

Subterranean fragmentation of magma during conduit initiation and evolution in the shallow plumbing system of the small-volume Jagged Rocks volcanoes (Hopi Buttes Volcanic Field, Arizona, USA)

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Abstract Monogenetic volcanoes have limited magma supply and lack long-lived sustained magma plumbing systems. They erupt once, often from multiple vents and sometimes over several years, and are rarely or never re-activated. Eruptive behavior is very sensitive to physical processes (e.g., volatile exsolution, magma-water interaction) occurring in the later stages of magma ascent at shallow crustal depths (<1 km), which yield a spectrum of eruptive styles including weak to moderate explosive activity, violent phreatomagmatism, and lava effusion. Jagged Rocks Complex in the late Miocene Hopi Buttes Volcanic field (Arizona, USA) exposes the frozen remnants of the feeding systems for one or a few monogenetic volcanoes. It provides information on how a shallow magmatic plumbing system evolved within a stable non-marine sedimentary basin, and the processes by which magma flowing through dikes fragmented and conduits were formed. We have identified three main types of fragmental deposits, (1) buds (which emerge from dikes), (2) pyroclastic massifs, and (3) diatremes; these represent three different styles and intensities of shallow-depth magma fragmentation. They may develop successively and at different sites during the evolution of a monogenetic volcano. The deposits consist of a mixture of pyroclasts with varying degrees of welding and country-rock

debris in various proportions. Pyroclasts are commonly welded together, but also reveal in places features consistent with phreatomagmatism, such as blocky shapes, dense groundmasses, and composite clasts (loaded and cored). The extent of fragmentation and the formation of subterranean open space controlled the nature of the particles and the architecture and geometry of these conduit structures and their deposits.

Keywords Monogenetic · Phreatomagmatic · Dike · Conduit · Fissure eruption · Scoria cone · Diatreme

Introduction

Small-volume, monogenetic, mafic volcanoes are the most common continental volcanic landform on Earth (Wood 1980). They range in form and size from simple eruptive fissures and scoria cones to more-complex small shields and maar-diatremes, reflecting the broad spectrum of possible eruptive processes (e.g., Connor and Conway 2000; Martin and Nemeth 2005, 2006; Valentine et al. 2006, 2007; Valentine and Gregg 2008; Nemeth 2010). The location, style, and duration of any eruption is affected by processes in the magmatic feeder system at shallow crustal depths (<1 km), such as volatile exsolution (Valentine and Gregg 2008), arrival of distinct magma batches (Brenna et al. 2010), flow localization (Valentine 2012), additional magma breakouts (Schipper et al. 2015), wall-rock entrainment (Valentine and Groves 1996), and interaction of water or wall-rock with magma (Lorenz 1986; White 1991). These processes are also controlled and, at the same time, influenced by the development of conduit shape and geometry (Delaney and Pollard 1981; Geshi et al. 2010). Exposed dikes and conduits in extinct volcanic fields, which once fed magma to the surface, reflect

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sub-surface processes that operate in active volcanoes at the transition from dikes to conduits at shallow depth. Dikes may reach the surface to erupt as fissures, but usually the eruptive activity soon focuses into one or a few aligned discrete vents (Delaney and Pollard 1981; Thordarson and Self 1993; Keating et al. 2008; Valentine 2012) that mimic patterns in the surrounding population of dikes (Kiyosugi et al. 2012; Le Corvec et al. 2013; Muirhead et al. 2015). Focusing of magma into localized conduits reflects a combination of processes within the shallow parts of the plumbing system. These involve thermal widening (Rubin 1995), hydraulic fracturing (Delaney and Pollard 1981), magma fragmentation (Hooten and Ort 2002), convective magma circulation (Genareau et al. 2010), wall-rock breakup and erosional widening of the dike (Valentine and Groves 1996; Keating et al. 2008), and their effectiveness is mediated by host-rock strength and continuity (Brown et al. 2007; Valentine and Gregg 2008).

In this study, we address the processes driving the transition from sub-planar dike intrusions to eruptive conduits through a field investigation of exposed intrusive and sub-volcanic products at Jagged Rocks Complex. We have chosen the Jagged Rocks Complex for detailed study because it contains among the most deeply eroded dikes and sills in the Hopi Buttes Volcanic Field, together with prominent pyroclastic massifs and a diatreme, thereby offering insight into a range of processes active in the subterranean plumbing system of Hopi Buttes volcanoes generally. These features hold information on how and where magma flowing through dikes began to fragment, revealing different stages in the transition from dikes through to incipient eruptive conduits and more-explosive maar-diatremes. Specifically, this study addresses the following questions for the study area. (1) Did sub-cylindrical conduits form in response to, or cause, focusing of magma flow? (2) Did conduits result from explosive magma fragmentation and, if so, how much fragmentation took place at Jagged Rocks? (3) Was magma fragmentation triggered by magma-country rock interaction, and what volume of country rock was involved in conduit-forming processes? (4) What was the role of magma rheology and volatile exsolution in conduit formation? Results of this study have broad implications for plumbing evolution in mafic volcanic fields, and for initially dike-fed eruptions generally.

Geological background of the Jagged Rocks Complex in the Hopi Buttes Volcanic Field

The Colorado Plateau is a physiographic region characterized by a flat and undeformed Paleozoic, Mesozoic, and Cenozoic sedimentary succession overlying a Paleoproterozoic metamorphic and igneous basement. Significant Cenozoic magmatic activity produced more than a dozen monogenetic volcanic fields along its margins and in its interior (Crow et al.

2011; Levander et al. 2011; Reid et al. 2012), including the Hopi Buttes, Navajo, Tuba City, San Francisco, and Springerville volcanic fields. The Hopi Buttes Volcanic Field (Fig. 1) is a dense cluster of volcanic centers (~300), which include maar-diatremes and scoria cones erupted at ~7 Ma (White 1990; Billingsley et al. 2013). During the period of magmatism, the Hopi Buttes area was characterized by an extremely uniform and low-relief playa-type surficial environment (White 1990), and non-volcanic channels deeper than 2 m have not been found. It now offers exposures at different volcano structural levels, because the depth of the erosion increases from north to south (see cross-section in Fig. 1), toward the Little Colorado River. For example, surficial volcanic deposits (e.g., lava flows, volcanic tuff), exposed in the northern part of the volcanic field, locally interfinger with the late Miocene Bidahochi Formation (White 1990). Toward the south are progressively exposed upper diatreme, lower diatreme, and intrusive dikes and sills, which represent the roots of monogenetic volcanoes at different stratigraphic depths (White 1991; Re et al. 2015; Lefebvre et al. 2016; Muirhead et al. 2016). The Jagged Rocks Complex lies in the southern Hopi Buttes and crops out within the Petrified Forest Member of the Upper Triassic Chinle Formation, which is the exposed host rock across the Jagged Rocks Complex. The Petrified Forest Member consists of weak mudstone and sandstone of fluvial origin, weakly consolidated during the late Miocene epoch and water-bearing (Cooley et al. 1969). Based on the area's known stratigraphic succession (Billingsley et al. 2013), we infer that the current Jagged Rocks Complex exposures, including ~50 m of present-day topographic relief, lay between 365 and 245 m below the paleo-surface at the time of eruption.

Jagged Rocks Complex (Fig. 2) comprises a suite of intrusive sheets associated with sub-volcanic features having compositions described as including analcite basalts and olivine-augite basalts (Williams 1936) or nephelinitic rocks (Alibert et al. 1986). MgO ranges from 5 to 14 % and SiO₂ from 40 to 47 %, and they plot on a TAS diagram as basanite-tephrite (Kjargaard et al. 2014). Together they represent the frozen remnants of a shallow magmatic plumbing system beneath one or a few monogenetic volcanoes at the surface. The emplacement mechanisms of dikes, sills and inclined sheets of Jagged Rocks were examined in detail by Re et al. (2015) and Muirhead et al. (2016). Building on these studies, this paper addresses the development of sub-surface volcanic-conduit features comprising varying proportions of fragmental and coherent rock (see Table 1). These features are defined herein as follows. *Buds* are anomalously widened sections of dikes (1–3 m), where the removal of the dilatational component of the dike would not bring adjacent walls back into contact (e.g., Delaney and Pollard 1981; Hooten and Ort 2002). Buds typically comprise juvenile and host-rock clasts together with coherent intrusive rocks. At Jagged Rocks Complex, most

Fig. 1 Simplified geological map of the Hopi Buttes Volcanic Field, modified from Lefebvre et al. (2016) and Muirhead et al. (2016). The stratigraphic log provides the sedimentary succession that represents the country rock across the Hopi Buttes, together with the epoch of deposition for each unit. Igneous rocks are in black. Depth is based on the average thicknesses from Billingsley et al. (2013) calculated from the pre-eruptive paleo-surface. On the map the locations of some volcanoes are noted and their deposits placed at the corresponding depth in the stratigraphic log. Schematic cross-section oriented (X-Y) north-south reveal the deepening of the erosion surface toward the south

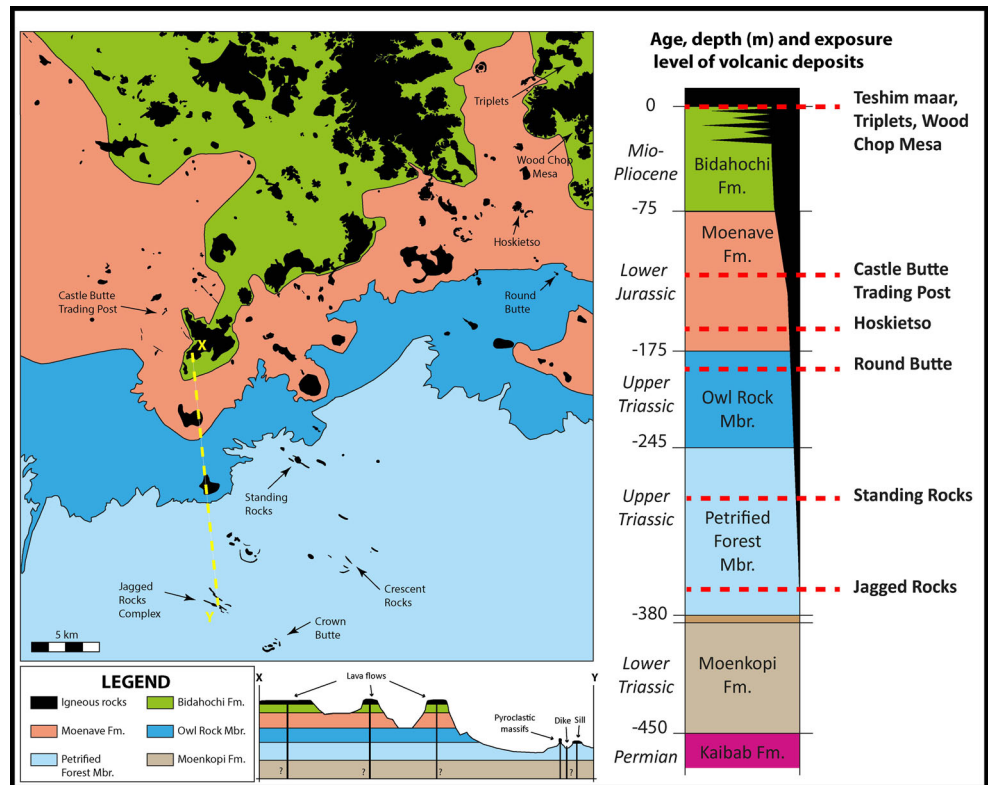


Fig. 2 Simplified geological map of Jagged Rocks Complex, modified from Billingsley et al. (2013). An inset reveals the location of the Colorado Plateau and Hopi Buttes Volcanic field in a portion of the North America map. In yellow are Quaternary deposits and in light blue the Petrified Forest Member of the Chinle Formation. Red lines represent the dike segments, orange pattern marks transgressive sills, and hunter-green denotes pyroclastic massifs. On the map the massif names and numbers are annotated and the diatreme outline drawn in violet. Other acronyms labeled on chart are NWD northwest dikes; SWD southwest dikes; CD central dike; SED southeast dike; SS south sill; SIS south inclined sheet; SEIS southeast inclined sheet; NEIS northeast inclined sheet

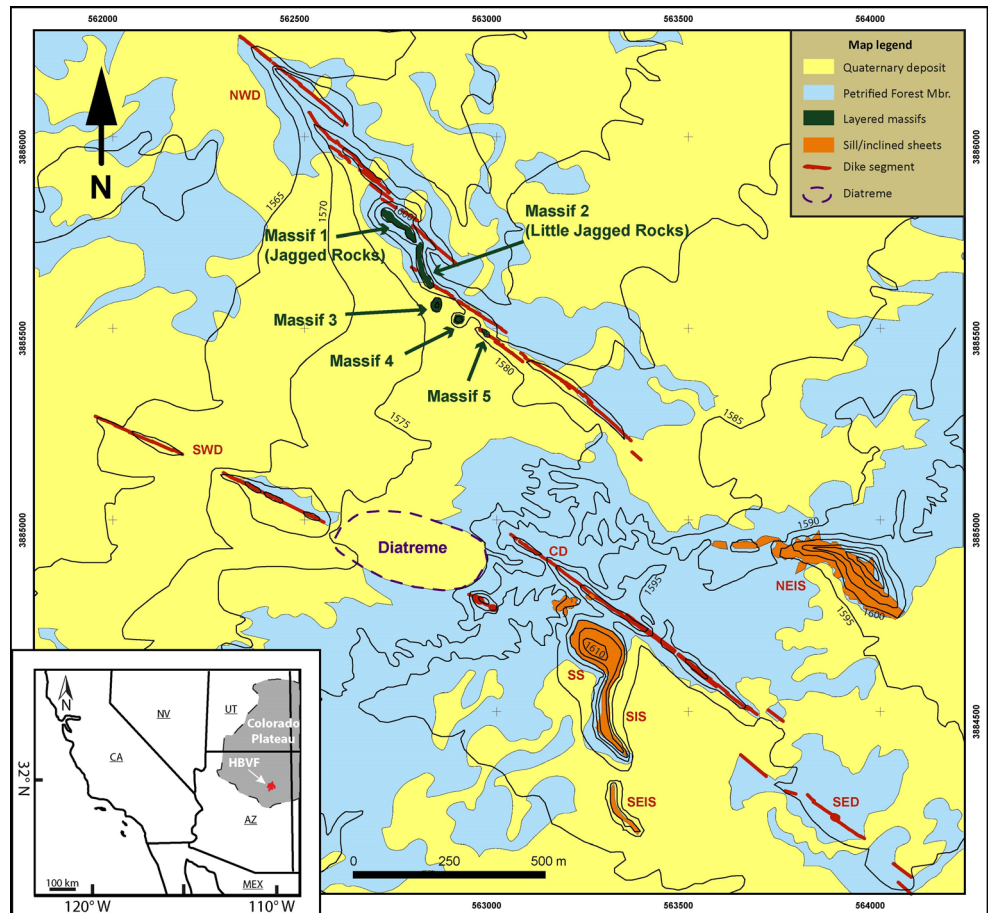


Table 1 Main features of dikes, buds, and massifs. Length, height, and thickness are in meters

	Length (m)	Width (m)	Height (m)	Geometric features	Rock type	Internal architecture	Country-rock content
Dikes	~250 ^a	~0.45 ^a	n.a.	Regular strike, local kinks, changes in dip angle and direction	Hypabyssal porphyritic coherent igneous intrusions	Symmetrical bands of crystals and vesicles (zonation)	Insignificant
Buds	2–20	1–3	~5 ^b	Elongated, bulged at one or both dike margins, occurred between offsets or inside the segments	Hypabyssal coherent igneous rock associated with lithic-rich breccia and lapilli tuff	Massive, without internal structures	High
Massifs	≥100 ^c	5–15 ^c	25–35 ^b	Elongate or sub-circular aligned in a chain, gently curving strike, slightly offset steps	Moderately to very highly welded, lithic-rich, breccia and lapilli tuff; regions of wall-rock mega-blocks	Primary depositional beds, mostly with conformable contacts	High to moderate

^a Mean value for dike segments^b Value estimated from photographic observation^c Refers to elongate massifs

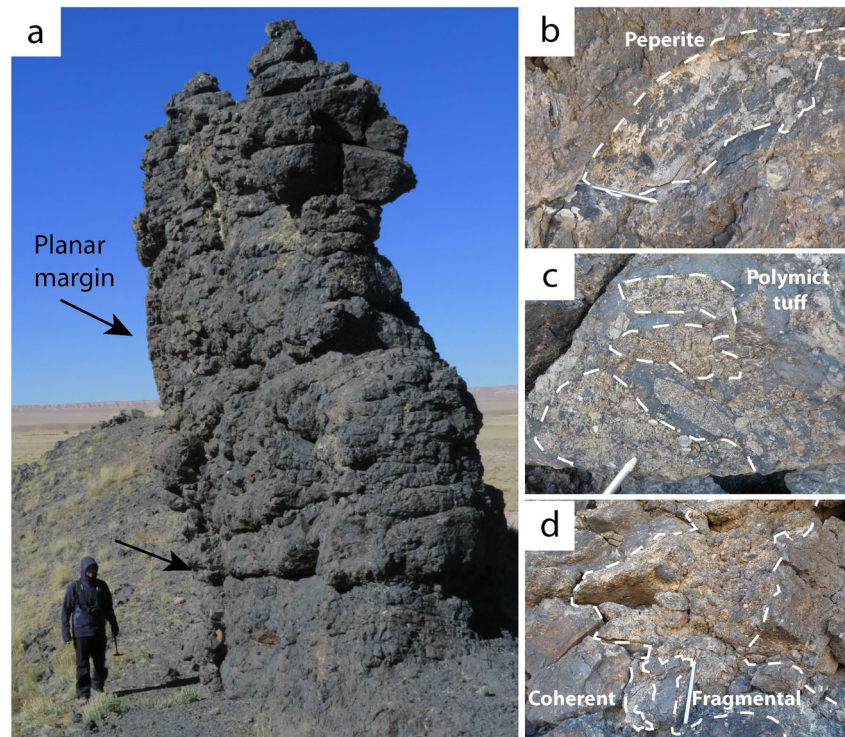
buds are exposed along the southwest dike (Re et al. 2015). *Massifs* are wide (>5 m) igneous bodies that project as cliffs well above the surrounding ground surface (~30 m). They consist of layered and closely packed pyroclastic bomb deposits with varying degrees of welding and proportions of country-rock (e.g., Lefebvre et al. 2012; Re et al. 2015; Muirhead et al. 2016). At Jagged Rocks Complex, five volcanoclastic massifs, which are numbered as massifs 1 to 5 from NW to SE in Fig. 2, are dispersed along the middle section of the NW *en echelon* dike. *Diatremes* are funnel-shaped conduits filled with primary volcanoclastic lapilli and coarse lapilli tuff, which contain mostly pyroclasts but also abundant country rock from different stratigraphic units (e.g., White and Ross 2011). At Jagged Rocks Complex, a poorly exposed diatreme truncates the eastern portion of the SW dike. Surficial eruptive products of the maar-diatreme, and any that were formed above massifs, buds or feeder dikes, have been stripped away by erosion. Therefore, we cannot directly demonstrate the relations between plumbing-system features and surface eruptive activity, and instead focus on the necessary conditions for formation of the observed features. By considering volcanic features seen elsewhere in the Hopi Buttes Volcanic Field (e.g., White 1991; Vazquez and Ort 2006), and the behavior of observed basaltic eruptions elsewhere, we infer the surficial expression of these features in the discussion.

Relations between dikes and buds at Jagged Rocks Complex: geometrical and lithological features

Dikes in the Jagged Rocks Complex consist of coherent igneous rock with a zonation attributed to pulsatory injections (Re et al. 2015). Dikes are segmented, with either irregular or *en echelon* segment arrangements. Segment thicknesses rarely exceed a meter (mean thickness value 43 cm) and segment lengths are typically tens to hundreds of meters (Re et al. 2015). Dike margins are sharp, with well-developed chilled surfaces, and locally preserve delicate textural features such as protruding phenocrysts, and imprints of host-rock clasts; dikes generally lack brecciated or peperitic margins. Rare angular to sub-rounded host-rock clasts are contained in the dikes, and may reflect local dike-tip bifurcation and country-rock wedging during propagation (Re et al. 2015).

Buds at Jagged Rocks Complex are up to 20 m long and 1–3 m wide, and occur between dike segments or at dike tips. They have a heterogeneous, chaotic structure, with no systematic layering or primary depositional structures, and they mostly consist of coherent igneous domains together with scoriaceous to fluidal and moderately welded clots of solidified magma (Fig. 3). Host-rock components are abundant as individual clasts, as well as elongated lenses of sediments extending into both

Fig. 3 Photographs of buds in outcrop. **a** Exposure of a bud along the SW dike; the *left margin* preserves in part the original dike margin with some planar and straight surfaces indicated by *arrows*. **b** Peperite domain consisting of globular juvenile clasts intruded into a continuous sedimentary host. **c** Finely fragmental polymict lapilli tuff (LT_L) consisting of juvenile and lithic clasts. **d** Scoriaceous juvenile clast with country-rock material in a fragmental LT_L domain, in contact with coherent intrusive igneous rock



coherent and scoriaceous domains. In some buds, the widening is confined to one margin, whereas the opposite margin remains planar and coherent (Fig. 3a), retaining a sharp contact against the host. The protruded margin is scoriaceous and heterogeneous, contains abundant country-rock fragments, and in places there are spots of peperite (Fig. 3b) and of pale medium-grained polymict lapilli tuff (LT_L; Fig. 3c, d). These marginal domains are very discontinuous, and the lateral contact with the juvenile-rich bud core is sharp and irregular. The polymict lapilli tuff (LT_L; Fig. 4) displays a framework-to matrix-supported texture, and consists of juvenile fine and coarse lapilli mixed with abundant host-rock clasts. The juvenile fraction includes angular to slightly elongate clasts (Fig. 4h) with groundmass that varies from sideromelane (all sideromelane now altered to palagonite) to microlitic sideromelane (Fig. 4c, d, e, f), to opaque tachylite (Fig. 4a, b, g), containing dispersed oxide and clinopyroxene crystals. The groundmass is moderately vesicular (Houghton and Wilson 1989) and locally displays an anisotropic fabric, with flattened elongate vesicles and aligned microlites. Composite pyroclasts are abundant as cored clasts, made up of a lithic fragment surrounded by a juvenile shell, and loaded clasts (Rossee et al. 2006) that are aggregates of individual juvenile clasts and lithic fragments (Fig. 4e). Juvenile clasts have a heterogeneous texture and variable groundmass. The boundaries between original juvenile clasts with different groundmasses are in some places well defined

(Fig. 4), and clasts sintered together exhibit swirly and diffuse transitions that produce a banded texture.

Conduit geometry, architecture and lithological characteristics of Jagged Rocks Volcanic Complex

Vent-conduit geometry

Jagged Rocks Complex massifs comprise five spatter bodies (Table 2), which reveal layers at scales of a meter to tens of meters. Elongate massif 1 (Fig. 5), called *Jagged Rock*, is an elongate parallel-sided NW-SE-trending body, more than 100 m long and standing ~35 m above the present-day surrounding land surface. Its width varies along strike, and the central part is narrower (~5 m wide) than the two tips, which are up to 15 and 12 m wide at the NW and SE tips, respectively. This massif slightly widens upward, with the top wider than the base and jutting out. Four small dextral steps (visible only on the cliff of the southern face) suggest some *en echelon* segmentation, but less than that of the NW dike. The massif's well-developed bedding shows progressive changes in dip of the layers, from ~20° NW at the SE tip, to ~50° NW dip of beds in the central part, to sub-vertical NW dips at the NW end. Elongate massif 2 (Fig. 5), called *Little Jagged Rock*, is a curved body trending for ~100 m from NNW-SSE to NW-SE, with vertical walls ~25 m high and a thickness ranging about 5 to 10 m. Its thickest section lies between two segments of a cross-cutting dike, having the same trend but offset to one another, which intersects the massif

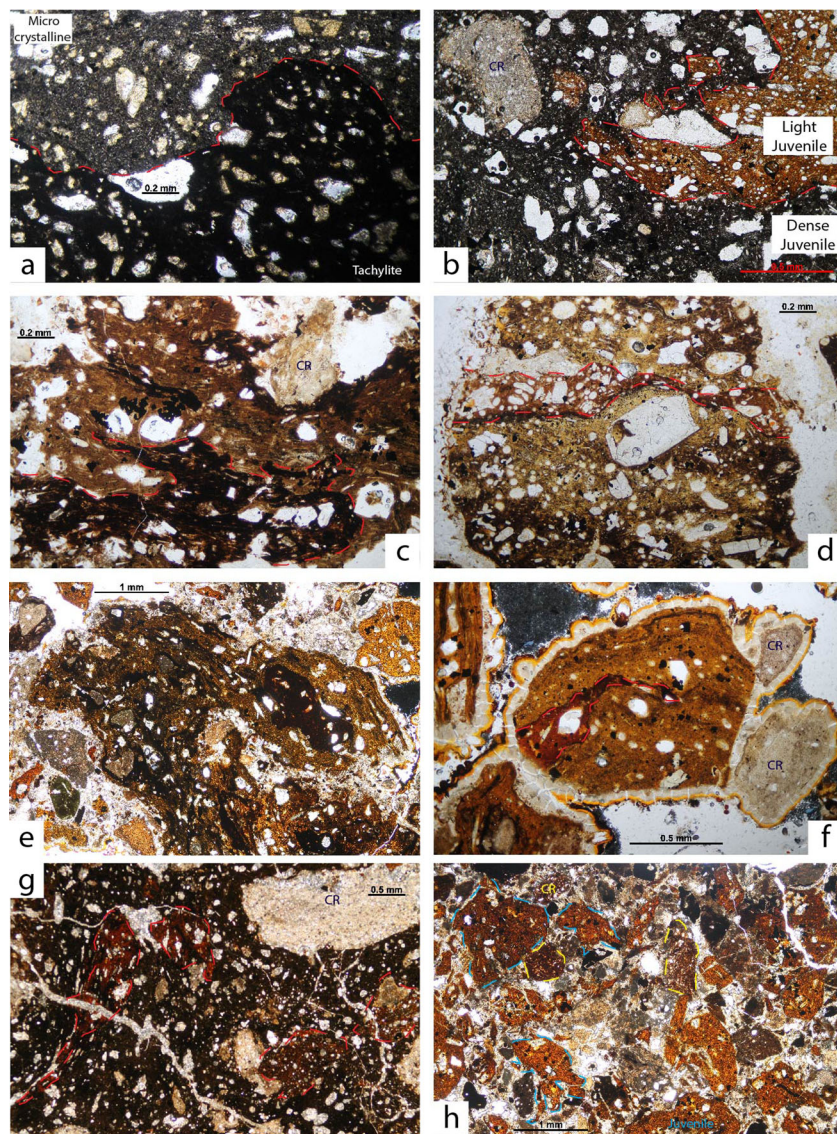


Fig. 4 Photomicrographs of bud deposit features. Some country-rock clasts are labeled as CR. **a** Welded bud deposit, individual juvenile clasts are sintered to one another revealing a coherent juvenile groundmass of different tonalities, which reveal different crystallinity, within a multitude of lithic fragments dispersed. **b** Juvenile clast with two types of juvenile groundmass and lithic components. These features highlight the composite nature of loaded pyroclasts. **c** Volcanic clasts reveal the sintering of pyroclasts that display an opaque glassy (tachylite) and a hypocrySTALLINE (honey) groundmass respectively. **d** Composite pyroclast displays dense scoriaceous and light honey-colored juvenile zones. **e** Elongate

juvenile clasts within a tuff deposit (LT_1) consist of amalgamated ghost pyroclasts with diffuse contacts, which form a domainal groundmass differing in crystallinity and vesicularity. This groundmass encloses lithic fragments, which display sharp edges. **f** Sub-angular dense juvenile lapilli and pale sandy clast, labeled, enveloped within isopachous cement rim. **g** Loaded clast composed of diverse juvenile domain and dispersed lithic clasts aggregated together; some juvenile domains display a flattened fabric. **h** Polymict lapilli tuff (LT_1), association of angular to sub-rounded juvenile and lithic clasts, annotated in *light blue* and *yellow*, respectively

at its SE end. Internal layering dips NW at shallow angles ($\sim 20^\circ$) near the NW tip, and much more steeply (up to 60°) in the central part. Sub-equant massifs 3, 4, and 5 are spaced about 50 m apart, are aligned NW-SE and are parallel with one branch of the *en echelon* dike. A dike strikes across the easternmost massif 5. Massif 3 is ~ 15 m high and has an elliptical outline in map view (semi-axes $\sim 15 \times 10$ m), with layers dipping NW with a dip angle changing from steep to sub-horizontal. Massifs 4 and 5 are comparatively poorly exposed and only a

few meters in diameter. South of these massifs, there is an eroded diatreme, elliptical in map view ($\sim 375 \times 180$ m), which trends NW-SE and is mostly covered by a thin screen of Quaternary deposits. No dikes extend at this erosional level into the diatreme, which lacks good outcrops even though its outline is well constrained by geomorphological and litho-stratigraphic observations at least in the eastern portion, where a semi-circular ridge, formed by a chain of hummocks, marks the boundary between the displaced and the in situ country rock.

Table 2 Average dimensions of massifs at current exposure level

Elongate massifs	Average length (l)	Average height (h)	Average thickness (w)	Minimum estimated volume ^a (m ³)	Maximum estimated volume ^b (m ³)
Jagged Rocks	110	30	8	26,400	308,000
Little Jagged Rocks	100	25	6	15,000	210,000
Sub-equant massifs	Average radius (r)	Average height (h)		Minimum estimated volume ^c	Maximum estimated volume ^d
Massif 3	10	15		4710	109,900
Massif 4	3	5		141	9891
Massif 5	2	4		50	4396
				Minimum	Maximum
Total massifs volume				46,301	642,187
Estimated volume of wall rock into the massifs (30 %)				13,890	
Estimated volume of juvenile into the massifs (70 %) ^e				32,410	

The volumes of the massifs, which most simply equate to the volume of removed country-rock minus the volume of country-rock blocks in the massif, is roughly calculated as a box (length*thickness*height), for the exposed height of the rock bodies. A rough estimate of the maximum volume indicates the dimension of the aligned massifs if they pierced to the surface with the same geometry observed at the current level. Estimated proportions of country-rocks (30 %) and juvenile material (70 %) are based upon field and photographic observation of outcrops and hand-samples. *Jagged Rock total massif volume is given by the sum of the volume from three boxes, in the nw-, mid-, and se- parts, because their lengths and thicknesses differ substantially

^a Calculated as the volume of a box ($l \cdot h \cdot w$)

^b Calculated as the massifs extend up to the surface ($l \cdot w \cdot 350$)

^c Calculated as the volume of a cylinder ($\pi \cdot (r^2) \cdot h$)

^d Calculated as the massifs extend up to the surface ($\pi \cdot (r^2) \cdot 350$)

^e Which also indicates the volume of ejected wall-rock to accommodate the massifs

Lithological features of the deposits

Five rock types, described below, share similar juvenile and lithic components, and have been classified based upon differences in grain size, degree of welding, and relative proportion among juvenile and lithic clasts (Sumner 1998; White and Houghton 2006).

Juvenile-dominated tuff breccia (TB_J)

The dominant lithotype in massifs 1, 2, and 3 is a framework-supported close-packed tuff breccia (White and Houghton 2006) with a crudely to well defined dm- to m-thick layering. It consists of pyroclastic bombs exhibiting moderate to very high degrees of welding with one another (Sumner 1998) and less than 30 % host-rock clasts (Fig. 6). Juvenile clasts of all sizes are generally dense (Fig. 6c) and globular (Fig. 6a), with chilled and irregular margins surrounding a more vesicular interior. The external shape of juvenile clasts ranges from smooth with fluidal ropy surfaces (Fig. 6b), to scoriaceous, irregular and cusped. Ghost pyroclasts, visible at a range of different scale, from hand sample (dm; Fig. 6d) to thin section (mm; Fig. 4e), are barely distinguishable in more-coherent domains, generated by strong welding of the original juvenile clasts. Individual juvenile clasts are porphyritic rock with a homogeneous texture, consisting of abundant coarse (~1 to up to 5 cm) clinopyroxene, Fe-Ti oxide and subordinate phlogopite crystals dispersed in a structureless groundmass

that has a wide range of crystallinity and vesicularity. Crystallinity ranges from glassy/cryptocrystalline tachylite to microcrystalline, with the majority being hypocrySTALLINE with a multitude of microlites. Juvenile clasts are dense to highly vesicular, with most clasts being weakly vesicular (Houghton and Wilson 1989). There is a wide range of vesicle sizes and vesicle shapes, from sub-spherical to ellipsoidal to highly contorted. Most of the bombs are composite loaded pyroclasts (Fig. 6d), which consist of aggregated pyroclasts sintered together (Rosseel et al. 2006), at a range of scales from mm to dm. Groundmasses reveal different color tones due to different levels of crystallinity. Sparse blocky to sub-rounded lithic clasts (generally less than 20 %) display different color tone that indicate incipient to intense thermal alteration. At massif 3 (Fig. 7a), the welded tuff breccia contains distinct lenses of disaggregated host-rock, occurring as sharp to diffuse layers of sand grains (Fig. 7 c, d).

Lithic- and juvenile-dominated lapilli tuff (LT_L) and tuff breccia (TB_L)

This subordinate type of rock (Fig. 8) is a framework-supported, non- to moderately welded (Sumner 1998) lapilli tuff (LT_L) to tuff breccia (TB_L) (White and Houghton 2006). It consists of bombs (TB_L; Fig. 8b, c, d) and subordinate coarse lapilli (LT_L; Fig. 8e) in a deposit dominated by cm- to dm-size host-rock clasts (more than 50 %), with a crudely defined layering (Fig. 8a). Juvenile components display the same

Fig. 5 Orthophoto and schematic map view of the elongate Jagged Rock and Little Jagged Rock massifs. *Greek letters* (α to ϵ) are homologous points for the cliff maps in Figs. 11 and 12. The orthophoto was created using Agisoft PhotoScan from a series of photos taken from a balloon-mounted camera at a height of 100 m. Note the changes in thickness of Jagged Rock, which has bulging ends and a narrow midsection. Little Jagged Rock curves slightly, and is cut by a dike with minor offset through the massif

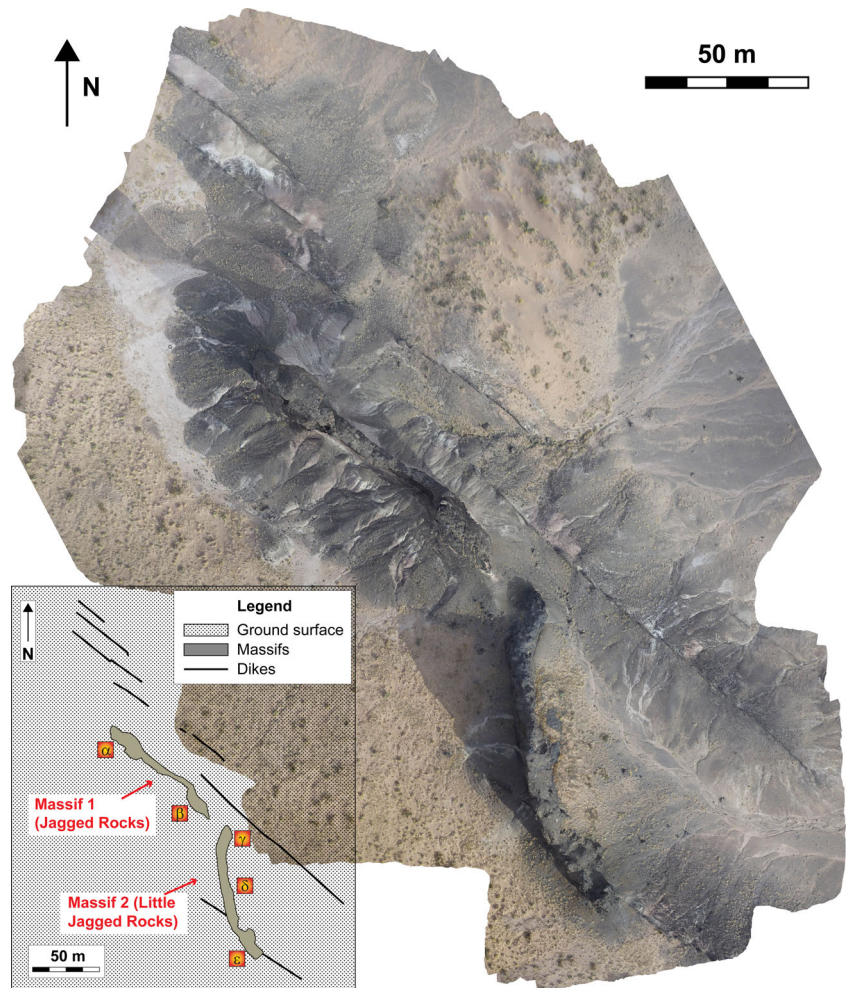


Fig. 6 Juvenile clasts from juvenile-dominated tuff breccia (TB_j). **a** Cluster of moderately to highly welded, globular pyroclastic bombs; scoria clast are mostly elongate, but clast margins are not all touching and merged together. **b** Fluidal fusiform pyroclast, with a smooth ropy flow surface. **c** Very highly welded pyroclasts of a typical TB_j coherent domain; margins of single magma clots are faint, and they have coalesced together into a dense and poorly vesicular block. **d** Polished slab section of the coherent domain in (c); ghost pyroclasts, outlined with the *white dashed lines*, are sintered to one another, and their margins are slightly detectable

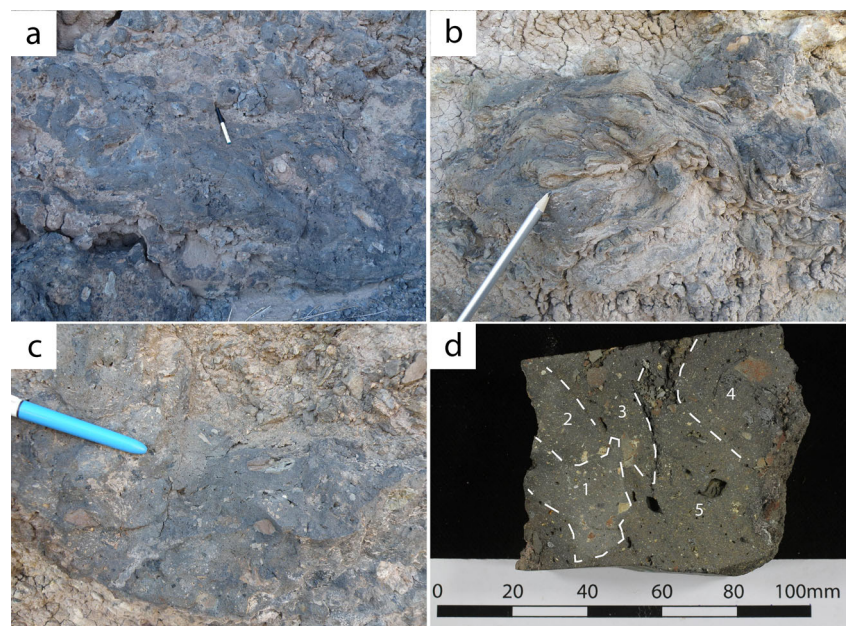
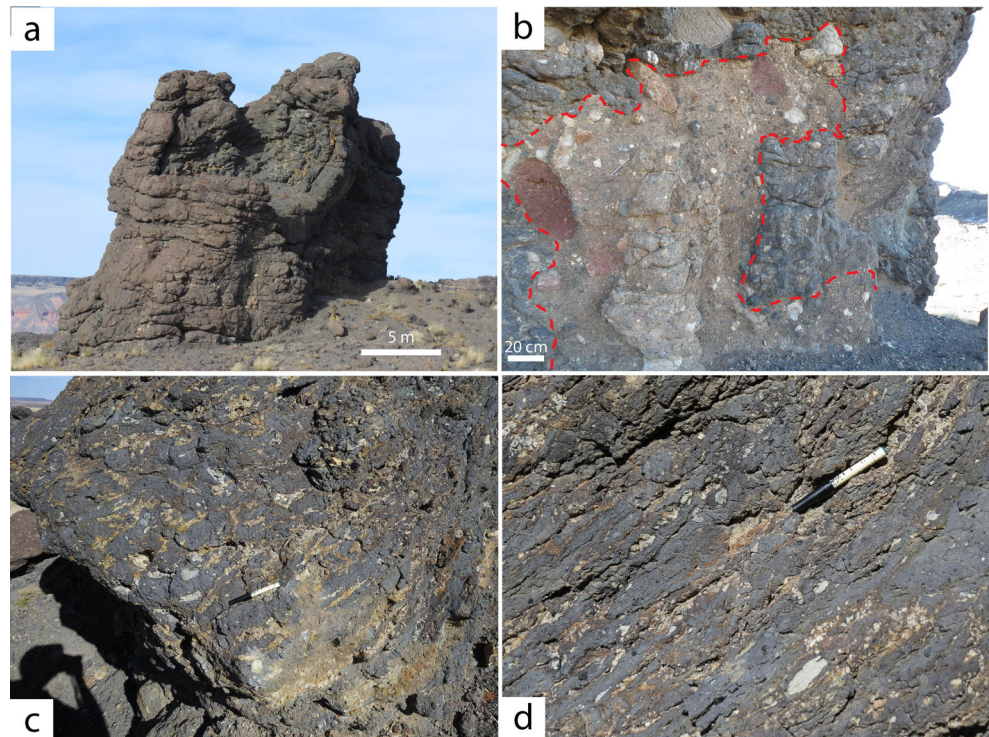


Fig. 7 **a** Overview from the south of massif 3; bedding surfaces dip crudely NW and sub-horizontal jointing is pervasive. **b** Juvenile-dominated breccia (TB_J) includes clasts of the unbedded lapilli tuff deposit (LT_m). The contact is marked with a red dashed line. There are large round boulders of country-rock within LT_m . **c, d** Semi-coherent igneous rock with abundant lenses of sediment defining layered fabric that dips NW



texture as observed in TB_J . The deposit consists of cauliflower bombs and other dense to scoriaceous pyroclasts with different external shapes resembling sub-spherical cannonballs, flattened teardrops, and irregular rugged lumps, together with sub-angular to rounded country-rock blocks. The contact between juvenile-dominated (TB_J) and lithic-dominated (TB_L) breccias is diffuse and gradational with changes in the proportion between juvenile and lithic components. The bedding keeps the same orientation across these units, and sharp discordances or truncation surfaces are absent. In places, layers of TB_J and TB_L interfinger and develop alternating layers enriched or depleted in lithic clasts.

Non-layered (massive) lapilli tuff (LT_m)

Coarse lapilli-tuff deposits (Fig. 9), which contrast with the other spatter deposits seen elsewhere at Jagged Rocks Complex, crop out with sharp, irregular and sub-vertical contacts at the base of massif 3 (Fig. 7b), as a few hummocks within the Quaternary debris that covers the poorly exposed diatreme, and at massif 5. It is a non-welded clast-supported deposit of coarse and fine lapilli consisting of a mixture of blocky angular to sub-equant and mostly dense juvenile fragments (Fig. 9) with subordinate fluidal and globular clasts, and loose crystals (about 1 cm; Fig. 9a, d). This lapilli tuff is poorly sorted, and contains some dense volcanic bombs and large (up to 50 cm) sub-spherical (apparently abraded) boulders of country-rock mudstone (Fig. 7b), some with preserved bedding. In places, there is a fine-grained clastic matrix, a mixture of juvenile and sedimentary rock fragments, which

has been subjected to secondary cementation. These deposits contain abundant country-rock fragments (up to 50 cm) from geological units other than the Petrified Forest Member, which hosts intrusions at Jagged Rocks Complex. For example, massif 3 contains clasts of pale-gray calcareous claystone of the Owl Rock Member (Fig. 9b), a unit that is stratigraphically higher than the Petrified Forest Member (Fig. 1).

Petrified Forest Member (PFM)

In situ Petrified Forest Member remnants are recognized from their preserved sub-horizontal bedding and cross-bedding and by their physical properties; the rock is competent, unaltered, and unbroken. It includes sandstone and subordinate muddy sandstone in discontinuous outcrops along massif cliffs (e.g., Fig. 10a), and is more extensive where it is efficiently sheltered from erosive processes. The contacts with tuff-breccia deposits are sharp and discordant.

Petrified Forest monomict country-rock breccia (CRB)

This is a very poorly sorted and framework-supported deposit of dm- to m-size blocks of sandstone with subordinate domains of mudstone from the Petrified Forest Member (<90 %) with small amounts of juvenile material (Fig. 10). Most of the sandstone blocks still preserve the original bedding (Fig. 10c), which is rotated into various orientations and displaced from the original position. Mudstone domains are rare, deformed and flattened, filling the spaces between the bigger and more coherent sandstone blocks. Juvenile material occurs as rare and discontinuous

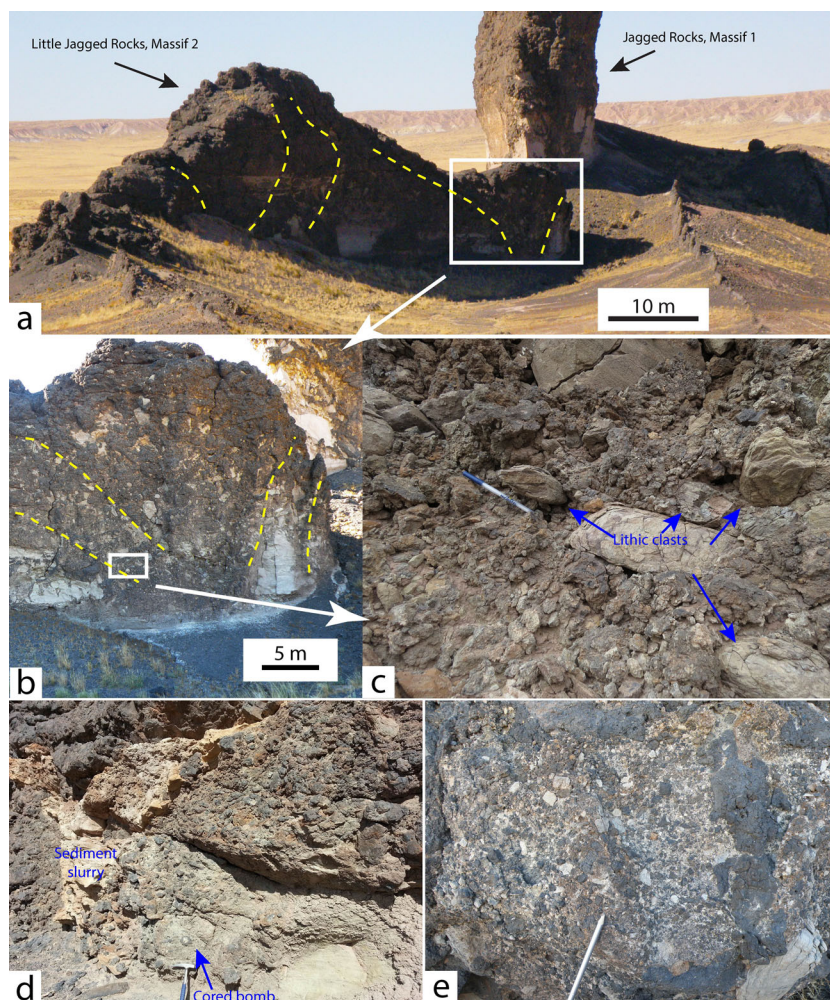


Fig. 8 **a** Overview toward NW of Little Jagged Rocks (Massif 2), with SE tip of Jagged Rocks (Massif 1) in background and dike swarms in foreground. Layering surfaces are highlighted with *yellow dashed line*. *Lines* with opposite dip reveal a local discordance of bedding and may represent a possible vent or a downward slip. *White square* indicates the close-up of figure **(b)**. **b** Block-and-bomb deposit, lithic- and juvenile-dominated (TB_L) with bomb and minor coarse lapilli associated with host-rock blocks. The deposit is incipiently welded, and displays reverse graded beds dipping NNW. The close-up in figure **(c)** is bounded by the white square. **c** Mixture of juvenile and lithic clasts of various size and

shape. Some lithic clasts preserve the original layering. Juvenile clasts range from angular to globular and display a scoriaceous surface. **d** Framework-supported TB_L deposit, overall well sorted with juvenile and lithic clasts of about the same size. The bottom part is enriched in matrix compared to the top. Cored bomb indicated by the *blue arrow*. The pale domain on the left might represent the remnant of a liquefied sediment slurry. **e** Fine-grained LT_L domain, with abundance of juvenile lapilli and a multitude of lithic fragments. This kind of coarse polymict lapilli tuff resembles the deposit recorded as discontinuous pockets at bud margins

cm- to dm-thick and highly welded layers along the contacts or between the blocks (Fig. 10a). Welding is locally enhanced beneath overlying host-rock blocks, indicating that still-hot juvenile fragments were compressed together beneath them. Discontinuous and irregular domains of TB_L/LT_L occur in places. The contact between country-rock breccia and the TB_L/TB_L deposit is discordant, and truncated to abrupt. The most extensive outcrop of this domain within the massifs lies at the southeastern edge of Jagged Rocks (Fig. 10).

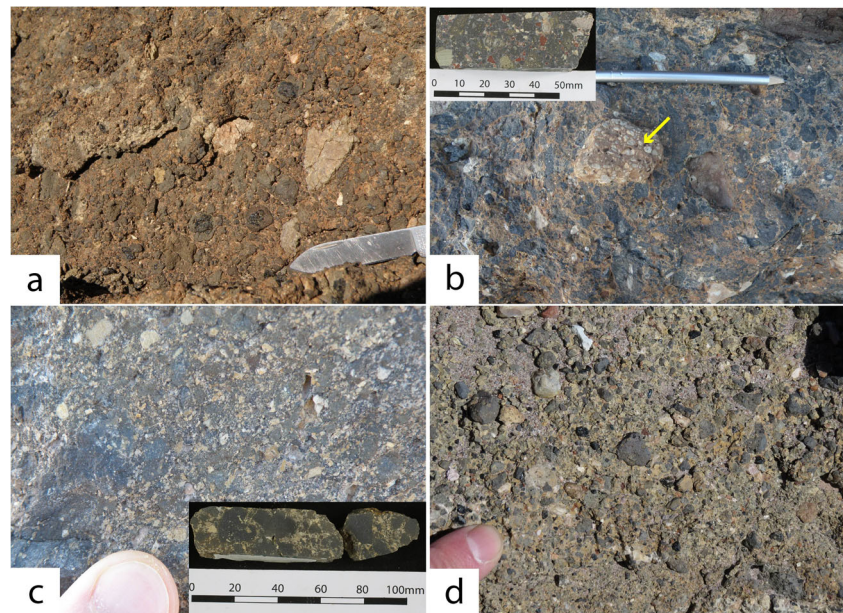
At the eastern edge of the diatreme, a ridge of hummocks, which reveal tilted and rotated blocks of Petrified Forest Member sandstone with subordinate mudstone, define a morphological barrier between the displaced rocks inside the diatreme and the in situ host-rock outside. Indeed, clusters of

several m-size boulders of Owl Rock Member and a red sandstone identified as the Moenave Formation (unit stratigraphically above the Owl Rock; Fig. 1) occur within the Quaternary deposit that cover the diatreme.

Interpretation and discussion

The Jagged Rocks Complex exposes both coherent intrusions and volcanoclastic clusters at the same stratigraphic depth. These deposits recorded magma that solidified in pathways toward the surface and focused into discrete sectors that triggered multiple styles of subterranean fragmentation and accumulation of pyroclasts, respectively. Intrusive and volcanoclastic rocks

Fig. 9 Unlayered lapilli tuff (LT_m) deposits. Figures **b** and **c** have an *inset* with a polished slab of the sample. **a** Clast-supported deposit of lapilli and a few small bombs from Massif 5 with lithic clasts and coarse crystals. **b** Coarse lapilli tuff at the base of Massif 3 with abundant juvenile lapilli and country-rock grains (the lithic clast indicated by the *yellow arrow* belong to the Owl Rock Member); the deposit has secondary cementation. **c** Lapilli tuffs at the eastern edge of the diatreme, with a multitude of minute lithic clasts and coarse lapilli. **d** Lapilli tuff inside the diatreme, association of juvenile lapilli, loose pyroxene crystals and lithic clasts of different sizes



exposed at Jagged Rocks Complex are inferred to constitute the solidified remnants of the upper few hundred meters of a magmatic plumbing system that fed multiple monogenetic vents at the surface (Re et al. 2015; Muirhead et al. 2016).

Mutual cross-cutting relations among dikes and pyroclastic massifs exposed in a few places at massifs 2 and 5 do not allow assessment the temporal and genetic evolution of the plumbing system. These contacts provide ambiguity since, in some places, they show massif deposits truncating a dike, but in others, the dike intruded the massif deposits, and, in still others, the two seamlessly merge with one another. The close proximity and the consistency of the NW-SE trend among the five Jagged Rocks massifs and the NW dike and the ambiguous dike-massif cross-cutting relations suggest that these volcano-related features had

an overall synchronous emplacement (Muirhead et al. 2016). It is likely that the NW dike fed the massifs' activity because unlike other rocks in the complex, they share a high abundance of pyroxene megacrysts (Re et al. 2015). From the stratigraphic and geometrical relations among pyroclastic breccias (TB_J and TB_L), we infer that Jagged Rocks (Fig. 11) and Little Jagged Rocks (Fig. 12) massifs were accreted from the southeast toward the northwest, as the fragmentation site migrated laterally. Based upon geometric structures of all the massifs, width changes, bedding characteristics and relations with coherent intrusions, we infer that up to six vents might have been active during the growth of the group of massifs.

In contrast, the diatreme apparently cross-cuts the SW dike, since collinear dike segments with the same trend crop out to the east and west of the diatreme structure (see Fig. 2), but are not observed within it. This diatreme is inferred to have been active subsequent to the intrusion of the SW dike, but may have been associated with the same magma emplacement event. Domains of displaced country rocks, including material sourced from higher in the stratigraphic section (e.g., Owl Rock Member and Moenave Formation), together with lapilli tuff are diagnostic features that record country-rock brecciation during diatreme excavation. These types of deposit result from phreatomagmatic explosions, which can take place at any level inside the diatreme, that cut deeply into the country rock and produce vertical mixing of material by upward-directed debris jets and downward subsidence (White and Ross 2011; Valentine and White 2012).

Development of elongate massif structures requires processes different to those forming sub-circular diatremes. Two different mechanisms of massif emplacement seem possible within the environment that probably existed after dike propagation to shallow levels: (1) by deep-seated fragmentation of

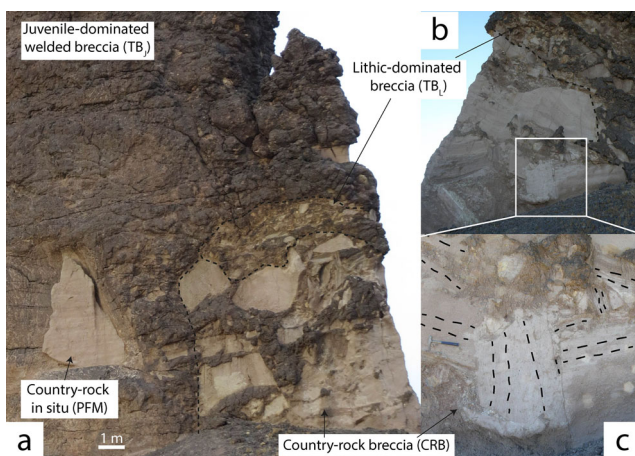


Fig. 10 Country-rock breccia (CRB) domains on the southern face of Jagged Rock (**a**) and on the northern (**b**, **c**) cliff, respectively. *Black dotted lines* in pictures **a** and **b** delimit different domains. In picture **c**, a close-up of the *white box* in **b**, the *dashed lines* depict the preserved bedding of individual host-rock blocks. PFM indicate the in situ host-rock

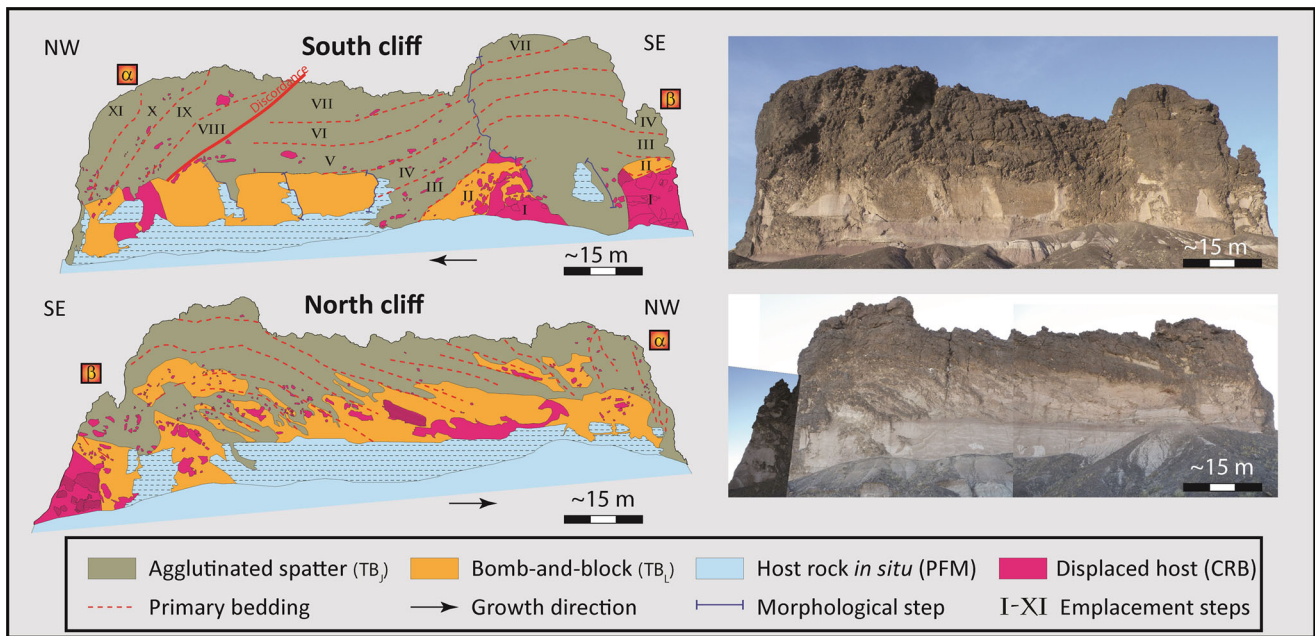


Fig. 11 Cliff-face maps and photographs of Jagged Rock. Greek letters represent homologous point annotated in Fig. 4. The red thick dotted line represents the layering of the spatter material, also visible in the field picture. The sequence from I to XI represent the progressive emplacement of spatter beds, which display conformable contacts; the main discordance is highlighted with a thick red line. The thick blue

line highlights the morphological step on the southern cliff. The light-blue pattern represents the in situ Petrified Forest Member (PFM), with preserved horizontal bedding. The country-rock breccia (CRB) is marked in magenta, the juvenile-dominated tuff breccia (TB_J) in gray and the lithic- and juvenile-dominated ones (TB_L) in orange

magma within a fissure conduit during the late stage of a surface eruption, or (2) by accumulation of fragments nearly in situ during deep-seated explosions, which

generated subterranean cavities with ephemeral life-times (e.g., explosion chamber; Lorenz and Kurszlauskis 2007), albeit with a vertical blade-like form.

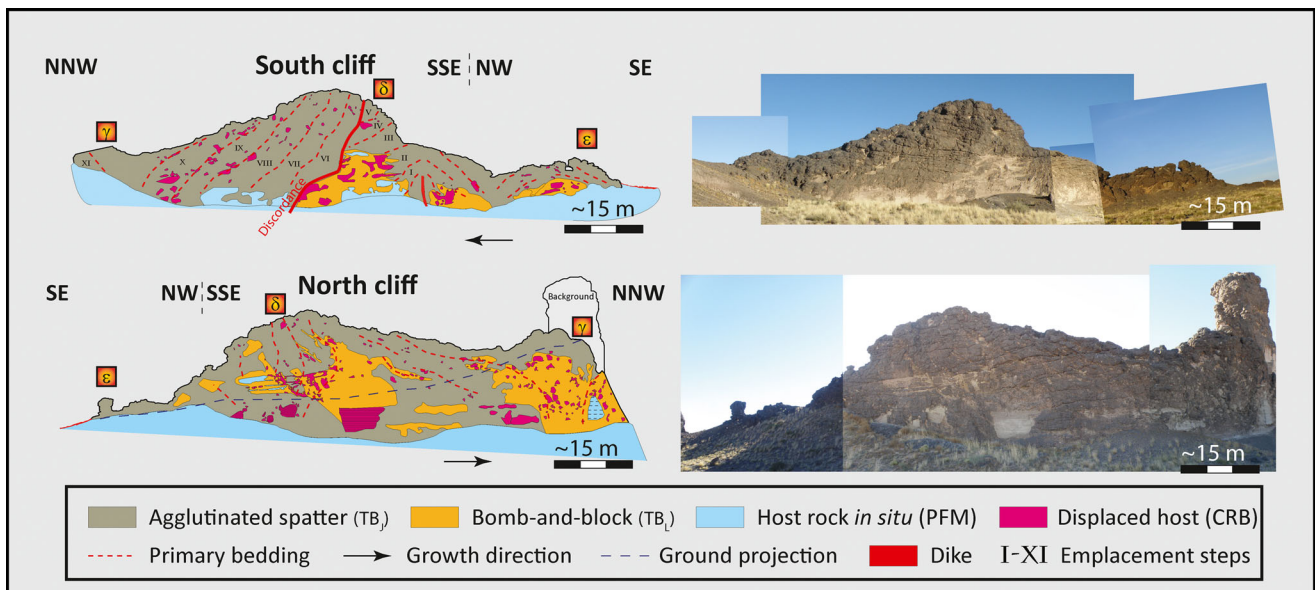


Fig. 12 Cliff-face maps and photographs of Little Jagged Rock. Greek letters represent the homologous point annotated in Fig. 4. The white shadow in the northern map is for the Jagged Rocks massif on the background. The red thick dotted line represents the layering of the spatter material, also visible in the field picture. The emplacement sequence of spatter beds is numbered from I to XI. The thick and dotted

blue line project the base of the southern cliff exposure on the northern one. The light-blue pattern represents the in situ Petrified Forest Member (PFM), with preserved horizontal bedding. The country-rock breccia (CRB) is marked in magenta, the juvenile-dominated tuff breccia (TB_J) in gray and the lithic- and juvenile-dominated ones (TB_L) in orange

Interpretation of juvenile and lithic -dominated tuff breccia (TB_J and TB_L) and massive lapilli tuff (LT_m) deposits

Most of the massifs consist of juvenile- and lithic- dominated pyroclastic deposits that comprise fresh juvenile bombs plus lapilli agglomerate with various proportions of country rock (Table 3). Evidences highlighting the pyroclastic nature of these deposits include the sub-parallel bedded architecture, with beds traceable over tens of meters, the variability in welding between dense (TB_J) and clastic lithic-rich deposits (TB_L), and the shapes of individual juvenile clasts and their internal textures. Composite pyroclasts (see Figs. 4 and 6d), which consist of conjoined igneous domains with dispersed country-rock fragments, hold similarities with volcanic products from other monogenetic eruptions, such as the Chaîne des Puys Volcanic Field in France (Camus 1975), the West Eifel Volcanic Field in Germany (Lorenz and Zimanowski 1984), the Great Toba eruption in Kamchatka (Fedotov and Markhinin 1983; Doubik and Hill 1999), and the 1886 Rotomahana eruption in New Zealand (Rosseel et al. 2006), all of which were associated with phreatomagmatic fragmentation of magma and agglomeration of smaller clasts to one another (Rosseel et al. 2006). A model to assemble these composite pyroclasts was described by Rosseel et al. (2006). Phreatomagmatic explosions shatter the magma, surrounding country-rock and previously emplaced but still semi-consolidated pyroclastic deposits. However, if this explosion does not have enough energy to sufficiently expand the particle mixture (e.g., when the expansion does not breach the free surface), the dispersion of debris may contract (e.g., because of the condensation or separation from the mixture of water vapor) and bring the constituents rapidly back into contact with one another. We infer that juvenile groundmasses with different colors, vesicularity, and crystallinity are evidence of individual juvenile clasts agglomerated and sintered together along with entrapped lithic clasts (Figs. 4 and 6d). Despite the absence of thermal alteration adjacent to dikes in the Petrified Forest Member (Re et al. 2015), host-rock clasts derived from the Petrified Forest Member are locally stretched and sheared to produce layers of disaggregated sandy debris along contacts with juvenile clasts (Fig. 7c, d). Other clasts remain intact, displaying rims with various levels of thermal alteration, whereas some others do not display any evidence for thermal alteration. This variability may reflect different period of residence within the magma or the hot pyroclastic deposit, different distance from the heat source at the time of wall-rock fragmentation, different grain sizes, or different properties of individual lithic clasts. The polymict and lithic-rich lapilli tuff (LT_L) present in the massifs and locally at bud margins shows that juvenile clasts mixed with simultaneously deposited host-rock fragments. We consider that these deposits are equivalent to the *heterobreccia* described by Delaney and Pollard (1981),

Table 3 Summary of the main feature of different rock types

Rock type	Abbreviation	Texture	Fabric	Components
Juvenile-dominated tuff breccia	TB _J	Coherent	Closely packed and clast-supported. Continuous to discontinuous dm- to m-thick beds	Highly welded spatter bombs; <30 % wall-rock clasts
Lithic- and juvenile -dominated lapilli tuff and tuff breccia	TB _L	Fragmental to locally coherent	Clast- to matrix-supported. Rare wall-rock clasts alignment, locally bedded	Juvenile bombs and minor lapilli; >50 % of wall-rock clasts
Non-layered (massive) lapilli tuff	LT _m	Fragmental	Clast- to matrix-supported. Massive and non-bedded	Juvenile lapilli, coarse lapilli and loose pyroxenes; ~30 % country-rock clasts
In situ Petrified Forest Member	PFM	Sedimentary	Cross to plane-parallel bedding	Mudstone, muddy sandstone and sandstone. Localized pebbles horizons
Petrified Forest monomict country-rock breccia	CRB	Chaotic	Framework-supported	~90 % PFM wall-rock blocks; accidental juvenile

Subscript letters indicate the following, *J* juvenile, *L* lithic, *m* massive TB tuff breccia, LT lapilli tuff

but do not necessarily originate in the way inferred by those authors. Ingestion of fractured and dislodged wet host rocks is inferred to have released pore water while enclosed in the magma, thus triggering magma-water interactions (Wohletz 1983; 1986; Zimanowski and Büttner 2002, 2003). In places, this water may have been provided by ingestion of liquefied wet sediments, although this appears to have happened only very locally (e.g., Fig. 8d). These deposits of well-mixed juvenile and lithic components are now found along zones of contact between the juvenile-rich interior and their enclosing in situ host.

Following these interpretations of massif bedding and other deposit characteristics, we suggest that Jagged Rocks Complex massifs were emplaced largely from weak pulsatory phreatomagmatic fragmentation. Episodes and/or sites of weak magmatic fragmentation may also have contributed to production of the spatter layers; the spatter clasts can be formed by both processes, and our preference for phreatomagmatic fragmentation rests on the lithic-clast characteristics and context of fragmentation. Phreatomagmatic processes here involved interaction of hot and fluid magma with water delivered by the sand-rich portion of the host, from locally permeable vuggy limestone and pebbly horizons in the overlying Owl Rock Member, or from fractures in the Petrified Forest Member fed from the Owl Rock horizons. These Chinle Formation rocks have a transmissibility coefficient calculated from pumping tests of 0.02 L/s/m (Cooley et al. 1969), and would have delivered modest amounts of water at moderate (where an Owl Rock horizon was exposed in the fissure wall) to low rates. Phreatomagmatic fragmentation is possible at a wide range of water/magma ratios, with Zimanowski et al. (1991) reporting strong explosions at ratios ranging from 1/6 to 1/25. Weak littoral/rootless cone-style spattering (e.g., Hamilton et al. 2010) such as suggested here does not involve strong explosions, and individual spattering events are more sensitive to contact geometries than to the amount of water available. Pyroclasts generated by breaking up magma into clots, entrained along with surrounding country-rock and material recycled into the vent, were transported along hyperbolic paths, and then accumulated together in different proportions. Beds of breccia in the massifs suggest semi-ballistic trajectories of pyroclasts that would require an open space of greater height than depositional width. Consistent primary orientations of layering and conformable contacts between adjacent pyroclastic units imply sequential emplacement by deposition and accretion of contiguous beds, which interfinger in places, of juvenile and lithic mixtures (TB_J and TB_L). These features suggest non-uniform deposition from pulsating fragmentation with discontinuous supply of host-rock material, limited juvenile-clast dispersion and, perhaps, short breaks between emplacement of different beds. In places, discordances, highlighted by edifice morphology and/or changes in layering orientation, suggest partial

reworking of the emplaced deposit through gravitational (downward) slip.

This kind of activity alternated, at least during emplacement of massif 3, with more intense but transient phreatomagmatic fragmentation. The non-sorted, non-graded, non-bedded and tightly packed lapilli-tuff deposits (LT_m) are inferred to have been produced by the efficient expansion and separation of particle mixtures shattered by phreatomagmatic explosions (Fig. 9). Loose individual particles were deposited into steep-sided cross-cutting bodies forcefully opened from below as transient conduits during propagation of debris jets (Andrews et al. 2015; Graettinger et al. 2014; McClintock and White 2006; Ross and White 2006; Ross et al. 2008a, 2008b), which are upward moving flows that propagate inside diatremes from explosion sites and contain gas, lithics, juvenile particles, and perhaps liquid water (Ross et al. 2013). Repeated explosions emplaced multiple debris-jet deposits cross-cutting the previously formed unconsolidated vent-filling deposits, and produced a volcanoclastic deposit at massif 3 that resembles the one exposed within the diatreme. This process affected a greater vertical range than at massifs 1 and 2, and involved country-rock blocks from stratigraphically higher unit(s). Vertical mixing occurred via two main mechanisms associated with the jets: (1) downward flow of material around the cavities temporarily opened by the debris-jet process (Ross et al. 2008a, b; Ross et al. 2013; Graettinger et al. 2014; Andrews et al. 2015); and (2) subsidence of blocks or country-rock slabs into the disrupted, or temporarily liquefied (if water-saturated), diatreme fill (Valentine and White 2012).

Interpretation of country-rock breccia

Country-rock breccias have been described at the edges of many diatremes worldwide (Clement 1982; Kurszlaukis and Barnett 2003; Downes et al. 2007; Brown et al. 2008; Kurszlaukis et al. 2009; Seghedi et al. 2009; van Straaten et al. 2009; Lefebvre et al. 2013), and commonly lie at margins of root zones, between coherent-looking igneous rock at root-zone cores and undisrupted host country rock (Clement and Reid 1989; Lorenz and Kurszlaukis 2007), though Lefebvre et al. (2016) describe such breccias enclosing an intra-diatreme fragmentation zone deposit. Country-rock breccia deposits generally consist of well-mixed country-rock blocks from different stratigraphic levels, and record gravitational collapses, such as rock falls, slides or avalanches. Therefore, their emplacement requires unstable weakened and/or fractured sidewalls and, especially, an open space where the debris can accumulate. Country-rock breccia of monomict composition is exposed at the bottom of Jagged Rock's southeastern tip, and has a discordant relations with the pyroclastic tuff breccia (TB_J and TB_L). Principal elements of the country-rock breccia are large and rotated blocks of Petrified Forest sandstone with a subordinate mudstone-clast

matrix and a small pyroclastic content. The main difference between the country-rock breccia observed at Jagged Rocks massifs and elsewhere in diatremes is the homogeneity of lithic blocks, which are exclusively from the surrounding Petrified Forest Member, with fragments from shallower or deeper units not detected. This indicates that displaced blocks were deposited close to the depth from which they were derived, without large vertical transport. This observation can be interpreted in different ways. The first possibility is that, at the time of deposition, Jagged Rocks massifs may not have extended upward into rocks at higher stratigraphic levels (e.g., Moenave or Bidahochi Formations), preventing the formation of heterolithic country-rock breccia. Alternatively, if the massifs formed in cavities spanning multiple sedimentary units above the Petrified Forest Member, or that were open to the surface as a volcanic fissure conduit, some mechanism must have been active to prevent vertical mixing of country-rock material. We infer that vertical mixing could have been impeded in two possible situations: (1) if during the collapse of the upper part of the conduit, wedges of country-rock blocks jammed together and bridged over the newly opened space so that they constituted a lid, through which overlying material could not descend, or (2) if the external margins of the fissure, the initial dike walls, constituted hardened coherent igneous rock have held back materials at shallow levels and kept them from falling downward (Wadsworth et al. 2015). For a cavity/fissure extending hundreds of meters below surface, situation 1 seems substantially more plausible.

How were subterranean cavities opened?

Each massif requires a subterranean space to allow the fragmentation of magma, pyroclasts dispersal and accumulation of thick volcanoclastic beds, and also to accommodate slides of country-rock from sidewalls that produced clasts observed in both pyroclastic (TB_J and TB_L) and country-rock breccias. Nevertheless, a clear understanding of how an open subterranean cavity, fracture or fissure becomes established at relatively shallow depths (upper half km) remains elusive, particularly when the country rocks are weak. Making the assumption that the volume of removed host-rock is equivalent to the massifs' volume minus the proportion of lithic clasts present in the massifs (~30 %), we estimate (see Table 2) that at Jagged Rocks a minimum of than 30,000 m³ of country rock were cleared to allow emplacement of the exposed massif deposits.

Any explanation of how a 0.5-m thick dike might widen into a tabular conduit up to 14 m in thickness, which reached the surface from ~300 m depth, must address displacement, transport, and ejection of country-rock material during eruption, as well as dilation of sidewalls to accommodate the volume of the conduit. We offer a detailed explanation in section 5.4, but note that the topic of widening dikes has been

addressed by many authors, with many different mechanisms inferred, here summarized:

1. hydraulic fracturing (Jébrak 1997; Brown et al. 2007);
2. increasing the pore pressure by heating the interstitial water in sandstone during dike rise (McBirney 1959; Delaney and Pollard 1981; Delaney 1982);
3. thermo-elastic spalling of wall rock (McBirney 1959) and wall-rock clasts entrainment (Valentine and Groves 1996);
4. magma viscosity variations induced by cooling of magma at dike margins, leading to flow localization (Wylie et al. 1999);
5. inclusion of wall-rock blocks where offshoot dikes rejoin the master dike;
6. damage and brecciation of wall rock by explosions of magmatic, phreatomagmatic (interaction of magma with groundwater or saturated sediments), or other origins (McBirney 1959; Delaney and Pollard 1981; Lorenz 1986, 2003; White 1991; Barnett 2004; McClintock and White 2006; Lorenz and Kurszlauskis 2007; Ross et al. 2008a; Ross et al. 2008b; Seghedi et al. 2009; Andrews et al. 2015);
7. implosion/collapse as a result of conduit processes as the eruption progresses, such as collapse of unsupported wall rock following magma withdrawal and/or pressure fluctuations within the cavity due to changes in magma supply, variations in magma pressure and shock/rarefaction waves (Wilson and Head 1981; Macedonio et al. 1994; Dobran 2001; Sparks et al. 2006; Carey et al. 2007);
8. progressive melting of the host rocks, enhancing localized flow (Bruce and Huppert 1989, 1990; Quarení et al. 2001).

These mechanisms can act together to decrease sidewalls strength and cohesion, some entirely underground, others in conduits, so a critical question concerns whether or not there was a surface eruption associated with emplacement of the Jagged Rocks massifs. A fissure open to the surface implies that Jagged Rocks Complex magmas fed surface eruptions of some sort, whereas if activity took place entirely in the subsurface, then a subterranean cavity was opened to host the subterranean “eruptive” processes without any surface eruption. The most critical mystery, if fully subterranean emplacement is inferred, is the fate of the country rock removed to accommodate the massifs. Creation of subterranean storage space for this removed country rock would ultimately require substantial inelastic compression (volume reduction) of host rock somewhere along the margins of the plumbing system; there is no evidence of any such deformation at current exposure levels. If instead we infer that there was a surface eruption above the massifs, it must have taken place before deposition within the fissure 300 m below the surface, because no feeder dikes pierce the massifs. It is an open question how closely infissure deposits of the massifs would resemble preceding surface-erupted deposits. Without preservation of the syn-eruptive surface deposits from Jagged Rocks, any statement

regarding the specific eruptive processes that ejected the missing country rock would be highly speculative.

From dikes to buds and pyroclastic massifs: record of conduits development

At Jagged Rocks Complex, we examined the mutual relations among dikes, buds, massifs, and a diatreme to learn about genetic links between coherent magma transport (in dikes and bud cores) and explosive activity. This range of dikes through buds to larger massifs and even diatremes is expected in many volcanic systems, and Jagged Rocks offers an exceptional example because such relations are most easily determined in simple, monogenetic volcanoes assembled on and within distinctively stratified non-volcanic country rock.

Dikes, buds, and massifs share many features, but are distinct from one another in several ways (Table 1). Jagged Rocks Complex massifs have vertical planar-tabular shapes like dikes (Fig. 5), but comprise volcanoclastic deposits with bedding over tens of meters (Figs. 11 and 12). Massifs (>10 m wide) are at least an order of magnitude wider than typical dikes in the southern Hopi Buttes Volcanic Field (average thickness 0.45 m; Re et al. 2015; Muirhead et al. 2016), and they widened into

fragmental bodies at ~300 m depth. For comparison, well-studied basaltic dikes inferred to have fed scoria cones typically did not open into wider clastic bodies until ~85 m below surface (Keating et al. 2008), or shallower (~15 m; Geshi and Neri 2014). Termination of a feeder dike at a slightly deeper level (220 m) is shown by Geshi et al. (2011), and in that case the overlying clastic body is a diatreme. At Castle Butte Trading Post in Hopi Buttes, the clastic fissure-form bodies, which exhibit similar depositional characteristics to the massifs described in this study, have thicknesses similar to those of Jagged Rocks massifs even at a depth of 150 m below the paleo-surface (Lefebvre et al. 2012). Not only are the Jagged Rocks Complex massifs wider than coherent dikes and characterized by fragmental deposits, but they have NW-dipping stratification that indicates pulsatory activity that ejected ballistics to the depositional surface during depositional phases alternated with short breaks. During pauses in this unsteady activity, strata may have been truncated due to downward slips (Lefebvre et al. 2012).

The Jagged Rocks Complex includes several vents that may have overlapped in activity or have been active successively, alternating weak eruptions with more violent ones. We suggest that the pyroclastic massifs at Jagged Rocks Complex represent the remnants of fissural conduits that fed a surface eruption (Fig. 13).

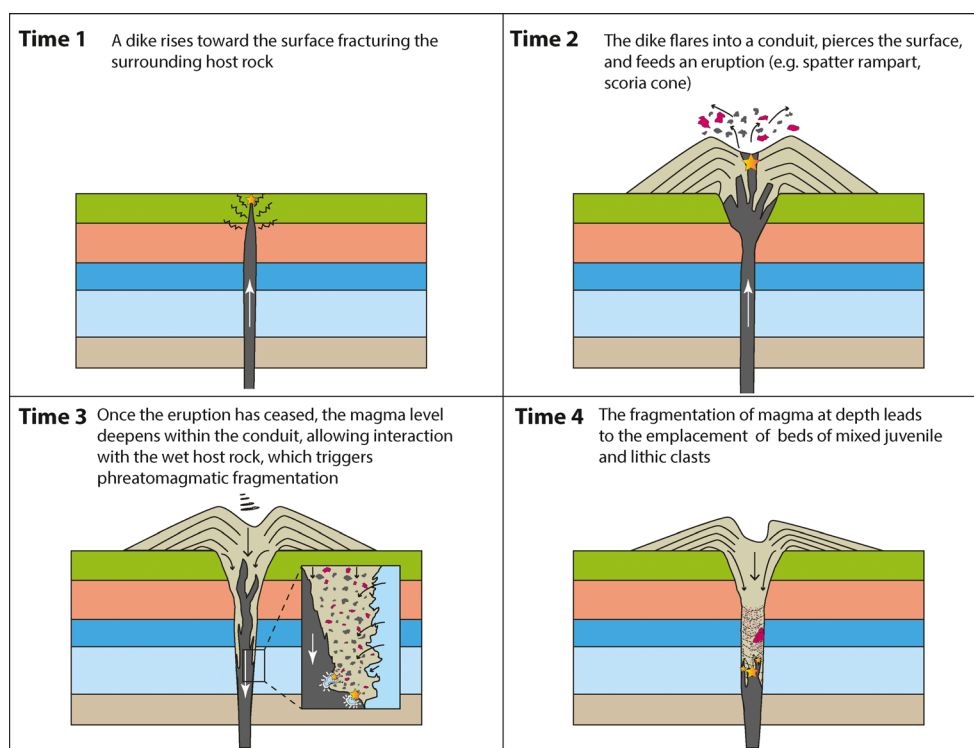


Fig. 13 Cross sections drawn at right angles to the trend of the massif illustrate the emplacement of a scoria cone at the surface, which may have preceded massif growth. Legend: the sedimentary sequence match with the stratigraphic log provided in Fig. 1, gray and magenta clasts are juvenile and lithic clasts, respectively, and the star symbols indicate the fragmentation sites. Time 1: a master dike rises through the coherent host by brittle fracture propagation and pierces the surface. Time 2: the upper part of the dike flares into a funnel-shaped conduit, and a pyroclastic cone

is emplaced at the surface. Time 3: the dike retreats at the end of the eruption, leading to slip of the volcanoclastic debris at depth. In the inset, the reduction of pressure at the conduit walls leads to efficient MFCI involving magma, and the pore water or sediment slurry. Meanwhile, unsupported side walls collapse and supply lithic debris. Time 4: new pyroclastic material consists of fragmental juvenile, mixed with shattered country rock and recycled pyroclasts, emplaced as a bedded succession into the conduit space

Conduits would have been modified by dynamic processes (e.g., changes in magma supply rate, magmatic-phreatomagmatic transitions, deepening of the fragmentation surface[s]) that occurred during the course of the eruption, thereby removing or overprinting earlier emplaced dikes or deposits at the exposed depths; thus, the current exposure best represents the very late stage of the eruption. Jagged Rocks Complex initiated as a suite of coherent dikes that propagated along magma-driven fractures (Re et al. 2015). A combination of mechanisms (e.g., conduit erosion due to shear of flowing magma or particle collision above the fragmentation level, country-rock brecciation, spalling, and collapse) acted together to enlarge fractures at sites where buds and then massifs (and at one site a diatreme) developed. We infer that a master dike pierced the surface (Fig. 13, Time 1) and started a dike-fed eruption. It is impossible to assess the course, duration, and type of eruption (explosive vs effusive), but we infer that activity probably began as a fissure eruption, which is typical of the initial stages of mafic eruptions in volcanic fields elsewhere (Delaney and Pollard 1981; Thordarson and Self 1993; Doubik and Hill 1999; Keating et al. 2008; Lefebvre et al. 2012, 2016). This volcanic fissure may have flared in its upper part (~100 m; e.g., Keating et al. 2008) into an elongate conduit, which would have quickly localized into discrete vents in alignment. This activity probably fed subaerial spattering and clastogenic lava flows, which led to scoria accumulation and growth of aligned cones (Fig. 13, Time 2). We suggest that, during this early phase of surface eruption, coherent magma flowed through a feeder dike (conduit) at the current exposure depth. The pressure of magma on the dike walls was probably greater than that of the hydrostatic pressure of the water contained in the host, preventing efficient magma-water interaction and thus phreatomagmatic fragmentation. Ejection of 30,000 m³ of country rock almost certainly required phreatomagmatic explosions (Valentine and Groves 1996), but at current exposure levels, the tabular form of massifs 1 and 2 precludes strong explosive excavation. It is likely that at this stage, magma supply to the surface had become pulsatory, with periods when magma pressure in the feeding system was reduced.

As magmatic activity waned further, surface eruptions probably became intermittent and later ceased as pulses of magma rose then withdrew into the conduits, deepening the site of fragmentation. Drain-back of magma was driven by some combination of lateral dike propagation and outgassing of the magma column. Episodes of magma retreat provoked the failure of unsupported walls and the downward slip (or subsidence) of the pyroclastic deposits from the upper parts of the conduit to deep levels (Fig. 13, Time 3). Furthermore, the decreasing pressure in the conduit may have allowed the influx of groundwater (and local sedimentary slurries) that triggered deep-seated phreatomagmatic fragmentation. In-conduit fragmentation disrupted most of the coherent dike and the surrounding host-rock and new fragmental debris (juvenile and lithic) generated by the explosions agglomerated into composite pyroclasts. Mixtures in various proportions of

ballistic bombs and host-rock clasts accumulated as bedded spatter, whereas host-rock boulders that collapsed from side walls were assembled locally as monomict country-rock breccia (Fig. 13, Time 4). The Jagged Rocks massifs complex might therefore have similarities with the feeder conduits of fissure eruptions, but it would represent the last activity from the magma withdrawn, associated with fragmentation at depth into an open conduit. Drain-back of magma has been observed repeatedly during basaltic eruptive fissure eruptions (e.g., Etna (Geshi and Neri 2014), White Island (Houghton and Nairn 1991), Tolbachik (Doubik and Hill 1999), and this is also consistent with features seen at other Hopi Buttes massifs (e.g., Castle Butte Trading Post; Lefebvre et al. 2012).

Conclusion

At Jagged Rocks Complex, intrusions and pyroclastic deposits seen in excellent exposures reveal key features of the shallow plumbing system of a monogenetic volcanic complex, which allow us to investigate its evolution from coherent magma flowing through dikes to pyroclastic fragmentation in developing conduits. Within the complex, three main types of fragmental deposits (buds, pyroclastic massifs, and a diatreme) show that activity shifted over time, from more-explosive to weakly explosive eruption styles. The different intensities of shallow-depth fragmentation may have developed at different vents that overlapped in time or were successively active during the evolution of a single monogenetic volcanic center. Jagged Rocks deposits are inferred to result from generally weak phreatomagmatic fragmentation, but weak magmatic bursts of broadly strombolian style could also have been involved in producing the spatter deposits. Different intensities and extents of fragmentation led to the formation of agglomerate and isolated pyroclasts, and the availability of open space controlled the architecture of the deposits, which are internally either bedded or chaotic.

1. Buds emerged from dikes and represent the weakest inception and shortest-lived phreatomagmatic fragmentation at depth. Pyroclasts and locally derived lithic debris accumulated nearly in situ within tiny spaces generated and enlarged by the explosions that drove the fragmentation, together with still coherent domains of intrusive rock.
2. The alignment of elongate and sub-circular massifs is inferred to have been associated with a fissure eruption at the surface. Spatter clasts were produced at depth once the magma retreated downward into the conduit, and they then accumulated in an open cavity along with host-rock to develop sub-parallel beds over tens of meters. Sub-circular massif 3 reveals some sort of short-lived and more energetic fragmentation below exposure depth, with emplacement of lapilli tuff deposits that truncate the bedded spatter.

3. Subterranean emplacement of narrow tabular (dike-like) pyroclastic massifs accompanied magma retreat at depth when the superficial activity of an initial fissure eruption waned. Phreatomagmatic fragmentation and spatter deposition occurred into the now-empty conduit, but there were no strong explosions. The bedding architecture of this deposit implies the availability of open space. The strongest explosions, where dike tips lay deepest below the surface, formed sub-cylindrical and heterolithic (diatreme) deposits that cross-cut the surrounding host.

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