentiated volcaniclastic deposits

Both the undifferentiated volcaniclastic units are interpreted as sequences of fallout ashes and related silt- and sand-grade epiclastic deposits. Normal graded bedding and de-watering structures are consistent with deposition of fallout ash into standing water and onto soft substrate, and the presence of ripples and erosional scours suggests that currents reworked the deposit (e.g., Nakayama and Yoshikawa 1997). The presence of palaeosols with calcified rootlets within both sequences suggests periods of non-deposition, plant growth, and pedogenesis, either in shallow water or exposed at the surface. The sources of fallout ashes are unknown; significant thicknesses of distally and medially sourced fallout ashes are reported from basins throughout the Snake River Plain and adjacent regions (e.g., Perkins et al. 1995; Perkins and Nash 2002).

The lower volcaniclastic unit fills and buries several graben developed in the Jackpot Member. We interpret that sustained fallout ash deposition occurred after, and possibly during, tectonic extension of the Jackpot Member and in the absence of contemporaneous ignimbrite emplacement. The early Rogerson Graben, and smaller graben within it, were probably host to small ephemeral lakes and short-lived (thin palaeosols) dry and vegetated high-stands.

Rabbit Springs Member

The Rabbit Springs Member is a high-grade, low aspect-ratio ignimbrite. The absence of elongation lineations, flow folds and autobreccias suggest it is not rheomorphic. We interpret it as a single ignimbrite emplacement unit because of its thinness, vitroclastic textures, and lack of internal breaks (e.g., autobreccias, intercalated fallout ashes or palaeosols). Furthermore, we interpret it is as a simple cooling unit because of its simple welding profile (Smith 1960). Normal faults that partition thickness variations, but do not deform the upper vitrophyre, are interpreted to be extensional growth faults (e.g., Childs et al. 2003) suggesting ignimbrite emplacement into an actively extending graben.

Undifferentiated volcaniclastic rocks

The upper volcaniclastic unit appears to be discordant with the underlying Rabbit Springs Member and may be unconformable, although an erosion surface has not been observed. Major planar erosion surfaces, possibly flooding surfaces, cut palaeosols within the unit, which were then buried by onlapping and discordant (west-dipping) volcaniclastic packages, suggesting that the half-graben was contemporaneously extending, and that the graben-floor was often not horizontal. The presence of thick palaeosols suggests sustained periods of non-deposition, plant growth and pedogenesis, between major erosive events and subsequent deposition of fallout ash.

Brown's View Member

The Brown's View Member is a high-grade, low aspect-ratio ignimbrite. We interpret the presence of ubiquitous vitroclastic textures, the thinness of the sheet, the simple welding profile, and the absence of breaks (e.g., intercalated palaeosols, fallout ashes, sedimentary layers, and autobreccias) as evidence for a single emplacement unit, and simple cooling unit (e.g., Smith 1960).

Backwaters Member

We tentatively interpret volcaniclastic units A and B of the Backwaters Member as non-welded ignimbrites because they are massive, poorly sorted, and contain sub-angular to sub-rounded pumice clasts. Furthermore, they appear to contain a substantial juvenile component where the glassy (and therefore possibly juvenile) ash matrix of unit B has been fused. The erosive base of unit B is also consistent with deposition from a pyroclastic density current. However, we cannot rule out deposition from debris flows (e.g., Smith 1986; Palmer and Walton 1990), an interpretation consistent with massive and poorly sorted deposits containing rounded pumice lapilli. The presence of palaeosols indicates significant pauses in deposition, representing periods of eruptive repose.

Grey's Landing Member

We interpret the basal stratified ash as a contemporaneous fallout ash, based on mantling of the substrate, very good sorting, laterally continuous lamination and thickness, as well as the absence of erosive features and internal truncations. We infer that the layers derive from the same eruption as that which emplaced the overlying ignimbrite because of the absence of an intercalated palaeosol or erosion surface.

Although the Grey's Landing Member is largely lava-like, we interpret it to be an ignimbrite on the basis of the vitroclastic textures in the upper and lower vitrophyres, its low aspect ratio, and the widespread absence of a basal autobreccia. Flow folds and elongation lineations characterize rheomorphic deformation (e.g., Schmincke and Swanson 1967; Chapin and Lowell 1979; Wolff and Wright 1981). Measurements of lineation-trends and rotation directions in crystals (Fig. 9a) suggest that, at least initially, the ignimbrite was emplaced from the east (Andrews 2006). We interpret the upper breccia to record in situ brecciation of welded ignimbrite in response to internal stress caused by rheomorphic flow while the upper part of the deposit started to cool and degas. We infer that the overlying aphyric, orange ash is a penecontemporaneous fallout ash, possibly co-ignimbritic, as it is partly fused against and folded into the underlying welded ignimbrite (e.g., Walker 1983; Branney et al. 1992; Branney and Kokelaar 2002). The origin of dimple-joints remains enigmatic; we interpret them to be a devitrification feature because they are only found in lithoidal rhyolite (e.g., Bonnichsen 1982b), and suggest that each dimple may be a formed at an oblate spherulite, originally surrounded by vitric rhyolite that has subsequently devitrified.

We interpret the basal stratified-fall deposit, lava-like ignimbrite and upper orange ash together as a simple cooling unit (e.g., Smith 1960), based on fusing of the upper and lower ash deposits by the ignimbrite and deformation of the upper ash. Therefore, the ignimbrite and both ashes are probably products of the same, single eruptive event. More tentatively, we interpret the ignimbrite to be a single flow unit based on the absence of any evidence in the sheet for a flow hiatus, although it is possible that such evidence would have been obscured by rheomorphism.

Coyote Creek Member

Although somewhat enigmatic in origin, we interpret, tentatively, the Coyote Canyon Member to be a non-welded ignimbrite based on the presence of juvenile ash and its massive appearance. However, once again we cannot rule out deposition from a volcaniclastic debris flow (e.g., Smith 1986; Palmer and Walton 1990).

Sand Springs Member

The Sand Springs Member is clearly pyroclastic and welded, based on eutaxitic vitroclastic textures and progressively flattened obsidian lapilli, and we interpret it as an ignimbrite. It is a single emplacement unit and the simple welding profile suggests it is a simple cooling unit.

Geochemical characteristics—petrogenesis and geothermometry

Anhydrous, metaluminous rhyolites are typical of rhyolite elsewhere in the Yellowstone–Snake River Plain volcanic province (e.g., Hughes and McCurry 2002; Cathey and Nash 2004), and are also characteristic of anorogenic A-type granitoids in other magmatic provinces (Whalen et al. 1987). Ignimbrites of the Idavada Group (Malde and Powers 1962) typically contain anhydrous crystal assemblages of plagioclase, sanidine, augite, pigeonite, quartz, and Fe–Ti oxides, and rarely, fayalite and orthopyroxenes (e.g., Bonnichsen and Citron 1982; Honjo et al. 1992). In contrast younger ignimbrites in the eastern Snake River Plain commonly contain Fe-rich amphibole (e.g., the Lava Creek Tuff; Christiansen 2001) or biotite (e.g., the Arbon Valley Tuff; Morgan and McIntosh 2005).

Those members of the Rogerson Formation that preserve non-hydrated vitrophyre are composed of ash shards with a restricted compositional range (73–77.5 wt.% SiO_2). There is no systematic variation in glass composition between or within members suggesting a homogeneous and well-mixed liquid before each eruption; moreover, these conditions appear to have been repeated at least four times, before the eruptions of the Rabbit Springs, Brown's View, Grey's Landing and Sand Springs ignimbrites.

Crystal chemistry shows subtle variations within the Rogerson Formation. Differences in the stratigraphic distribution of crystal phases (e.g., abundant sanidine and quartz; Fig. 12) and differences in crystal chemistry (e.g., oligoclase and andesine; Fig. 13) establish that the Jackpot and Rabbit Springs members are significantly different from the rest of the Rogerson Formation. Only the Grey's Landing Member shows any internal variation in crystal assemblage where augite decreases with increasing height and pigeonite remains uniformly abundant. We interpret this to indicate subtle, vertical compositional zonation within the Grey's Landing Member, which in turn, may indicate that it was erupted from a compositionally zoned magma chamber (e.g., Hildreth 1979, 1981), with the most evolved batch of liquid (augite = pigeonite) tapped first, followed by progressively less evolved liquid (augite ≤ pigeonite), and finally, the least evolved liquid (augite << pigeonite).

Pre-eruptive temperature

The extremely high-grade and rheomorphic nature, and the lack of hydrous minerals in ignimbrites of the Rogerson Formation, suggest high rhyolitic magmatic temperatures (850–1,025°C). This is consistent with conclusions from studies of other ignimbrites in the Snake River Plain volcanic province (Ekren et al. 1984; Honjo et al. 1992; Cathey and Nash 2004) and some large igneous provinces, such as Etendeka-Parana (Bellieni et al. 1984; Milner et al. 1992; Kirstein et al. 2001), the Whitsunday volcanic province, Australia (Bryan et al. 2000), the Keweenawan rift, Minnesota (Green and Fitz 1993), and Trans-Pecos, Texas (Henry et al. 1988).

There is a subtle increase in pre-eruptive temperature estimate with height in each member (Fig. 12), best displayed by estimates from the QUILF geothermometer that displays the lowest uncertainties (≤±20°C). We interpret, tentatively, that this suggests compositional zoning within the Rabbit Springs, Brown's View, Grey's Landing and Sand Springs members, where each time a cooler liquid is tapped first and followed by progressively a hotter liquid from deeper within the magma chamber (e.g., Hildreth 1979, 1981).

Criteria for distinguishing lavas and lava-like ignimbrites

Investigations of lava-like rhyolites inevitably lead to discussion over emplacement mechanism: (1) as a lava, flowing *en masse* from the vent; or (2) as an ignimbrite, deposited from a pyroclastic density current. We have interpreted each member as an ignimbrite based on several criteria: (1) unit form and thickness, (2) textures preserved in vitrophyre, and (3) the absence of basal autobreccias. Most rhyolite lavas in the Snake River Plain are thick (≥50–300 m) and have aspect ratios ~1:10^2 (Branney et al. 2007). Moreover, they exhibit widespread basal and carapace autobreccias (e.g., Bonnichsen 1982b; Henry and Wolff 1992; Manley 1996a), and typically vitroclastic textures are rare and limited to where autobreccia has been entrained into the flowing lava (e.g., Manley 1996b). In contrast, lava-like ignimbrites are thin (typically < 100 m thick) and have aspect ratios of ~ 1:10^3. Vitroclastic textures are ubiquitous, although they may be obscured by rheomorphism and devitrification, and lower autobreccias are very rare and localised (e.g., Sumner and Branney 2002). Generally, the presence of abundant broken crystals is characteristic of ignimbrites rather than of lavas (e.g., Fisher and Schminke 1984).

Tectonic framework of the Rogerson Graben

We have begun to establish the tectonic history of the graben using the thickness distributions of ignimbrites, volcaniclastic sediments, and lavas; and crosscutting relationships between stratigraphic members and faults; back as far as the emplacement of the Jackpot Member (>>10.37 Ma), beyond which we have no stratigraphic or tectonic constraints. The evolution of the graben can be divided into three phases: (1) initiation; (2) syn-ignimbrite emplacement; and (3) post-ignimbrite emplacement.

Several small, NNE-trending graben (≤10% E–W extension) developed in the Jackpot Member, and were infilled by undifferentiated volcaniclastic sediments (Figs. 1 and 14). The status of the graben-bounding Brown's Bench fault at this time is unknown. However, the orientation and scale of the fault is consistent with major Basin and Range faults further south in central Nevada, suggesting that it is an inherited structure affecting both pre-Miocene basement and Snake River Plain volcanics.

The extending graben-floor (NNE-trending growth faults) was inundated by the west-thickening Rabbit Springs Member (Fig. 14), suggesting the Rogerson Graben was an asymmetric half-graben. Subsequent deposition of bedded volcaniclastic sediments was interrupted with repose periods (palaeosols), and graben-floor tilting and erosion (minor angular unconformities). The Brown's View, Backwaters and Grey's Landing members thickened westward against, and buried, the Brown's Bench Fault (onlapping and overstepping older ignimbrites in the footwall; Figs. 1 and 14). The relationship between the Coyote Creek and Sand Springs members and graben formation is unknown.

Graben development has continued since the deposition of the Rogerson Formation, displacing late Miocene–Pliocene basalt lavas by 40 m and an accompanying northward propagation of the tip-point of the Brown's Bench Fault.

In summary, the Rogerson Formation and overlying lavas record ~10 Ma of episodic extension, graben-floor tilting, and scarp burial, related to the formation of the Rogerson Graben. The Rogerson Graben, therefore, shares many characteristics (e.g., rapid in-filling by ignimbrites, long repose periods, growth faults, prolonged extension) with basins along the margins of the Snake River Plain (e.g., the Oakley and Raft River basins, Idaho; Rodgers et al. 2002), and other volcanic provinces associated with extensional tectons (e.g., extensional arcs, Fackler-Adams and Busby 1998; Basin and Range, Aguirre-Diaz and Labarthe-Hernández 2003). Basins adjacent to the eastern Snake River Plain have been interpreted to form through the localised reactivation of Basin and Range normal faults by the migration of the Yellowstone hot-spot (Anders et al. 1989; Rodgers et al. 1990, 2002), and we infer that the same scenario occurred regarding the Rogerson Graben.

Conclusions

Eruption history

The Rogerson Formation is the product of prolonged, explosive rhyolitic volcanism in the central Snake River Plain. A history of ≥8 eruptions is recorded; the duration of which is unknown but may have been c. 8–11 Ma. The eruptive history of the Rogerson Formation, from oldest to youngest is as follows.

1. A rapid succession of pyroclastic density currents entered the Rogerson Graben, possibly from a source near Bruneau–Jarbidge (lineation data; Fig. 1 inset) and deposited a voluminous, lava-like ignimbrite (Jackpot Member). A cooler phase of the eruption produced non-welded, traction cross-stratified tuffs with accretionary lapilli ('Jackpot 6') before a return to higher-temperature emplacement ('Jackpot 7').

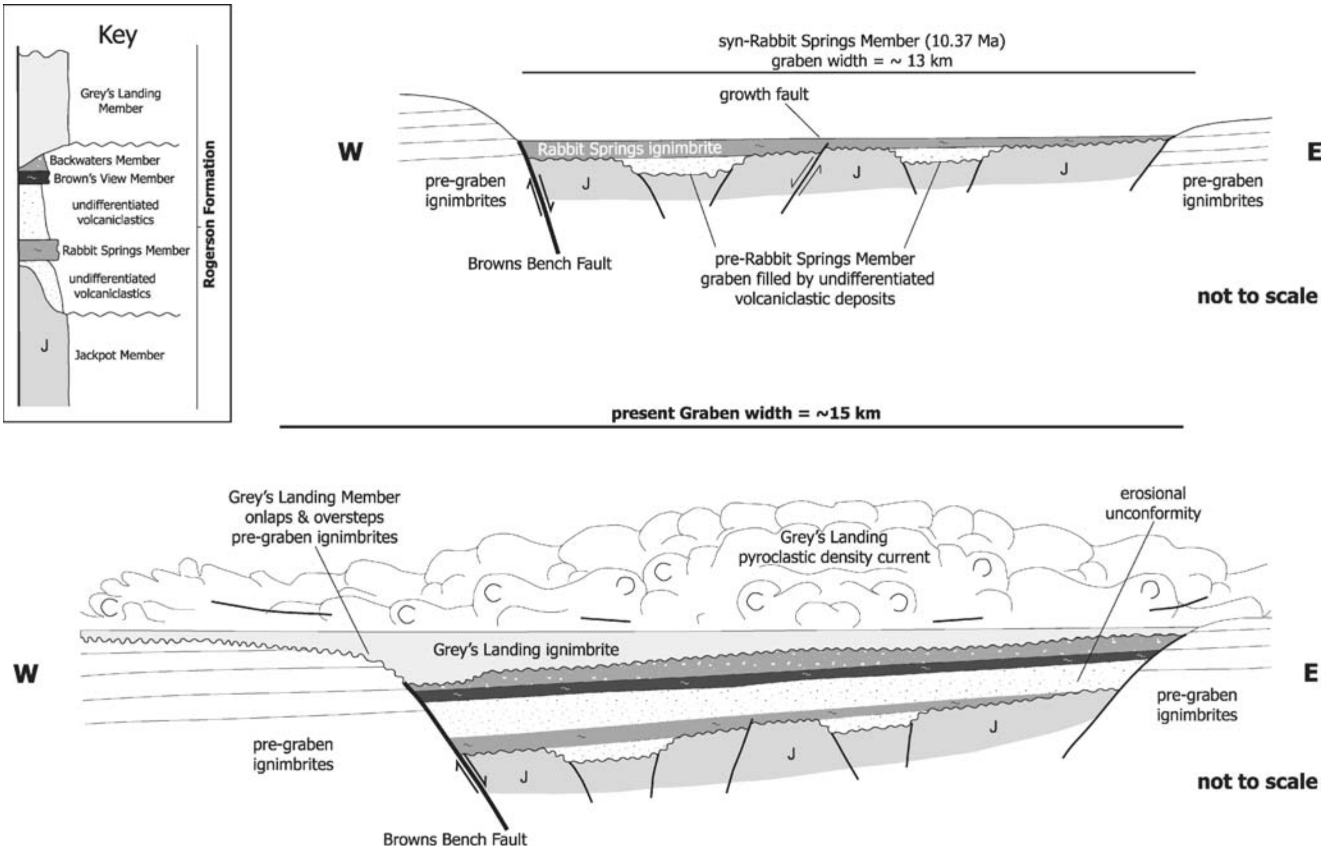


Fig. 14 Schematic cross-sections through the Rogerson Graben (Fig. 1): (*top*) immediately after emplacement of the Rabbit Springs Member. Note growth fault and burial of earlier graben; (*bottom*) during emplacement of the Grey's Landing Member. Note that the Grey's Landing Member onlaps and oversteps pre-graben ignimbrites and the Brown's Bench Fault scarp

2. Several NNE–SSW trending graben developed (Fig. 1) forming local depocentres for fallout ashes possibly erupted from the Bruneau–Jarbidge area, and reworked to form bedded volcaniclastic sediments. Periods of quiescence are recorded as soils.
3. Another ignimbrite eruption, possibly near Bruneau–Jarbidge, emplaced the welded Rabbit Springs Member (10.37 Ma±0.13). Contemporaneous graben extension is indicated by growth faults in the ignimbrite.
4. Continued regional extension led to subsidence and westward tilting of the Rogerson Graben floor, while the basin accumulated non-welded rhyolitic ash and volcaniclastic sediment with several extended periods of soil formation.
5. The next major pyroclastic density currents to enter the graben may have had a different magmatic source, possibly near Twin Falls (Fig. 1 inset). It deposited a single cooling unit, the eutaxitic Brown's View ignimbrite.
6. Following a repose period (soil horizon) further pyroclastic inundations deposited two, non-welded ignimbrites or debris-flow deposits (Backwaters Member) separated by another significant period of repose.
7. A large-volume, compositionally zoned, rhyolitic explosive eruption deposited a 1.5 m stratified ashfall layer and overlying 60 m thick rheomorphic ignimbrite (the Grey's Landing Member). The eruption may have been from the northeast (kinematic criteria indicate emplacement from the east), near Twin Falls. The rheomorphic character of the ignimbrite reflects hot magmatic temperatures (925–1,025°C).
8. Following repose periods (palaeosols) further explosive eruptions deposited the non-welded Coyote Creek ignimbrite and the welded Sand Springs ignimbrite, possibly also from the north.
9. Extension of the Rogerson Graben with NNE- and NNW-trending normal faulting and the eruption of at least three late-Miocene basalt lavas (Bonnichsen and Godchaux 2002).
10. Salmon Falls Creek incised a ≥ 50 m deep canyon into the basalt lavas and Grey's Landing ignimbrite (late Miocene, Bonnichsen and Godchaux 2002).
11. The creek was dammed by basalt lava from Salmon Butte (Salmon Dam, Fig. 1) and then subsequently re-incised (late Pliocene–Pleistocene, Bonnichsen and Godchaux 2002).

Relation to Yellowstone–Snake River Plain volcanic province stratigraphy

We interpret the Rogerson Formation to record deposition of fallout ashes and ignimbrites from the Yellowstone–Snake River Plain volcanic province into the Rogerson Graben. During the time represented by the Rogerson Formation the graben was actively extending and propagating northwards, becoming a major depo-centre no later than 10.37 Ma when the Rabbit Springs ignimbrite was emplaced. Of the several graben and half-graben developed along the margins of the Snake River Plain (e.g., Rodgers et al. 2002) the Rogerson Graben is the most westerly and contains the oldest graben-fill succession reported (Fig. 1 inset).

Further examination of adjacent successions is required to better constrain the distributions, ages, and sources of members within the Rogerson Formation, however, we attempt to draw some preliminary conclusions regarding the stratigraphic significance of the formation. The Jackpot and Rabbit Springs (≤10.37 Ma) Members are characteristically sanidine and quartz-phyric; the presence of these crystal types is typical of members of the contemporaneous Cougar Point Tuff Formation (12.7–10.4 Ma) and associated ignimbrites and lavas erupted from the Bruneau–Jarbidge area (e.g., Bonnichsen 1982a, b; Cathey and Nash 2004). Moreover, NW–SE trending lineations are consistent with emplacement from the Bruneau–Jarbidge area (Fig. 1 inset). In contrast, the Brown's View, Grey's Landing (7.62 Ma) and Sand Springs Members are devoid of sanidine and quartz, and the Grey's Landing ignimbrite preserves kinematic indicators suggesting emplacement from the east; all criteria typical of eruptions from the Twin Falls area (10.9–8.6 Ma; McCurry et al. 1996, Wright et al. 2002).

The Rogerson Formation, therefore, may record the gradual migration of the locus of volcanism from the Bruneau–Jarbidge area to the Twin Falls area following the track of the Yellowstone hotspot (Fig. 1 inset), and the final stages of the 'ignimbrite flare-up' period (11.7–10.0 Ma) of Bonnichsen (2004). Furthermore, it records contemporaneous basin development coincident with lithospheric stretching around the hotspot locus (e.g., Anders et al. 1989) and the adjacent Basin and Range province (e.g., Rodgers et al. 1990, 2002).

Acknowledgements This work forms part of NERC-funded PhD research by GDMA at the University of Leicester (NERC Award NER/S/A/2001/06292). Formal reviews by Cathy Busby and an anonymous reviewer greatly improved the manuscript; early reviews by Steve Temperley and Richard Brown are appreciated. Thanks to Martha Godchaux, Sarah Brown, Steve Rippington and Karen Colclough for discussion and help in the field, and Lawrence Coogan, Rob Wilson, Mike Norry, and Andy Saunders for assistance with geochemical analysis. Special thanks also to Mark Ghiorso and Craig White.

References

Aguirre-Diaz GJ, Labarthe-Hernández G (2003) Fissure ignimbrites: fissure-source origin for voluminous ignimbrites of the Sierra Madre Occidental and its relationship with Basin and Range faulting. Geology 31:773–776. DOI 10.1130/G19665.1

Anders MH, Geissman JW, Piety LA, Sullivan JT (1989) Parabolic distribution of circum-eastern Snake River Plain seismicity and latest Quaternary faulting: migratory pattern and association with the Yellowstone hotspot. J Geophys Res 94:1589–1621

Andersen DJ, Bishop FC, Lindsley DH (1991) Internally consistent solution models for Fe–Mg–Mn–Ti oxides: Part II Fe–Mg–Ti oxides and olivine. Am Mineral 76:427–444

Andersen DJ, Lindsley DH, Davidson PM (1993) QUILF: a Pascal program to assess equilibria among Fe–Mg–Mn–Ti oxides, pyroxenes, olivine, and quartz. Comp Geosci 19:1333–1350

Andrews GDM (2006) Emplacement and deformation history of high-temperature, lava-like tuffs: a structural analysis of the Grey's Landing ignimbrite, Idaho, USA. PhD thesis, University of Leicester

Bacon CR, Hirschmann MM (1988) Mg/Mn partitioning as a test for equilibrium between coexisting Fe–Ti oxides. Am Mineral 73:57–61

Bellieni G, Brotzu P, Comin-Chiaramonti P, Ernesto M, Melfi A, Pacca IG, Piccirillo EM (1984) Flood basalt to rhyolite suites in the southern Parana Plateau (Brazil): palaeomagnetism, petrogenesis and geodynamic implications. J Petrol 25:579–618

Bonnichsen B (1982a) The Bruneau–Jarbidge Eruptive Center, southwestern Idaho. In: Bonnichsen B, Breckinridge RM (eds) Cenozoic Geology of Idaho. Idaho Bur Min Geol Bull 26:237–254

Bonnichsen B (1982b) Rhyolite lava flows in the Bruneau–Jarbidge Eruptive Center, southwestern Idaho. In: Bonnichsen B, Breckinridge RM (eds) Cenozoic Geology of Idaho. Idaho Bur Min Geol Bull 26:283–320

Bonnichsen B (2004) The Snake River Plain 11.7–10.0 Ma ignimbrite flare-up. Geol Soc Am Abs w/Prog 36:24

Bonnichsen B, Citron GP (1982) The Cougar Point Tuff, southwestern Idaho. In: Bonnichsen B, Breckinridge RM (eds) Cenozoic Geology of Idaho. Idaho Bur Min 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, Kauffman DF (1987) Physical features of rhyolite lava flows in the Snake River Plain volcanic province, Southwestern Idaho. Special Pap Geol Soc Am 212:119–145

Bonnichsen B, Leeman WP, McIntosh WC (2007) Miocene silicic volcanism in southwestern Idaho: geochronology, geochemistry, and evolution of the central Snake River Plain. Bull Volcanol (in press)

Branney MJ, Barry TL, Godchaux MM (2004) Sheath folds in rheomorphic ignimbrites. Bull Volcanol 66:485–491

Branney MJ, Bonnichsen B, Andrews GDM, Barry TL, Ellis BS, McCurry M (2007) Snake River (SR)-type volcanism: enigmatic styles of rhyolitic super-eruptions from the Columbia River–Yellowstone hotspot of North–West USA. Bull Volcanol (this issue)

Branney MJ, Kokelaar P (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, Kokelaar, P (2002) Pyroclastic density currents and the sedimentation of ignimbrites. Geol Soc Mem 27

Branney MJ, Kokelaar P, McConnell BJ (1992) The Bad Step Tuff: a lava-like rheomorphic ignimbrite in a calc-alkaline piecemeal caldera, English Lake District. Bull Volcanol 53:187–199

Bryan SE, Ewart A, Stephens CJ, Parianos J, Downes PJ (2000) The Whitsunday volcanic province, central Queensland, Australia: lithological and stratigraphic investigations of a silicic-dominated large igneous province. J Volcanol Geotherm Res 99:55–78

Camp VE, Ross ME (2004) Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific Northwest. J Geophys Res 109. 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

Chapin CE, Lowell GR (1979) Primary and secondary flow structures in ash-flow tuffs of the Gribbles Run palaeovalley, central Colorado. In: Chapin CE, Elston WE (eds) Ash-flow tuffs. Geol Soc Am Sp Pap 180:137–154

Childs C, Nicol A, Walsh JJ, Watterson J (2003) The growth and propagation of syn-sedimentary faults. J Struct Geol 25:633–648

Christiansen RL (2001) The Quaternary and Pliocene Yellowstone Plateau volcanic field of Wyoming, Idaho and Montana. US Geol Surv Prof Pap 729-G

Ekren EB, McIntyre DH, Bennett EH (1984) High-temperature, large-volume, lavalike ash-flow tuffs without calderas in southwestern Idaho. US Geol Surv Prof Pap 1272

Fackler-Adams BN, Busby CJ (1998) Structural and stratigraphic evolution of extensional oceanic arcs. Geology 26:735–738

Fisher RV, Schminke H-U (1984) Pyroclastic rocks. Springer-Verlag, New York, p 472

Freundt A (1998) The formation of high-grade ignimbrites; 1: Experiments on high- and low-concentration transport systems containing sticky particles. Bull Volc 59:414–435

Fuhrman ML, Lindsley DL (1988) Ternary-feldspar modelling and thermometry. Am Mineral 73:201–215

Ghiorso MS (1984) Activity/composition relations in the ternary feldspars. Contrib Mineral Petrol 87:282–296

Ghiorso MS, Sack RO (1991) Fe–Ti oxide geothermometry; thermodynamic formulation and the estimation of intensive variables in silicic magmas. Contrib Mineral Petrol 108:485–510

Green JC, Fitz III TJ (1993) Extensive Felsic lavas and rheoignimbrites in the Keweenawan Mid-continent Rift plateau volcanics, Minnesota: petrographic and field recognition. J Volcanol Geotherm Res 54:177–196

Hart WK, Aronson JJ (1983) K–Ar ages of rhyolites from the western Snake River Plain area, Oregon, Idaho, and Nevada. Isochron West 36:17–19

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

Henry CD, Wolff JA (1992) Distinguishing strongly rheomorphic tuffs from extensive silicic lavas. Bull Volcanol 54:171–186

Hildreth W (1979) The Bishop Tuff: evidence for the origin of compositional zonation in silicic magma chambers. Geol Soc Am Spec Pap 180:43–75

Hildreth W (1981) Gradients in silicic magma chambers: implications for lithospheric magmatism. J Geophys Res 86:10153–10192

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

Hughes SS, McCurry M (2002) Bulk major and trace element evidence for a time-space evolution of Snake River Plain rhyolites, Idaho. In: Bonnichsen B, White CM, McCurry, M (eds) Tectonic and magmatic evolution of the Snake River Plain Volcanic province. Idaho Geol Surv Bull 30:161–176

Kirstein LA, Hawkesworth CJ, Garland FG (2001) Felsic lavas or rheomorphic ignimbrites: is there a chemical distinction? Contrib Mineral Petrol 142:309–322

Lindsley DH (1983) Pyroxene thermometry. Am Mineral 68:477–493

McCurry M, Watkins AM, Parker JL, Wright K, Hughes SS (1996) Preliminary volcanological constraints for sources of high-grade, rheomorphic ignimbrites of the Cassia Mountains, Idaho: implications for the evolution of the Twin Falls Volcanic Center. Northwest Geol 26:81–91

Malde HE, Powers HA (1962) Upper Cenozoic stratigraphy of the western Snake River Plain, Idaho. Geol Soc Amer Bull 73:1197–1210

Manley CR (1996a) Physical volcanology of a voluminous rhyolite lava flow: the Badlands lava, Owyhee plateau, SW Idaho. J Volcanol Geotherm Res 71:129–153

Manley CR (1996b) In situ formation of welded tuff-like textures in the carapace of a voluminous silicic lava flow, Owyhee County, SW Idaho. Bull Volcanol 57:672–686

Manley CR, Bacon CR (2000) Rhyolite thermobarometry and the shallowing of the magma reservoir, Coso Volcanic Field, California. J Petrol 41:149–174

Milner SC, Duncan AR, Ewart A (1992) Quartz latite rheoignimbrite flows of the Etendeka Formation, northwestern Namibia. Bull Volcanol 54:200–219

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

Nakayama K, Yoshikawa S (1997) Depositional processes of primary to reworked volcaniclastics on an alluvial plain; an example from the Lower Pliocene Ohta tephra bed of the Tokai Group, central Japan. Sed Geol 107:211–229

Palmer BA, Walton AW (1990) Accumulation of volcaniclastic aprons in the Mount Dutton Formation (Oligocene–Miocene), Marysvale volcanic field, Utah. Geol Soc Amer Bull 102:734–748

Perkins ME, Nash BP (2002) Explosive silicic volcanism of the Yellowstone hotspot: the ash fall tuff record. Geol Soc Amer 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 Plains volcanic province. Geol Soc Amer Bull 107:1484–1506

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

Rodgers DW, Hackett WR, Ore HT (1990) Extension of the Yellowstone plateau, eastern Snake River Plain, and Owyhee plateau. Geology 18:1138–1141

Rodgers DW, Ore HT, Bobo RT, McQuarrie N, Zentner N (2002) Extension and subsidence of the Eastern Snake River Plain, Idaho. In: Bonnichsen B, White CM, McCurry, M (eds) Tectonic and Magmatic Evolution of the Snake River Plain Volcanic Province. Idaho Geol Surv Bull 30:121–155

Schmincke H-U (1974) Volcanological aspects of peralkaline silicic welded ash-flow tuffs. Bull Volcanol 38:594–636

Schmincke H-U, Swanson DA (1967) Laminar viscous flowage structures in ash-flow tuffs from Gran Canaria, Canary Islands. J Geol 75:641–664

Smith GA (1986) Coarse-grained non-marine volcaniclastic sediment: terminology and depositional process. Geol Soc Amer Bull 97:1–10

Smith RL (1960) Zones and zonal variations in welded ash-flows. US Geol Surv Prof Pap 354-F. New Mex Geol Soc Spec Pub 9:149–158

Sumner JM, Branney MJ (2002) The emplacement history of a remarkable heterogeneous, chemically zoned, rheomorphic and locally lava-like ignimbrite: 'TL' on Gran Canaria. J Volcanol Geotherm Res 115:109–138

Walker GPL (1983) Ignimbrite types and ignimbrite problems. J Volcanol Geotherm Res 17:65–88

Wen S, Nekvasil H (1994) SOLVCALC: an interactive graphics program package for calculating the ternary feldspar solvus and for two-feldspar geothermometry. Comp Geosci 20:1025–1040

Whalen JB, Currie KL, Chappell BW (1987) A-type granite: geochemical characteristics, discrimination and petrogenesis. Contrib Mineral Petrol 95:407–419

Williams PL, Mytton JA, Morgan WA (1999) Geologic map of the Stricker 3 quadrangle, Twin Falls and Cassia counties, Idaho. US Geol Surv Misc Invest Ser Map I-2633, 1:48,000

Wolff JA, Wright JV (1981) Rheomorphism of welded tuffs. J Volcanol Geotherm Res 10:13–34

Wright KE, McCurry M, Hughes SS (2002) Petrology and geochemistry of the Miocene Tuff of McMullen Creek, central Snake River Plain, Idaho. In: Bonnichsen B, White CM, McCurry, M (eds) Tectonic and magmatic evolution of the Snake River Plain Volcanic province. Idaho Geol Surv Bull 30:177–194