

Discovery of two new super-eruptions from the Yellowstone hotspot track (USA): Is the Yellowstone hotspot waning?

Thomas R. Knott¹, Michael J. Branney¹, Marc K. Reichow¹, David R. Finn¹, Simon Tapster² and Robert S. Coe³

¹School of Geography, Geology and the Environment, University of Leicester, Leicester LE1 7RH, UK

²British Geological Survey, Nottingham NG12 5GG, UK

³Earth and Planetary Science Department, University of California–Santa Cruz, Santa Cruz, California 95064, USA

ABSTRACT

Super-eruptions are amongst the most extreme events to affect Earth's surface, but too few examples are known to assess their global role in crustal processes and environmental impact. We demonstrate a robust approach to recognize them at one of the best-preserved intraplate large igneous provinces, leading to the discovery of two new super-eruptions. Each generated huge and unusually hot pyroclastic density currents that sterilized extensive tracts of Idaho and Nevada in the United States. The ca. 8.99 Ma McMullen Creek eruption was magnitude 8.6, larger than the last two major eruptions at Yellowstone (Wyoming). Its volume exceeds 1700 km³, covering ≥12,000 km². The ca. 8.72 Ma Grey's Landing eruption was even larger, at magnitude of 8.8 and volume of ≥2800 km³. It covers ≥23,000 km² and is the largest and hottest documented eruption from the Yellowstone hotspot. The discoveries show the effectiveness of distinguishing and tracing vast deposit sheets by combining trace-element chemistry and mineral compositions with field and paleomagnetic characterization. This approach should lead to more discoveries and size estimates, here and at other provinces. It has increased the number of known super-eruptions from the Yellowstone hotspot, shows that the temporal framework of the magmatic province needs revision, and suggests that the hotspot may be waning.

INTRODUCTION

Explosive super-eruptions (≥450 km³; magnitude ≥8; Mason et al., 2004) are landscape-changing extreme events that perturb global climate and devastate environments (Self, 2006). They have occurred through much of Earth history, but few robustly documented examples are known (e.g., Rougier et al., 2018). Further recognition from the geologic record is essential to quantify global frequencies, the range of eruption styles, and impacts (Robock, 2002). One approach is to assess their frequency in particular tectonic settings. Several examples are known in continental arcs (Lipman and McIntosh, 2006; de Silva, 2008), but fewer have been found in intraplate settings. Therefore, we targeted the Yellowstone hotspot track in the United States because it is one of the best-preserved intraplate large igneous provinces, where time-transgressive magmatism (due to 2 cm/yr plate motion; Armstrong et al., 1975;

Anders et al., 2019) allows study of the temporal relationships among magma production, residence, recycling, and crustal response (Leeman et al., 2008).

Yellowstone has produced super-eruptions (e.g., magnitude 8.7 Huckleberry Ridge Tuff; Christiansen, 2001), but the number generated as the hotspot tracked across the central Snake River Plain (SRP; Fig. 1) is not known. A Miocene ignimbrite flare-up has been proposed (Nash et al., 2006), and evidence for very large Miocene eruptions is emerging (Finn et al., 2016; Ellis et al., 2019), but, until now, none exceeded the magnitude of the Yellowstone super-eruptions.

We report the discovery of two super-eruptions revealed by meticulous correlation of central SRP ignimbrites previously thought to be smaller localized units. We show they were larger and more frequent than those at Yellowstone, and we propose that the hotspot was perhaps more vigorous in the Miocene.

Super-Eruption Recognition

Recognizing a super-eruption requires quantification of the dense rock equivalent (DRE) volume of the erupted deposit (Pyle, 2000). However, several similar deposits may coexist in a succession, presenting a challenge to distinguish and correlate individual deposits. Successions of similar-looking ignimbrites occur throughout southern Idaho in the United States (Fig. 1; Branney et al., 2008), so we developed a robust approach to distinguish and regionally correlate individual units by combining trace-element and mineral chemistry, paleomagnetic data, and detailed field characterization. Critically, any one correlation technique proved insufficient in isolation.

MCMULLEN CREEK IGNIMBRITE

The McMullen Creek super-eruption is recorded by an extensive rhyolitic ignimbrite hitherto known only locally in the Cassia Hills (Ellis et al., 2010; Knott et al., 2016a). We now correlate it widely across southern Idaho, where it overlies members of the Cassia Formation (Knott et al., 2016a), and for the first time across to the north of the SRP, where it overlies the Challis Volcanic Group (Fig. 1; for previous local names, see Table S1 in the Supplemental Material¹). It is widely overlain by the Grey's Landing Ignimbrite (see below), aiding the recognition of both units in tandem. A ≥12,000 km² distribution as estimated using field mapping, logging, and the contemporaneous topography (Fig. 1; Williams et al., 1990; Michalek, 2009). It erupted from the Twin Falls eruptive center, as inferred from the distribution, distally decreasing grain sizes and thicknesses, and rheomorphic lineations and kinematic data (Fig. 1; Knott et al., 2016a).

¹Supplemental Material. Unit summaries, previous nomenclature, methodologies, and all raw data. Please visit <https://doi.org/10.1130/GEOL.S.12360149> to access the supplemental material, and contact editing@geosociety.org with any questions.

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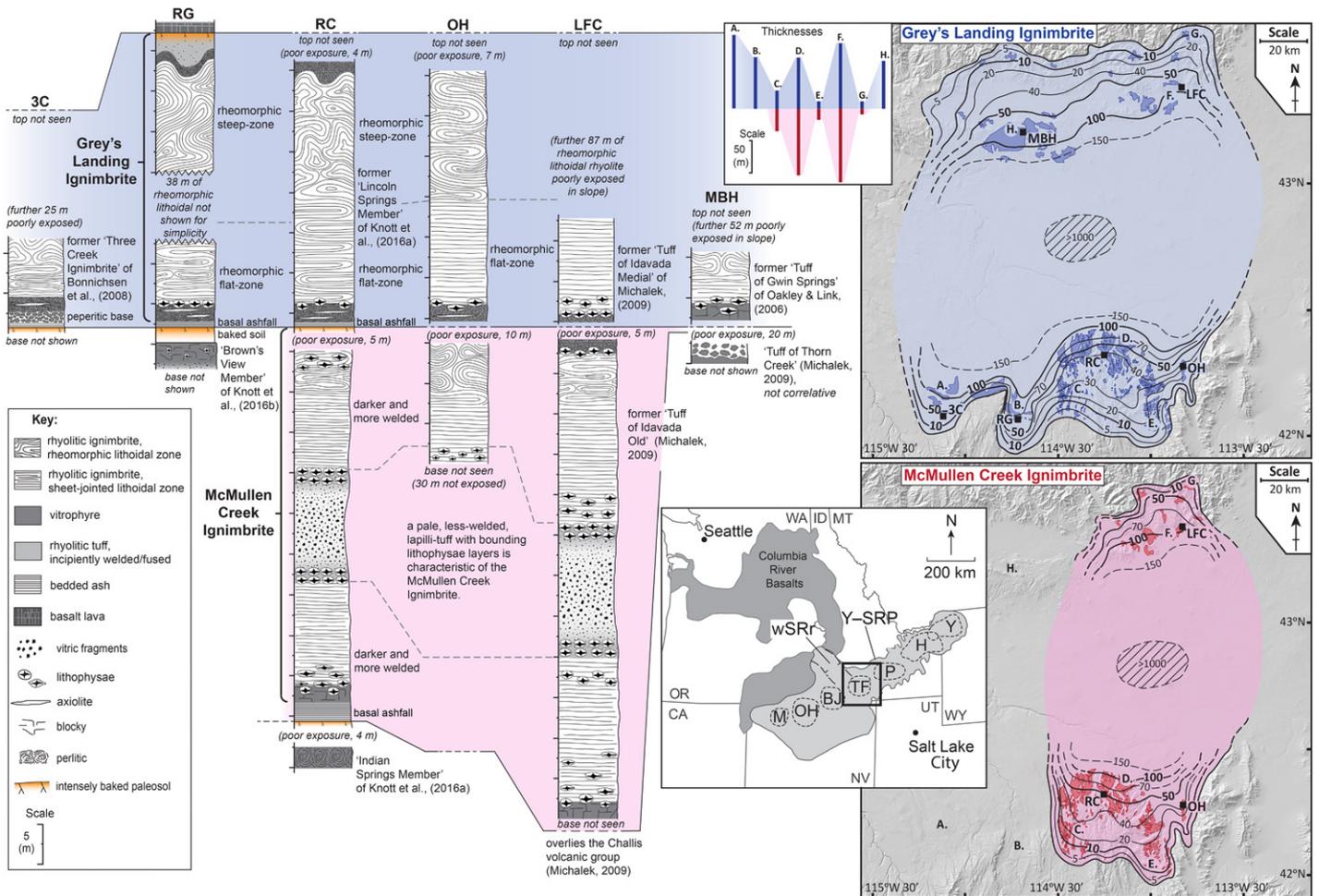


Figure 1. Field area (black square) within the Yellowstone–Snake River volcanic province (Y-SRP) in the northwest United States, showing rhyolitic eruptive centers: M—McDermitt; OH—Owyhee-Humboldt; BJ—Bruneau-Jarbidge; TF—Twin Falls; P—Picabo; H—Heise; Y—Yellowstone. Other: wSRr—western Snake River Plain. State abbreviations: WA—Washington; ID—Idaho; MT—Montana; OR—Oregon; CA—California; NV—Nevada; UT—Utah; WY—Wyoming. (Left) Select logs through McMullen (red) and Grey's Landing (blue) super-eruption deposits from Twin Falls eruptive center. Site abbreviations: 3C—Three Creek; RG—Rogerson graben; RC—Rock Creek, Cassia Hills; OH—Oakley Hills; LFC—Little Fish Creek, Lake Hills; MBH—Mount Bennett Hills. (Right) Distribution maps and isopachs given in meters with representative outcrop thickness (from >50 logged sites) shown for reference (inset).

Deposit Distinction

The McMullen Creek Ignimbrite is distinguished from others in the region using a combination of seven characteristics:

(1) Broad color layering reflects a compound welding profile with two dark intensely welded zones and a pale, less-welded center (Fig. 1). Distinct lithophysal bands enclose the less-welded center and persist distally beyond where the central zone pinches out.

(2) The center has a distal-finishing concentration of angular nonvesicular vitric lapilli supported in devitrified tuff (Fig. 1; Knott et al., 2016a).

(3) The entire deposit has a normal paleomagnetic polarity, and thermoremanent magnetic (TRM) directions are tightly clustered and indistinguishable at all sites and differ from other units (Fig. 2).

(4) It contains 5%–15% crystals of plagioclase, pigeonite, augite, magnetite, apatite, and zircon, but no sanidine, a phase ubiquitous in

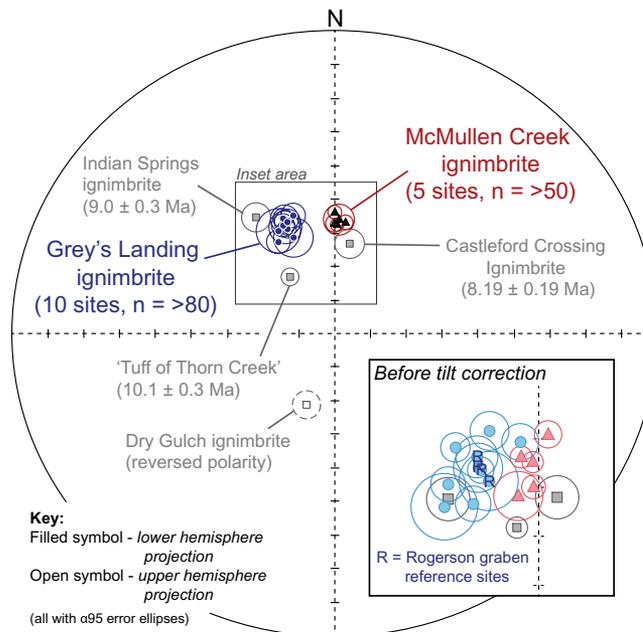


Figure 2. Stereonet of site-mean thermoremanent magnetization (TRM) directions showing tightly clustered McMullen Creek (red) and Grey's Landing (blue) Ignimbrites from both flanks of the Snake River Plain (SRP; northwest United States), demonstrating a clear distinction from one another and from other units nearby (grays). Data were corrected for postemplacement tilting. Inset: Uncorrected TRM directions, complicated by postemplacement tilting, shown for comparison (see the method in the Supplemental Material [see footnote 1]).

central SRP ignimbrites older than ca. 10 Ma (Cathey and Nash, 2004).

(5) It has a single equilibrium pair of pigeonite and augite (Fig. 3), whereas the Grey's Landing ignimbrite has an additional, second pair of pyroxenes of different composition.

(6) Trace-element ratios plot into fields distinct from those of most other ignimbrites in the region (Fig. 3). Where fields overlap, contrasting stratigraphic positions, mineral chemistry, and paleomagnetic signatures distinguish the other units.

(7) The preferred age interpretation from high-precision zircon geochronology is a $^{206}\text{Pb}/^{238}\text{U}$ age of 8.989 ± 0.031 Ma (Fig. 4; see the Supplemental Material) consistent with previous ^{40}Ar - ^{39}Ar ages (e.g., 9.0 ± 0.2 Ma; Knott et al., 2016a).

Volume and Magnitude

Sourceward thickening of the McMullen Creek Ignimbrite (Fig. 1) and sourceward-directed paleoflow indicators (Knott et al., 2016a) show that the eruption occurred into a regional northeast-trending "Snake River basin" that was actively subsiding at the time in response to the intense magmatism, heating, softening, and extension of the crust (Anders and Sleep, 1992; McCurry and Rodgers, 2009; Knott et al., 2016a, 2016b). The preferred volume estimate is ≥ 1700 km³ (DRE), based on a measured ignimbrite density of 2340 kg m⁻³ and a rock density of 2380 kg m⁻³ (Ochs and Lange, 1999). This equates to magnitude 8.6 (method of Pyle, 2000; Fig. 4). This estimate is conservative in (1) excluding dispersed Plinian and coignimbrite ash-fall deposits; (2) excluding likely density current flow further east and

west along the basin axis, where evidence is concealed; and (3) assuming a caldera of modest dimensions (one tenth that of Yellowstone) and a fill of only 1 km, which is reasonable given the >1.35 -km-thick adjacent caldera fill of the Castleford Crossing eruption of comparable volume (Knott et al., 2016a). A minimum volume for the McMullen Creek Ignimbrite is >1000 km³, if evidence for known sourceward thickening and the presence of a caldera concealed beneath the SRP are excluded. However, calderas are well reported elsewhere in the province (e.g., ~ 5000 km² Yellowstone caldera; Christiansen, 2001; Swallow et al., 2019). Assuming a caldera of comparable dimensions, it is possible that the ignimbrite volume could exceed 6000 km³, still excluding the substantial ash-fall component. However, we consider our preferred volume to be the most geologically reasonable.

GREY'S LANDING IGNI MBRITE

The rhyolitic Grey's Landing super-eruption deposit covers $>23,000$ km² of southern Idaho and northern Nevada (Fig. 1). Hitherto, it had been documented only locally, around Rogerson, Idaho (Fig. 1; Andrews and Branney, 2011; Knott et al., 2016b). However, it correlates with deposits formerly thought to be unrelated at numerous sites along both flanks of the SRP (see Table S1 for previous local names). In the west, it caps all successions, whereas in the east, it overlies the McMullen Creek Ignimbrite, is overlapped by the Castleford Crossing Ignimbrite (Knott et al., 2016a), and proximally is overlain by basalts (Fig. 1).

Deposit Distinction

The deposit is distinguished by a combination of eight characteristics:

(1) It is the region's most intensely welded unit, with original vitroclast outlines obliterated by hot coalescence.

(2) It is the region's most rheomorphic unit, with ubiquitous flow folds, including sheath folds, which reflect unusually high magmatic and emplacement temperatures (966 °C; Laval-lée et al., 2015).

(3) A distinctive, fused basal fall sequence ~ 0.5 m thick rests on a baked paleosol (Fig. 1).

(4) It forms a simple cooling unit with lower and upper vitrophyres, a lithoidal center, and a nonwelded top. The lower vitrophyre has red devitrification lenses.

(5) Its magnetic polarity is normal, and TRM directions at all sites are indistinguishable and different from the adjacent McMullen Creek and Castleford Crossing Ignimbrites, with angular separations of $\sim 14^\circ$ and $\sim 16^\circ$, respectively (Fig. 2).

(6) It is the only unit younger than ca. 10 Ma that at all sites contains four discrete compositional modes of pyroxene (Fig. 3).

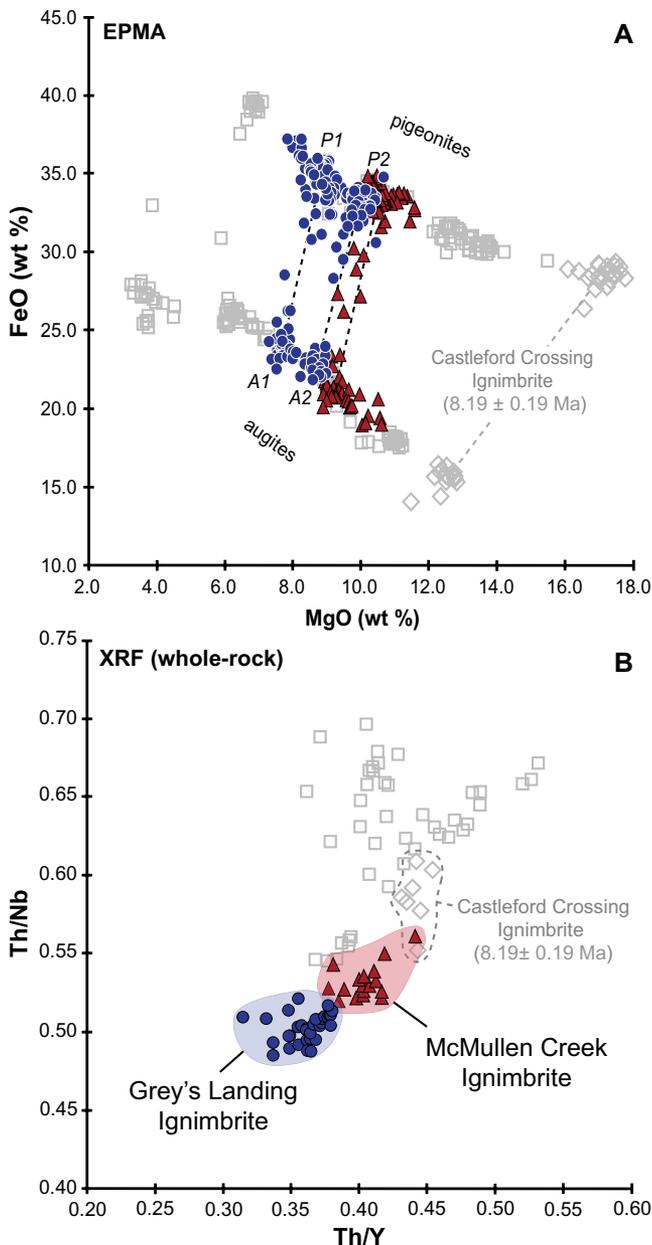


Figure 3. Chemical distinction of two super-eruption deposits (filled) from other deposits nearby (gray). (A) Presence of two discrete equilibrium pigeonite-augite pairs (blue spots) characterize Grey's Landing (Idaho, USA) deposits, in contrast to single pigeonite-augite pair of McMullen Creek Ignimbrite (red triangles). (B) Super-eruption discrimination using ratios of immobile trace elements. EPMA—electron probe microanalysis; XRF—X-ray fluorescence.

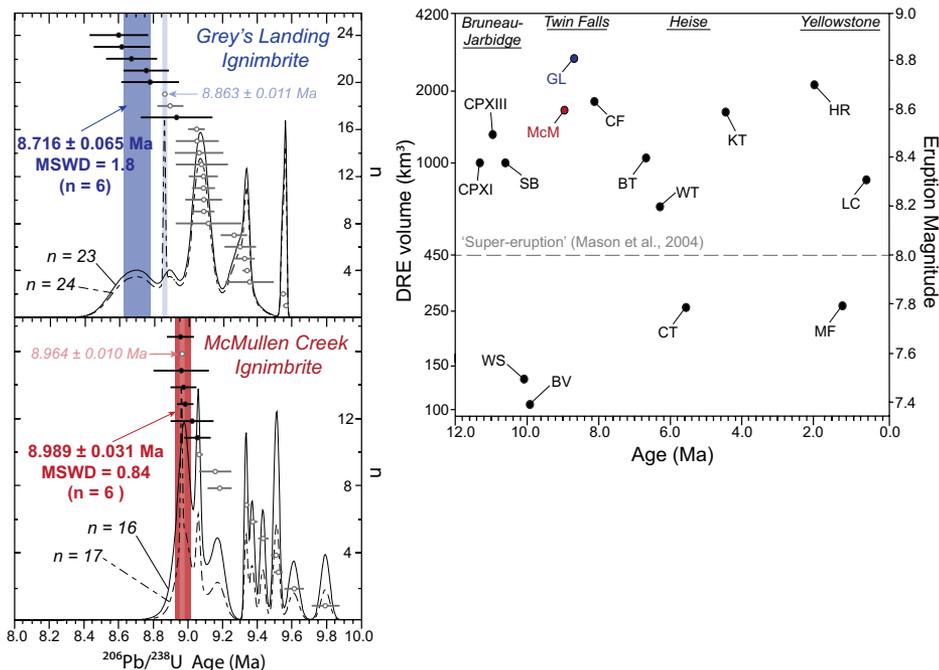


Figure 4. (Left) Zircon $^{206}\text{Pb}/^{238}\text{U}$ single-crystal age determinations and probability density plots for two super-eruptions with 2σ uncertainty. Filled (black) symbols indicate zircons used in preferred weighted mean age interpretations (age in bold); open circles are potential antecrysts, including single high-U zircon age (in italics). MSWD—mean square of weighted deviates. (Right) Super-eruption sizes (DRE—dense rock equivalent) and ages from the central Snake River Plain (SRP; see text), Heise (Morgan and McIntosh, 2005), and Yellowstone (Christiansen, 2001) showing correspondence of temporal clusters within individual eruptive centers (underlined). Ignimbrite abbreviations: CPXI, CPXIII—numbered Cougar Point Tuffs; SB—Steer Basin; WS—Wooden Shoe; BV—Brown's View; McM—McMullen Creek; GL—Grey's Landing; CF—Castleford Crossing; BT—Blacktail Creek; WT—Walcott; CT—Conant Creek; KT—Kilgore; HR—Huckleberry Ridge, MF—Mesa Falls; LC—Lava Creek.

(7) Ratios of incompatible trace elements define a field distinct from other units, with minor overlap of McMullen Creek data (Fig. 3).

(8) It yields a preferred high-precision zircon $^{206}\text{Pb}/^{238}\text{U}$ age of 8.716 ± 0.065 Ma; a higher-precision age interpretation of 8.863 ± 0.011 Ma is plausible, but it critically depends on an individual zircon (Fig. 4; see the Supplemental Material).

Volume and Magnitude

The Grey's Landing Ignimbrite is a colossal Snake River-type ignimbrite (Branney et al., 2008). At $\geq 23,000$ km², it has the broadest documented distribution in the province ($\sim 30\%$ larger than the Huckleberry Ridge Tuff). Its shape reflects emplacement into a subsiding basin, recorded by marked thickening and basinward, gravity-induced paleoflow indicators (Knott et al., 2016a). Preferred eruption volume and magnitude estimates are ≥ 2800 km³ DRE and 8.8, respectively, which conservatively exclude the distal ash-fall component and assume modest caldera dimensions relative to others in the province (Fig. 1), making it currently the largest documented super-eruption in the province (Fig. 4). Similar to the underlying McMullen Creek Ignimbrite, we report a lower to upper volume for the Grey's Landing Ignimbrite of

$>1700\text{--}6700$ km³. However, the preferred estimate presented above is considered the most geologically reasonable.

DISCUSSION: A SUPER-ERUPTION FLARE-UP?

The fact that each deposit represents a single eruption is demonstrated by (1) consistent TRM directions throughout the vertical thickness of the deposit (Fig. 2; Finn et al., 2015), showing it was emplaced during an interval too brief to record secular variation, (2) single cooling-unit profiles, and (3) separation by well-developed soils, but no internal soils or sediments.

In their seminal work on the magmatic evolution of the province, Bonnicksen et al. (2008) proposed that rhyolitic magmatism did not migrate systematically eastward in the central SRP, and that magmas broadly became less evolved with time but with significant fluctuations. The analysis was based on 16 proposed "composition and time (CAT) groups," each populated by ignimbrites and lavas thought to be broadly related and invoked to represent a time interval through the region's history. However, the present study reveals stratigraphic misallocations in the scheme. Deposits hitherto thought to be unrelated and spanning six different "CAT groups" are demonstrably from a single erup-

tion (Grey's Landing; see Table S1). This may account for some of the "noise" in the apparent province-wide patterns of migration and composition, and it shows that a robust stratigraphic approach as outlined herein is essential to assess the temporal evolution of a province, including the number, size, and frequency of large eruptions and varying productivity.

The discoveries reported herein, together with other widespread central SRP eruption units (e.g., CPXI and Steer Basin—Ellis et al., 2012; Finn et al., 2016; CPXIII—Ellis et al., 2019; Castleford Crossing—Knott et al., 2016a; Fig. 4), reduce the total number of explosive eruptions during the Miocene ignimbrite flare-up (Nash et al., 2006) by one third, to 31. However, the sizes of the events have increased significantly, with 11 super-eruptions now documented on the Yellowstone hotspot track (Fig. 4).

SUPER-ERUPTION PRODUCTIVITY WITH TIME: IS THE HOTSPOT WANING?

Super-eruption productivity has declined at the Yellowstone hotspot since the Miocene to the present day. It was $\geq 3\times$ greater in the central SRP, with a marked decline after 6.2 Ma (Fig. 4).

In the late Miocene, the super-eruption frequency averaged 1 per 520 k.y. Two temporal clusters, one ca. 11.3–10.6 Ma and a second ca. 9.0–8.2 Ma, are separated by ~ 1.6 m.y. (during which only smaller eruptions occurred; Fig. 4). Within a single cluster, super-eruption recurrence rates were on the order of $\sim 300\text{--}500$ k.y. (Fig. 4). We interpret each temporal cluster to reflect magmatism at an individual eruptive center (e.g., Bruneau-Jarbidge center; Bonnicksen and Citron, 1982), whereas the intervening time gap marks the eastward migration of magmatism and establishment of a new center, in this case, at Twin Falls (Fig. 4). The eastward step is marked by an abrupt change in chemistry that records the onset of a new magmatic cycle (Knott et al., 2016a).

The average super-eruption frequency after the Miocene has been just 1 per 1550 k.y.: For example, the most recent super-eruptions at Yellowstone are separated by 1.5 m.y. (Fig. 4). This represents a threefold decrease in super-eruption productivity over time. Also, the largest documented eruption from the hotspot occurred back in the late Miocene (Grey's Landing eruption; $\sim 30\%$ larger than the Huckleberry Ridge Tuff), in a period when eruptions were significantly hotter, in terms of both magmatic and ignimbrite emplacement temperatures (Nash et al., 2006; Branney et al., 2008). Together, these features suggest that the hotspot may be waning.

CONCLUSIONS

We have demonstrated that a multitechnique approach robustly distinguishes between

individual eruption units in a succession and enables correlations across tens of thousands of square kilometers to estimate eruption sizes. The method should benefit further investigations in this province and elsewhere.

Two new catastrophic super-eruptions were discovered: the ca. 8.99 Ma McMullen Creek eruption (magnitude 8.6) and the ca. 8.72 Ma Grey's Landing eruption (magnitude 8.8), the largest known eruption on the Yellowstone hotspot track.

The discoveries have reduced the number of eruptions in the Miocene "flare-up" of the Yellowstone hotspot by a third, but the super-eruption count overall is increased to 11. Moreover, the size, frequency, and emplacement temperatures of the super-eruptions have decreased with time. Together, these features indicate that the hotspot activity may be waning.

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