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High-precision U-Pb geochronology links magmatism in the Southwestern Laurentia large igneous province and Midcontinent Rift

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ABSTRACT

The Southwestern Laurentia large igneous province (SWLLIP) comprises voluminous, widespread ca 1.1 Ga magmatism in the southwestern United States and northern Mexico. The timing and tempo of SWLLIP magmatism and its relationship to other late Mesoproterozoic igneous provinces have been unclear due to difficulties in dating mafic rocks at high precision. New precise U-Pb zircon dates for comagmatic felsic segregations within mafic rocks reveal distinct magmatic episodes at ca. 1098 Ma (represented by massive sills in Death Valley, California, the Grand Canyon, and central Arizona) and ca. 1083 Ma (represented by the Cardenas Basalts in the Grand Canyon and a sill in the Dead Mountains, California). The ca. 1098 Ma magmatic pulse was short-lived, lasting $0.25^{+0.67}_{-0.24}$ m.y., and voluminous and widespread, evidenced by the ≥100 m sills in Death Valley, the Grand Canyon, and central Arizona, consistent with decompression melting of an upwelling mantle plume. The ca. 1083 Ma magmatism may have been generated by a secondary plume pulse or post-plume lithosphere extension.

The ca. 1098 Ma pulse of magmatism in southwestern Laurentia occurred ∼2 m.y. prior to an anomalous renewal of voluminous melt generation in the Midcontinent Rift of central Laurentia that is recorded by the ca. 1096 Ma Duluth Complex layered mafic intrusions. Rates of lateral plume spread predicted by mantle plume lubrication theory support a model where a plume derived from the deep mantle impinged near southwestern Laurentia, then spread to thinned Midcontinent Rift lithosphere over ∼2 m.y. to elevate mantle temperatures and generate melt. This geodynamic hypothesis reconciles the close temporal relationships between voluminous magmatism across Laurentia and provides an explanation for that anomalous renewal of high magmatic flux within the protracted magmatic history of the Midcontinent Rift.

INTRODUCTION

The Southwestern Laurentia large igneous province (SWLLIP) comprises >750,000 km^2 of ca. 1.1 Ga mafic dikes, sills, and lava flows and minor felsic rocks across the southwestern United States and northern Mexico (Howard, 1991; Bright et al., 2014). Thick (≥100 m) sills intrude Mesoproterozoic strata of the Pahrump Group in the Death Valley, California, region (Wright et al., 1967), the Unkar Group of the Grand Canyon Supergroup (Timmons et al., 2012), and the Apache Group of central Arizona (Wrucke, 1990). A variety of radioisotope chronometers have previously been applied to date SWLLIP mafic rocks (see the compilation of Bright et al., 2014), but inherent difficulties in precise and accurate dating of ancient mafic rocks have hindered an understanding of the tempo of SWLLIP magmatism and its correlation to other tectonic and magmatic events of Laurentia, such as the Midcontinent Rift (MCR).

The temporal resolution achieved by modern high-precision U-Pb zircon geochronology underpins the defining traits of large igneous provinces (LIPs), namely punctuated (<1 m.y.) episodes of high magmatic flux (Ernst et al., 2021; Kasbohm et al., 2021). While paucity of zircon in mafic rocks typically precludes U-Pb zircon dating, caches of zircon are often hosted in late-stage felsic differentiates (Krogh et al., 1987) or can be obtained using novel rock-digestion and mineral separation methods that concentrate zircon micro-inclusions (Oliveira et al., 2022). We present new precise ages for SWLLIP rocks in California and Arizona obtained from zircon crystals extracted from a basalt flow and localized felsic segregations in mafic sills (Fig. 1). These new ages are then used to explore a geodynamic connection between voluminous magmatic pulses in two Late Mesoproterozoic (Stenian) LIPs, the SWLLIP and the MCR.

U-Pb GEOCHRONOLOGY

We measured U-Pb dates for zircon crystals by chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS; Mattinson, 2005). Preparation, analytical, and data-reduction methods and data for all individual U-Pb analyses are provided in the Supplemental Material[1]. Weighted mean ages

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[1]Supplemental Material. Full U-Pb geochronology data and additional analytical methods. Please visit https://doi.org/10.1130/GEOL.S.24844002 to access the supplemental material; contact editing@geosociety.org with any questions.

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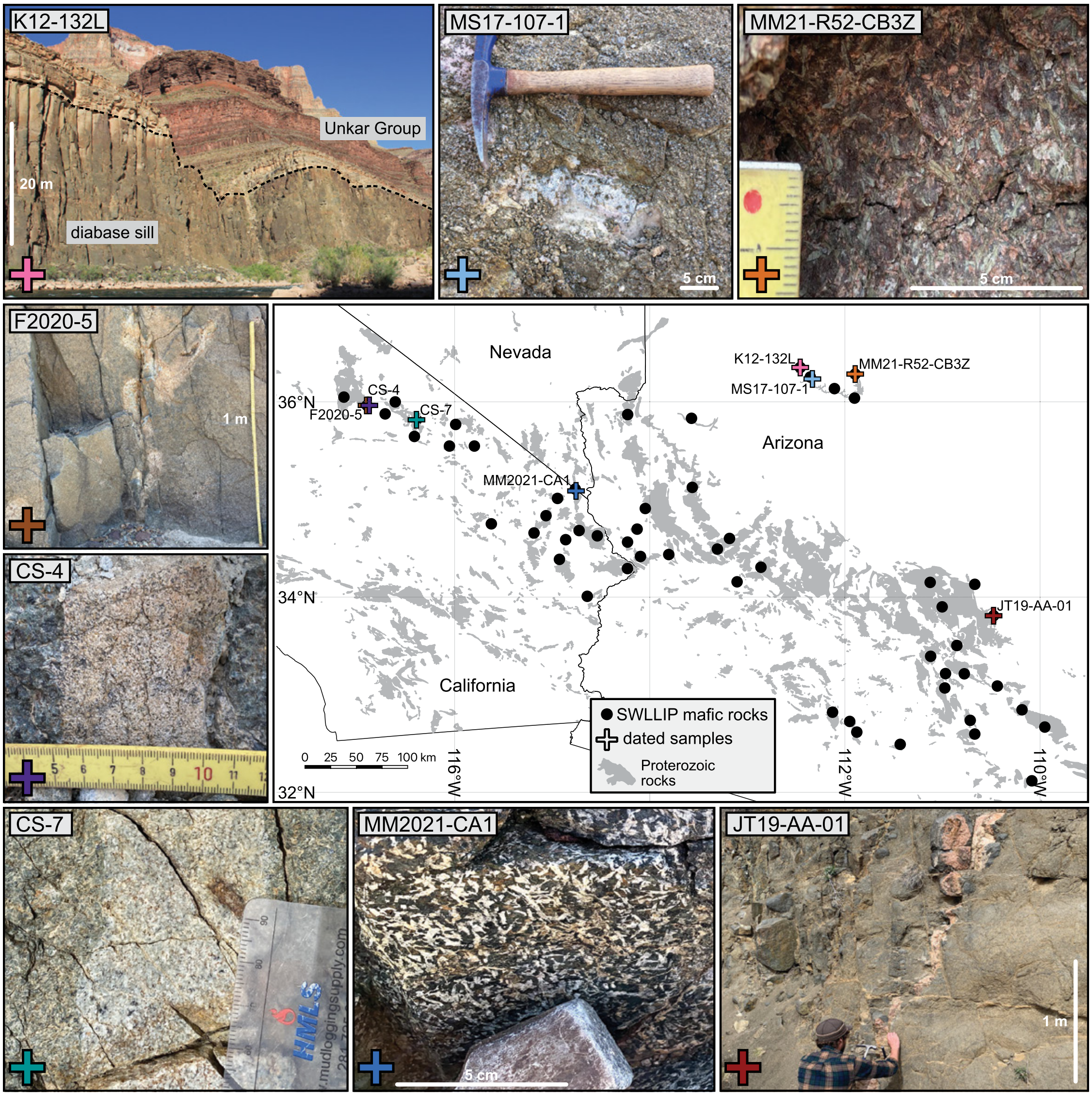

Figure 1. Map of the sampling region in the southwest United States, with Proterozoic geology, known locations of ca. 1.1 Ga mafic rocks (adapted from Howard, 1991; Bright et al., 2014), and locations and outcrop photos of samples in this study. See Table 1 for sample descriptions. SWLLIP—Southwestern Laurentia large igneous province.

interpreted from concordant $^{206}Pb/^{238}U$ zircon dates are reported herein and in Figure 2 with 95% confidence analytical uncertainties, and in Table 1 with mean square of weighted deviates (MSWD) values, additional sources of uncertainty, and sample descriptions. Discordant dates were excluded from age calculations but have implications for interpreting previously published, lower-precision data sets (discussed below and in the Supplemental Material).

Felsic segregations from three diabase sills intruding the Crystal Spring Formation in the Death Valley region gave ages of 1097.91 ± 0.29 Ma, 1098.27 ± 0.27 Ma, and 1098.09 ± 0.91 Ma (Fig. 2). A felsic segregation in a sill in Salt River Canyon, Arizona, gave an age of 1097.97 ± 0.12 Ma. In the Grand Canyon, felsic segregations from two sills gave ages of 1098.09 ± 0.34 Ma and 1098.16 ± 0.59 Ma, and the sampled Cardenas Basalt gave an age of 1082.18 ± 1.25 Ma. A felsic zone within a diabase sill in the Dead Mountains of California, within the Colorado River trough (Fig. 1; see also fig. 4B *in* Howard, 1991) gave an age of 1082.60 ± 0.30 Ma.

Both ca. 1098 Ma and ca. 1083 Ma episodes of SWLLIP magmatism are expressed in the Unkar Group of the Grand Canyon Supergroup. Previously, sills in the Grand Canyon were considered coeval feeders of the Cardenas Basalt (Timmons et al., 2012). Our new ages indicate that sills intruding the Bass and Hakatai Formations in western Grand Canyon (Fig. 1) were emplaced at ca. 1098 Ma, while the Cardenas Basalt erupted at ca. 1083 Ma. The Cardenas Basalt flows are conformable with the Dox Formation, making their 1082.18 ± 1.25 Ma age a new chronostratigraphic constraint for the Unkar Group.

Discrepancies between our data and the previous 1094 ± 2 Ma to 1080 ± 3 Ma ages for SWLLIP mafic rocks established from U-Pb dating of baddeleyite (Bright et al., 2014) demonstrate the importance of high-precision data and Pb-loss mitigation offered by zircon CA-ID-TIMS geochronology for accurately dating LIPs. Baddeleyite is not amenable to chemical abrasion (Rioux et al., 2010) and has been shown to often yield anomalously young dates, likely due to Pb loss, in studies measuring U-Pb dates of both zircon and baddeleyite (Gaynor et al., 2022). While closed-system U-Pb decay is evaluated by agreement between $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ dates within analytical uncertainty (i.e., "concordance"), the apparently concordant, low-precision baddeleyite analyses for SWLLIP mafic rocks also encompass ca. 1098 Ma and ca. 1083 Ma discordia trajectories defined by our more precise CA-ID-TIMS zircon data for samples K12-132L and MM2021-CA1, respectively (Fig. 2; Fig. S2 in the Supplemental Material). Consequently, the range of ages reported by Bright et al. (2014) likely stem from inaccurate $^{206}Pb/^{238}U$ dates due to unmitigated Pb loss that is hidden by large analytical uncertainties. Concordia upper-intercept regressions for baddeleyite data reported by Bright et al. (2014) yield ages of 1104.6 ± 59.9 Ma, 1085.4 ± 12.9 Ma, 1113.8 ± 43.0 Ma, and 1091.3 ± 17.9 Ma

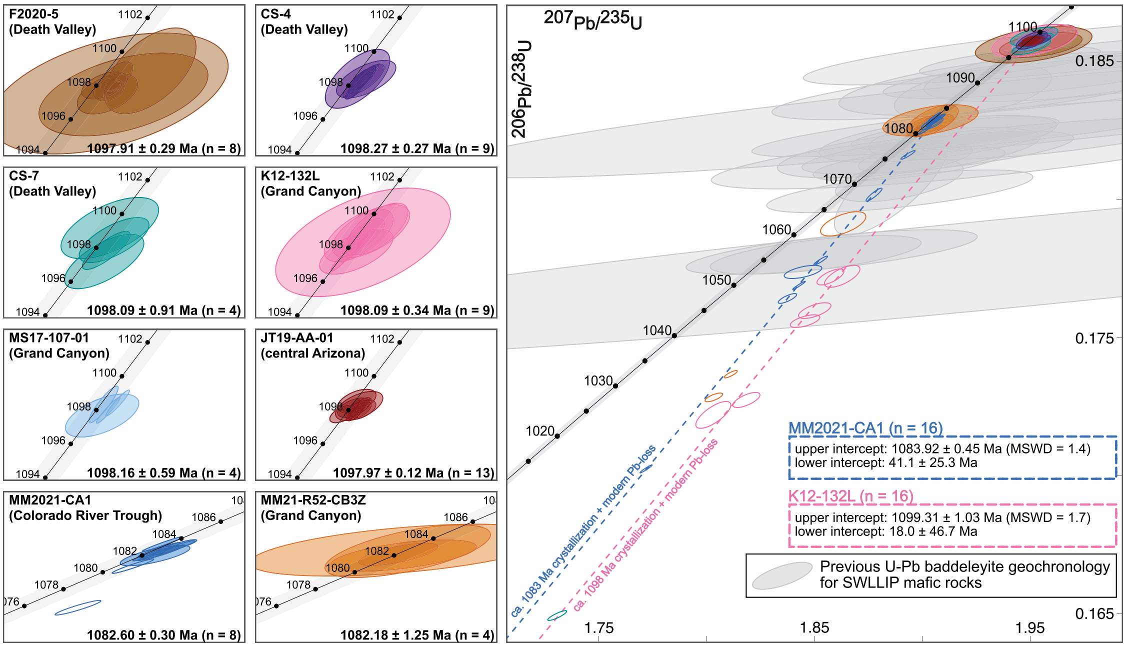

Figure 2. Wetherill Concordia plots of new U-Pb zircon and previous U-Pb baddeleyite geochronology for Southwestern Laurentia large igneous province (SWLLIP) mafic rocks (ages in Ma). Left panels show concordant zircon analyses (filled ellipses) interpreted for crystallization ages. Open ellipses are discordant analyses. Weighted mean $^{206}Pb/^{238}U$ ages for samples are in the bottom right of each panel with 95% confidence analytical uncertainties. Right panel compares new U-Pb zircon chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) data with existing U-Pb baddeleyite data for SWLLIP mafic rocks (Bright et al., 2014). Discordia trajectories for ca. 1098 Ma (pink) and ca. 1083 Ma (blue) crystallization with modern Pb-loss show how previously dated SWLLIP mafic rocks cannot be differentiated into the ca. 1098 Ma or ca. 1083 Ma groups because the imprecise baddeleyite analyses overlap with both Pb-loss trajectories.

(±95% confidence; Fig. S3), which are unable to resolve whether these sills were emplaced at ca. 1098 Ma, ca. 1083 Ma, or during another unknown episode of magmatism in southwestern Laurentia.

TIMING AND TEMPO OF THE SWLLIP

High-precision U-Pb zircon geochronology of Stenian (1.2–1.0 Ga) mafic rocks in California and Arizona significantly refines the timing of SWLLIP magmatism and its relationship to other Laurentian tectonic and magmatic events. The 0.75–1.5 × 10^6 km^2 extent of the SWLLIP (Bright et al., 2014; Ernst et al., 2021) based on the regional distribution of ca. 1.1 Ga mafic and felsic rocks in southwestern Laurentia (Fig. 3) was previously interpreted to have been emplaced over ~20 m.y. (see the compilation of Bright et al., 2014). Our more precise ages reveal punctuated magmatic episodes at ca. 1098 Ma and ca. 1083 Ma. Published ε_{Nd} data sets are consistent with two distinct pulses of mafic magmatism in the SWLLIP, as sills in Death Valley, the Grand Canyon, and western and central Arizona have ε_{Nd} values of +3 to +5 (Hammond and Wooden, 1990) while the Cardenas Basalts have lower ε_{Nd} values of +0.5 to +2 (Larson et al., 1994), as do sills in western and central Arizona, and southwestern New Mexico (Bright et al., 2014). With no clear spatial trends in ε_{Nd} values (Hammond and Wooden, 1990), we hypothesize that isotopic differences reflect tapping of different mantle reservoirs during temporally distinct pulses of magmatism. Felsic magmatism may have occurred with each pulse of mafic magmatism, as indicated by populations of ca. 1098 Ma ages for granitoids in central Texas and ca. 1083 Ma ages for granitoids in southwestern New Mexico and northern Mexico (Fig. 3), but existing ages for Stenian felsic rocks in southwestern Laurentia are based on discordant, pre–chemical abrasion U-Pb zircon analyses and should be reassessed by U-Pb zircon CA-ID-TIMS dating to more robustly establish their age and relationships to SWLLIP mafic magmatism.

A prevailing hypothesis for the formation of the SWLLIP is that a mantle plume pooled under thin southwestern Laurentia lithosphere (Howard, 1991; Bright et al., 2014). Voluminous melt production is evident in the SWLLIP's initial ca. 1098 Ma pulse by numerous sills that exceed thicknesses of 100 m in portions of Death Valley (Wright et al., 1967), the Grand Canyon (Timmons et al., 2012), and in central Arizona (Smith and Silver, 1975), and likely more within the extensive network of Stenian sills imaged in the Arizona subsurface (Litak and Hauser, 1992) and associated lavas that have likely been removed by erosion. Our data suggest that the ca. 1098 Ma pulse was rapid, lasting $0.25^{+0.67}_{-0.24}$ m.y. (median ± 95% credible interval of pairwise Monte Carlo resampling of ca. 1098 Ma ages and uncertainties), and thus consistent with voluminous, widespread, and rapidly emplaced mafic rocks characteristic of plume-related LIPs (see Ernst et al., 2021).

The ca. 1083 Ma episode of SWLLIP mafic magmatism may have been generated by a secondary pulse caused by a separation of the plume head at the lower–upper mantle boundary (Bercovici and Mahoney, 1994) or from regional extension and/or delamination due to thermomechanical alteration of the lithosphere during plume-lithosphere interaction (Black et al., 2021). The regional extension hypothesis is consistent with interflow sediments in the Cardenas Basalts that suggest subsidence and sedimentation coeval with ca. 1083 Ma Cardenas Basalts eruption(s), and with the bimodal nature of ca. 1086–1080 Ma magmatism throughout southwestern Laurentia (Fig. 3).

A GEODYNAMIC LINK BETWEEN SWLLIP AND MCR MAGMATISM?

The precise U-Pb zircon CA-ID-TIMS geochronology on the SWLLIP presented here can be compared with that of the MCR (i.e., Keweenawan LIP) to assess hypothesized geodynamic relationships between these two LIPs (e.g., Bright et al., 2014; Swanson-Hysell et al., 2021). Our new ages reveal that ca. 1098 Ma SWLLIP magmatism was coeval with protracted MCR magmatism in central Laurentia, overlapping with the beginning of the MCR's "main magmatic stage" (Vervoort et a., 2007), but a ca. 1083 Ma SWLLIP episode postdated known MCR magmatism. While mechanisms for the initiation of the MCR are debated (cf. Nicholson and Shirey, 1990; Stein et al., 2015), magmatism within the rift basin occurred from ca. 1109 Ma to ca. 1084 Ma (Swanson-Hysell et al., 2019) with intervals of high melt volumes requiring mantle temperatures in excess of ambient Mesoproterozoic mantle (Hutchinson et al., 1990; Gunawardana et al., 2022) and geochemical signatures consistent with the influence of an enriched mantle source (Nicholson and Shirey, 1990; Shirey, 1997).

TABLE 1. SAMPLE METADATA AND SUMMARY OF U-Pb ZIRCON CA-ID-TIMS GEOCHRONOLOGY FOR STENIAN MAFIC ROCKS IN THE SOUTHWESTERN LAURENTIA LARGE IGNEOUS PROVINCE, SOUTHWESTERN UNITED STATES

Sample	Location	Description	Latitude (°N)	Longitude (°W)	$^{206}Pb/^{238}U$ age* (Ma)	MSWD†	n/N§
F2020-5	Panamint Mountains, CA	~20-cm-wide felsic segregation hosted in the coarse-grained interior of diabase sill intruding near the contact of the argillite and cherty dolomite members of the Pahrump Group Crystal Spring Formation in Warm Spring Canyon of the Panamint Mountains	35.96230	116.90123	1097.91 ± 0.29 (0.42) [1.17]	0.79	8/8
CS-4	Panamint Mountains, CA	5-cm-thick medium-grained felsic dike that is layer parallel to the strike of the host diabase sill 77 m from the base of the 101-m-thick sill. The sill intrudes the stromatolite member of the Crystal Spring Formation in Warm Spring Canyon of the Panamint Mountains at a stratigraphically higher position than the sill of sample F2020-5.	35.96244	116.88572	1098.27 ± 0.27 (0.41) [1.16]	0.35	9/9
CS-7	Ibex Range, SE CA	~5-cm-thick coarse-grained felsic dike that cuts obliquely through an ~100-m-thick sill of coarse-grained diabase intruding the argillite member of the Crystal Springs Formation in the central Ibex Range.	35.81503	116.38968	1098.09 ± 0.91 (0.96) [1.45]	1.58	4/5
MM2021-CA1	Dead Mountains, SE CA	Felsic zone within subophitic interior of an ~80-m-thick diabase sill that is part of a suite of parallel, steeply dipping, northeast-striking sheets intruding ca. 1.4 Ga granite in the Dead Mountains (see also fig. 4B *in* Howard, 1991).	35.08636	114.75425	1082.60 ± 0.30 (0.43) [1.16]	1.53	8/16
MM21-R52-CB3Z	Grand Canyon rm. 52, N AZ	Pegmatoidal interior of a 57-m-thick Cardenas basalt lava flow at Nankoweap Canyon, Grand Canyon river mile 52. Zircon grains were extracted employing the bulk phenocryst dissolution methods of Oliveira et al. (2022), which yielded zircon microlites (<50 μm; Figure S1 in the Supplemental Material [see text footnote 1]).	36.28344	111.89260	1082.18 ± 1.25 (1.29) [1.68]	0.09	4/8
MS17-107-01	Grand Canyon, rm. 107, N AZ	20-cm-wide granophyre pod near the margin of a sill intruding the Bass Formation and Hakatai shale at Bass Canyon, Grand Canyon river mile 107.	36.23335	112.33145	1098.16 ± 0.59 (0.66) [1.28]	0.67	4/7
K12-132L	Grand Canyon, rm. 132, N AZ	20-cm-wide granophyre segregation within an ~50-m-thick sill intruding the Bass Formation and Hakatai shale at Grand Canyon river mile 132.	36.35093	112.45621	1098.09 ± 0.34 (0.46) [1.18]	1.53	9/16
JT19-AA-01	Salt River Canyon, central AZ	~10-cm-wide portion of a subplanar vertical felsic dike within a subhorizonal diabase sill in Salt River Canyon that intrudes the Apache Group.	33.80767	110.47423	1097.97 ± 0.12 (0.32) [1.14]	1.54	13/13

Note: CA—California; AZ—Arizona; SE—southeast; N—northern; rm.—river mile.

*Weighted mean ages are calculated from n concordant grains guided by Thompson's Tau rejection criteria. Reported errors on weighted means are ±x, ±(y), and ±[z], where x is the internal error at 95% confidence (Including a Student's-T multiplier) based solely on analytical uncertainties, y additionally incorporates tracer calibration uncertainty, and z additionally incorporates the ^{238}U decay constant uncertainty, all propagated in quadrature.

†MSWD—mean square of weighted deviates.

§n—number of grains used in weighted mean age calculation; N—total number of grains analyzed.

A persistent question regarding the history of the MCR is: what caused renewal of voluminous magmatism at ca. 1096 Ma that produced the massive Duluth Complex layered mafic intrusion (one of the largest mafic intrusive complexes on Earth) and comagmatic lavas after a period of relative magmatic dormancy (Vervoort et al., 2007), and after Laurentia had drifted >3000 km since the rift's initiation (Swanson-Hysell et al., 2019, 2021)? Swanson-Hysell et al. (2021) suggested that distal plumes could have been funneled to the thinned lithosphere under the MCR via "upside-down drainage" (terminology of Sleep, 1997); however, the previous chronology of the SWLLIP was too imprecise to test this hypothesis.

The voluminous, punctuated, initial pulse of magmatism in southwestern Laurentia, constrained by ages between 1098.27 ± 0.27 Ma and 1097.91 ± 0.29 Ma, occurred ~2 m.y. prior to the 1096.19 ± 0.19 Ma to 1095.69 ± 0.18 Ma emplacement of the Duluth Complex (Swanson-Hysell et al., 2021), and buoyant plume heads can spread ~2000 km during impingement with the lithosphere (Campbell and Griffiths, 1990). Interactions of buoyant plumes with continental lithosphere may be complex (Duvernay et al., 2022), but time-dependent spreading velocities can be estimated by plume lubrication theory (Sleep, 1997). Figure 3C shows analytical results from the model of Sleep (1997) that predict radial spreading velocities for impinging mantle plumes derived from the core-mantle boundary (CMB) and from the mantle transition zone (MTZ), with upper-mantle plume head diameters of 1000 km and 300 km, respectively (Campbell and Griffiths, 1990). The solutions show dramatically decreasing lateral velocity with time due to diminishing buoyancy from flattening and thinning during spreading of a plume head (e.g., Griffiths and Campbell, 1991), but demonstrate that a 1000-km-diameter plume could spread ~1600 km (~2100 km total radius) in 2 m.y., consistent with the location of the Duluth Complex relative to the SWLLIP and the time lag in magmatism revealed by the precise geochronology. The slower spreading velocities associated with a smaller plume head (<550 km over 2 m.y.) could not reasonably advect plume material from the SWLLIP to the MCR over ~2 m.y. Laurentia's ~30 cm/yr drift during this time (Swanson-Hysell et al., 2019) would have displaced the MCR ~600 km eastward during 2 m.y. of plume spreading;

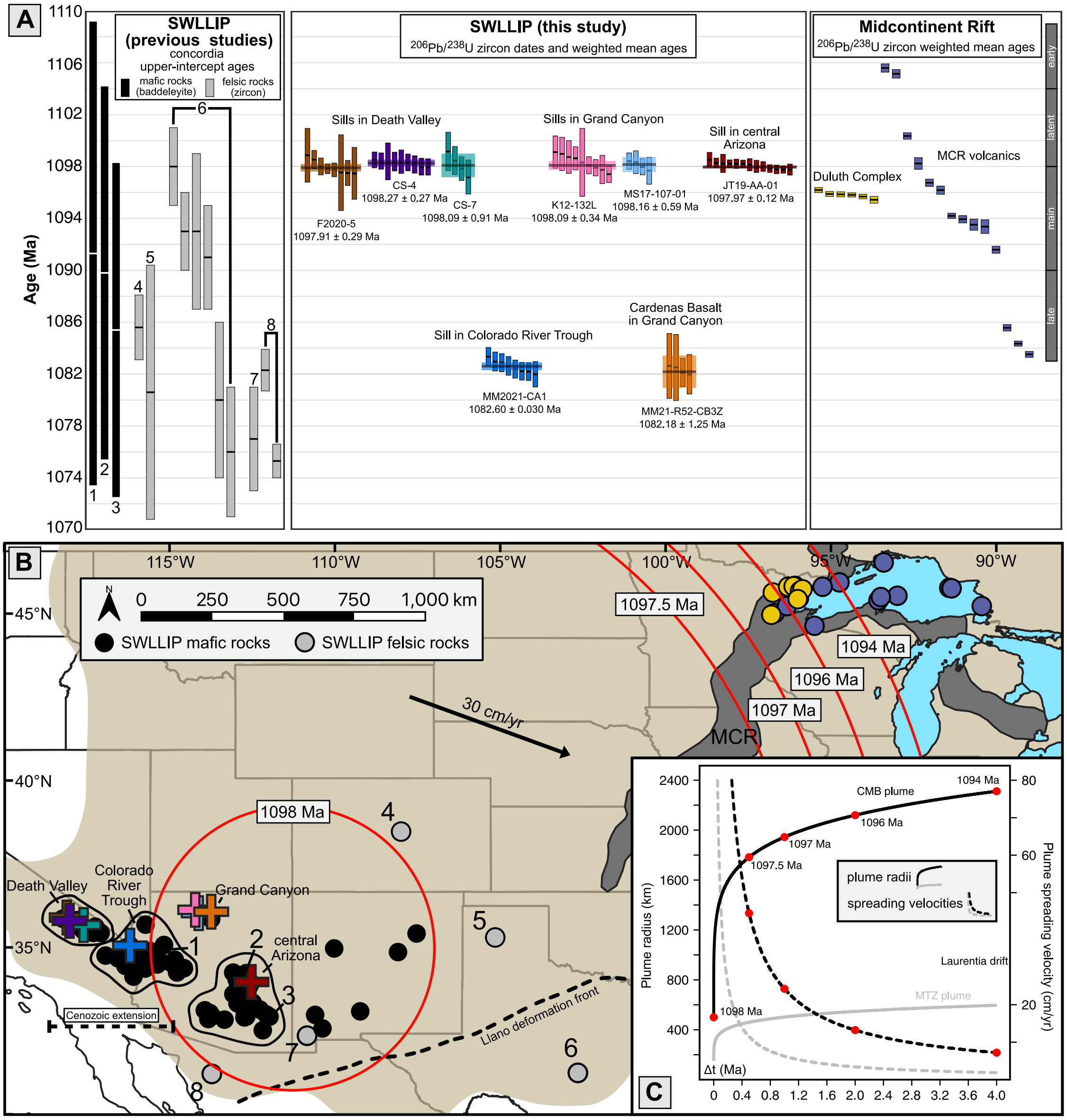

Figure 3. (A) Ranked bar plot of ages for Southwestern Laurentia large igneous province (SWLLIP) mafic rocks in context with published ages for ca 1.1 Ga mafic and felsic rocks in southwestern Laurentia and the Midcontinent Rift (MCR) (Swanson-Hysell et al., 2019, 2021). Numbers: 1, 2, 3 are recalculated baddeleyite upper intercept ages for SWLLIP sills (Bright et al., 2014); 4 is Pike's Peak Granite (Smith et al., 1999); 5 is quartz diorite in drill core (Li et al., 2007); 6 is felsic intrusions in the Llano uplift (Walker, 1992); 7 is Little Hatchet Mountains Granite (Amato and Mack, 2012); and 8 is Aibo Granite (Farmer et al., 2005). Locations are shown in B. (B) Map view (square projection) showing locations of dated SWLLIP and MCR rocks (colors keyed to the ranked bar plots in A) with core-mantle boundary (CMB) plume spreading radii (red) from initial impingement beneath the SWLLIP; vector shows motion and displacement of Laurentia over 2 m.y. Note that the western-most sills have been displaced ~400 km by Cenozoic extension. (C) Analytical solutions predicting spreading of plume heads with initial diameters of 1000 km (sourced from the core-mantle boundary [CMB]) and 300 km (sourced from the mantle transition zone [MTZ]).

however, this movement is only significant relative to the rates of plume spreading after ~0.8 m.y., when a spreading plume under this scenario would have already been channelized into the MCR (e.g., Sleep 1997).

CONCLUSIONS

New ages for SWLLIP mafic rocks established by CA-ID-TIMS U-Pb zircon dating of comagmatic felsic segregations refine the timing of the SWLLIP and resolve temporally distinct ca. 1098 Ma and ca. 1083 Ma magmatic episodes. Geochronology of the ca. 1098 Ma primary magmatism of the SWLLIP and the ca. 1096 Ma pulse of magmatism in the MCR is consistent with predicted lateral plume spreading rates beneath continental lithosphere. We present a plume-spreading relationship between SWLLIP and MCR magmatism as a hypothesis to be tested by future geochronological studies integrated with geochemical data and advanced geodynamic modeling. Our study reinforces how high-precision U-Pb zircon geochronology lays a foundation for defining and correlating ancient magmatic episodes and yields the temporal resolution needed to test complex interactions between plume magmatism and continental lithosphere.

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