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

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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 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) 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 chemistry 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 Material}). It is widely overlain by the Grey’s Landing Ignimbrite (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).
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-fining 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 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: wSRp—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).

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 Pb/U age of 8.989 ± 0.031 Ma (Fig. 4; see the Supplemental Material) consistent with previous Ar-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 IGNIMBRITE**

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 Rosseron, 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; Lavalée 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 ~14° and ~16°, 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).
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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REFERENCES CITED
Anders, M.H., and Sleep, N.H., 1992, Magmatism and extinction: The thermal and mechanical effects of the Yellowstone hotspot: Journal of Geophysical Research: Solid Earth, v. 97, no. B11, p. 15379–15393, https://doi.org/10.1029/92JB01376.

Anders, M.H., DiVenere, V.J., Hemming, S.R., and Gombiner, J., 2019, “Art”/Ar and paleomagnetic constraints on the age and areal extent of the Picabo volcanic field: Implications for the Yellowstone hotspot: Geoscience, v. 15, p. 716–735, https://doi.org/10.1130/GEOS1589.1.

Andrews, G.D.M., and Bonnichsen, M.J., 2011, Emplacement and rheomorphic degradation of a large rhyolitic ignimbrite: Grey’s Landing, southern Idaho: Geological Society of America Bulletin, v. 123, p. 725–743, https://doi.org/10.1130/B30167.1.

Armstrong, R.L., Leeman, W.P., and Malde, H.F., 1975, K-Ar dating, Quaternary and Neogene volcanism of the Snake River Plain, Idaho: American Journal of Science, v. 275, p. 225–251, https://doi.org/10.2475/ajs.275.3.225.

Bonnichsen, B., and Citron, G.P., 1982, The Cougar Point Tuff, southwestern Idaho and vicinity, in Bonnichsen, B., and Breckenridge, R.M., eds., Cenozoic Geology of Idaho: Idaho Bureau of Mines and Geology, Bulletin 26, p. 235–281.

Bonnichsen, B., Leeman, W., Honjo, N., McIntosh, W., and Godchaux, M., 2008, Miocene silicic volcanism in southwestern Idaho: Geochronology, geochemistry, and evolution of the central Snake River Plain: Bulletin of Volcanology, v. 70, p. 315–342, https://doi.org/10.1007/s00445-008-0141-6.

Brunner, M., Bonnichsen, B., Andrews, G., Ellis, B., Barry, T., and McCurry, M., 2008, Snake River (SR)-type volcanism at the Yellowstone hotspot track: Distinctive products from unusual, high-temperature silicic super-eruptions: Bulletin of Volcanology, v. 70, p. 293–314, https://doi.org/10.1007/s00445-007-0140-7.

Cathey, H.E., and Nash, B.P., 2004, The Cougar Point Tuff: Implications for thermochemical zonation and longevity of high-temperature, large-volume silicic magmas of the Miocene Yellowstone hotspot: Journal of Petrology, v. 45, p. 27–58, https://doi.org/10.1093/petrology/egg081.

Christiansen, R.L., 2001, The Quaternary and Pliocene Yellowstone Plateau Volcanic Field of Wyoming, Idaho, and Montana: U.S. Geological Survey Professional Paper 729-G, 146 p., https://doi.org/10.1130/0313-2229(2001)49<146:QTAPWP>2.3.CO;2.

de Silva, S., 2008, Arc magmatism, calderas, and supervolcanoes: Geology, v. 36, p. 671–672, https://doi.org/10.1130/0091-7613(2008)036<0671:AMCAAS>2.0.CO;2.

Ellis, B., Barry, T., Branney, M.J., Wolff, J.A., Binde- man, I., Wilson, R., and Bonnichsen, B., 2010, Petrologic constraints on the deformation of a large-volume, high-temperature, silicic magma system: The Twin Falls eruption centre, central Snake River Plain: Lithos, v. 120, p. 475–489, https://doi.org/10.1016/j.lithos.2010.09.008.

Ellis, B., Branney, M.J., Barry, T.T., Borfod, D., Bin deman, I., Wolff, J.A., and Bonnichsen, B., 2012, Geochemical correlation of three large-volume ignimbrites from the Yellowstone hotspot track, Idaho, USA: Bulletin of Volcanology, v. 74, p. 261–277, https://doi.org/10.1007/s00445-011-0510-z.

Ellis, B.S., Schmitz, M.D., and Hill, M., 2019, Reconstructing “McPhee” and “McKee” compositional fingerprinting and high-precision U/Pb zircon geochronology: Contributions to Mineralogy and Petrology, v. 174, p. 101, https://doi.org/10.1007/s00410-019-1614-z.

Finn, D.R., Coe, R.S., Kelly, H., Branney, M., Knott, B., and Reichow, M., 2015, Magnetic anisotropy in rhyolitic ignimbrite, Snake River Plain: Implications for using remnant magnetism of volcanic rocks for correlation, paleomagnetic studies, and geological reconstructions: Journal of Geophysical Research: Solid Earth, v. 120, p. 4014–4033, https://doi.org/10.1002/2014JB011868.

Finn, D.R., Coe, R.S., Brown, E., Branney, M., Reichow, M., Knott, T., and Bonnichsen, B., 2016, Distinguishing and correlating deposits from large ignimbrite eruptions using paleomagnetism: The Cougar Point Tuffs (mid-Miocene), southern Snake River Plain, Idaho, USA: Journal of Geophysical Research: Solid Earth, v. 121, no. 6, p. 6293–6314, https://doi.org/10.1002/2015JB013306.

Knott, T.R., Branney, M.J., Reichow, M.K., Finn, D.R., Coe, R.S., Storey, M., Borfod, D., and McCurry, M., 2016a, Mid-Miocene record of large-scale Snake River-type explosive volcanism and associated subsidence on the Yellowstone hotspot track: The Cascade volcanic field, USA: Geological Society of America Bulletin, v. 128, p. 1121–1146, https://doi.org/10.1130/B31324.1.

Knott, T.R., Reichow, M.K., Branney, M.J., Finn, D.R., Coe, R.S., Storey, M., and Bonnichsen, B., 2016b, Rheomorphic ignimbrites of the Rogerson Formation, central Snake River Plain, USA: Journal of Volcanology and Geothermal Research, v. 309, p. 209–225, https://doi.org/10.1016/j.jvolgeores.2016.04.005.

Rougier, J., Sparks, R.S.J., Cashman, K.V., and Self, S., 2006, The effects and consequences of very large explosive eruptions from thermo-kinetics of glass shards: Eos (Washington, D.C.), v. 83, p. 472–472, https://doi.org/10.1093/petrology/egz034.

Swallow, E.J., Wilson, C.J.N., Charlier, B.L.A., and Gamble, J.A., 2019, The Huckleberry Ridge Tuff, San Diego, California: Academic Press, p. 263–269.

Robock, A., 2002, Blowin’ in the wind: Research priorities for climate effects of volcanic eruptions: Eos (Washington, D.C.), v. 83, p. 472–472, https://doi.org/10.1029/2002EO000333.

Rougier, J., Sparks, R.S.J., Cashman, K.V., and Self, S., 2018, The global magnitude-frequency relationship for large explosive volcanican eruptions: Earth and Planetary Science Letters, v. 482, p. 621–629, https://doi.org/10.1016/j.epsl.2017.11.015.

Pyle, D.M., 2000, Sizes of volcanic eruptions, in Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: San Diego, California, Academic Press, p. 263–269.

Sel, S., 2006, The effects and consequences of very large explosive volcanic eruptions: Philosophical Transactions of the Royal Society: Mathematical, Physical, and Engineering Sciences, v. 364, p. 2073–2097, https://doi.org/10.1098/rsta.2006.1814.

Swallow, E.J., Wilson, C.J.N., Charlier, B.L.A., and Gamble, J.A., 2019, The Huckleberry Ridge Tuff, Yellowstone: Evacuation of multiple magmatic systems in a complex episodic eruption: Journal of Petrology, v. 60, p. 1371–1426, https://doi.org/10.1093/petrology/egz034.

Williams, P.L., Myton, J.W., and Covington, H.R., 1990, Geologic Map of the Striker 1 Quadrangle, Cassia, Twin Falls, and Jerome Counties, Idaho: U.S. Geological Survey Miscellaneous Investigations Series Map 1-2078, scale 1:48,000, 1 sheet.

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