Wyoming on the run—Toward final Paleoproterozoic assembly of Laurentia

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ABSTRACT

Paleoproterozoic suture zones mark the formation of supercontinent Nuna and provide a record of North America's assembly. Conspicuously young ages (ca. 1.715 Ga) associated with deformation in southeast Wyoming craton argue for a more protracted consolidation of Laurentia, long after peak metamorphism in the Trans-Hudson orogen. Using paleomagnetic data from the newly dated 1899 ± 5 Ma Sourdough mafic dike swarm (Wyoming craton), we compare the relative positions of Wyoming, Superior, and Slave cratons before, during, and after peak metamorphism in the Trans-Hudson orogen. With these constraints, we refine a collisional model for Laurentia that incorporates Wyoming craton after Superior and Slave cratons united, redefining the Paleoproterozoic sutures that bind southern Laurentia.

INTRODUCTION

Paleoproterozoic amalgamation of Laurentia's Archean cratons likely involved closure of expansive oceans (Hoffman, 1988) born from fragmentation of Neoarchean supercratonic landmasses (Bleeker, 2003). One ancestral connection, between Superior and Wyoming cratons, is compatible with both stratigraphic (Roscoe and Card, 1993) and paleomagnetic (Kilian et al., 2015) records from both blocks, while their 2.1–2.0 Ga mafic dike swarms (Bowers and Chamberlain, 2006; Cox et al., 2000; Mueller et al., 2005) document their rifting and breakup. This breakup initiated a brief period of independent movement of Wyoming craton prior to its incorporation into Laurentia. Because the dates of sutures surrounding Wyoming craton suggest multiple episodes of deformation, metamorphism, and arc collisions after development of the Trans-Hudson orogen (THO), especially along the northwestern and eastern margins, there is some question of when Wyoming craton joined Laurentia and which pieces were contiguous with Wyoming craton prior to its docking (Fig. 1). Was Wyoming craton fused to the Medicine Hat block (MHB) long before collision with Hearne craton (Boerner et al., 1998)? Was Wyoming craton connected with both the MHB and Hearne craton before collision with Superior craton in the THO (Eglington et al., 2013)? Or was Wyoming craton on its own (or with the MHB) during development of the THO, subsequently becoming a late addition to Laurentia (Chamberlain et al., 2002; Dahl et al., 1999)?

We present a precisely dated primary paleomagnetic pole for the ca. 1.899 Ga Sourdough dikes, which represent a newly recognized swarm and a significant addition to the mafic magmatic record of Wyoming craton. By comparing this new paleomagnetic datum with coeval data from Superior and Slave cratons, we investigate their positions at a crucial time interval, providing initial conditions for the subsequent series of collisions that stitched Laurentia together. Coupled to existing geochronologic constraints on suturing along Wyoming's margins, we present a novel kinematic model for the late stages of assembly of Laurentia.

COLLISIONAL CONSTRAINTS

The best exposures of Wyoming's Paleoproterozoic suture zones are found along the southeastern and northern margins of the craton. In the south, the Medicine Bow orogeny and the Cheyenne belt are well defined by metamorphic and deformational pulses from 1.78 to 1.74 Ga (Chamberlain, 1998; Houston et al., 1989; Jones et al., 2010) and have been interpreted to document accretion of the Yavapai arc terrane to Wyoming craton (Condie, 1992). The best age constraints for sutures along Wyoming's eastern

Figure 1. Geologic map of Precambrian basement from central Laurentia with Archean cratons (green) and orogens labeled and colored according to rock age. Dark gray area represents 1.715 Ga suture discussed in this study. LSC—Little Sand Creek xenoliths (Barnhart et al., 2012; Bolhar et al., 2007); SGH—Sweet Grass Hills xenoliths (Davis et al., 1995); LBM—Little Belt Mountains; BT—Beartooth Mountains; BGH—Bighorn Mountains; LM—Laramie Mountains; aeromag.—aeromagentic. The Mid-Continent Rift System (ca. 1.1 Ga) is stippled. Magnetic anomalies between Superior, Wyoming, and Hearne cratons may represent small crustal fragments (e.g., Sask) of Archean to early Proterozoic crust that were sutured into Trans-Hudson orogen (THO) and Black Hills–Dakotan orogens. It is uncertain how far south THO extended and which fragments were connected before Wyoming craton arrived. Archean basement ages from drill cores in northeastern Wyoming and southeastern Montana (USA) likely derive from fragments within Dakotan orogen (Peterman, 1981). Boundaries of Great Falls tectonic zone are estimated from Ross (2002). Other margins modified after Foster et al. (2006) and Worthington et al. (2016).
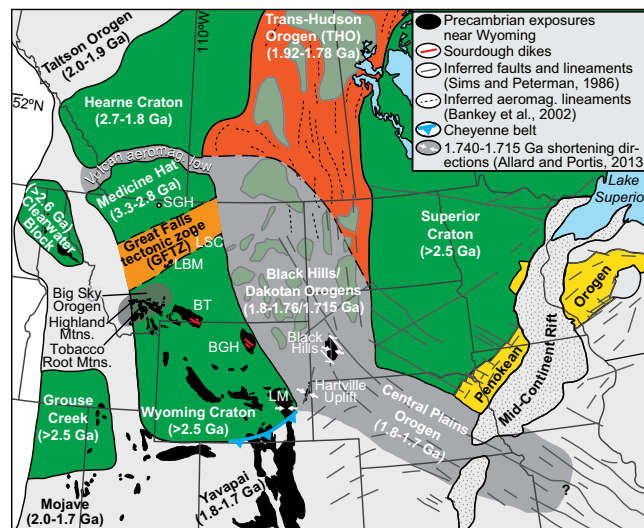
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margin come from syn-deformational pegmatites in northwest-vergent thrusts of the Hartville uplift directly dated at 1714 ± 2 Ma (U-Pb zircon; Krugh, 1997) and late deformational fabrics superimposed on Cheyenne belt metamorphism in the eastern Laramie Mountains (Wyoming) at 1722 ± 6 Ma ($^{207}Pb/^{206}Pb$ titanite; Allard, 2003). The Black Hills region (South Dakota and Wyoming) experienced WSW-ENE shortening (1.770–1.740 Ga; Allard and Portis, 2013; Dahl et al., 1999), WNW-ESE compression (1.740–1.715 Ga; Allard and Portis, 2013; Dahl et al., 2005), and thrust-related shear heating that produced the Harney Peak granite (Dahl et al., 1999; Nabelek and Liu, 1999) at 1.715 Ga (Redden et al., 1990). This tectonic history contrasts greatly with the timing of peak metamorphic conditions (ca. 1.81 Ga) for various locations of the THO (Ansdell et al., 2005).

On the northern margin of Wyoming craton is the Great Falls tectonic zone (GFTZ), a broadly defined and poorly exposed orogenic belt that connects the MHB to Wyoming craton (Fig. 1; Boerner et al., 1998). The Little Belt Mountains (Montana) host magmatic and deformational ages of ca. 1.87–1.86 Ga (Mueller et al., 2002), which are also prevalent in the Clearwater block in northern Idaho (Vervoort et al., 2016). Linear aeromagnetic anomalies within the GFTZ are truncated on their northeast end by north-south structures interpreted as part of the THO (Ross, 2002). Farther north, the prominent Vulcan aeromagnetic low (Fig. 1) is interpreted to be the suture between the MHB and Hearne craton (Eaton et al., 1999), and although there are no direct dates for this event, lower crustal xenoliths from the MHB are as young as 1.745 Ga (Davis et al., 1995).

Along the northwest margin of Wyoming craton (southwest portion of the GFTZ), the Highland Mountains (Montana) yield K-Ar and $^{40}Ar/^{39}Ar$ cooling ages from 1.8 to 1.7 Ga (Harlan et al., 1996; Mueller et al., 2005; Roberts et al., 2002), and the Tobacco Root Mountains (Montana) contain cooling ages from 1.78 to 1.70 Ga (Brady et al., 2004), defining the Big Sky orogeny (Harms et al., 2004; Condit et al., 2015). An abrupt end to the orogeny is documented by rapid cooling of the region; hornblende, biotite, monazite, and zircon all yield similar isotopic dates from 1.75 to 1.71 Ga (Brady et al., 2004; Cheney et al., 2004a, 2004b). Collisions in northern and eastern Wyoming thus occurred simultaneously, correlating the Big Sky event with tectonism in the east and in the MHB (Davis et al., 1995).

SOURDOUGH DIKES

Far from these Paleoproterozoic tectonic events on the margins of Wyoming craton, Laramide basement uplifts in the interior of the craton expose regions characterized by Proterozoic orogenic quiescence, interrupted only by

emplacement of numerous mafic dike swarms. Most of these are older than 2.0 Ga (Kilian et al., 2015), but herein we document one younger swarm. We name this the Sourdough swarm and present its paleomagnetic, trace element geochemistry, and U-Pb age results.

Field and laboratory methods are described in the GSA Data Repository[1]. The Sourdough dikes crop out in the central Bighorn and Beartooth uplifts where Laramide tilting is negligible. Most dikes have subophitic texture, dominated by plagioclase, pyroxene, and magnetite (with minor sericite), and typically have northwest-southeast trends (335°–290°) and widths ranging from 0.3 m to ~30 m. The vast majority of samples contain a single-component remanence held by (titano)magnetite. Principal component analysis (Fig. 2A) yielded notably steep northeast-down (or southwest-up) directions that are confirmed to record primary thermal remanence from the time of initial cooling by two positive baked-contact tests into older mafic dikes (see the Data Repository). Geochemical analysis of 15 Sourdough dikes yielded similar concentrations of

trace elements (Fig. 2). The slopes of the rare earth element (REE) patterns for all samples (Fig. 2C and 2D) are consistent, with only minor variation among mostly the light REEs. Collectively, the data suggest that all dikes represent the same magmatic event, with minor geochemical differences being the product of interactions with different crustal rocks.

All analyses of baddeleyite (U-Pb isotope dilution thermal ionization mass spectrometry [ID-TIMS]) from dike BH10 are within 1.7% of the concordia curve (N = 3); one analysis is concordant (Fig. 2B; see also the Data Repository). A linear regression of the data yields an upper intercept date of 1896 ± 3 Ma, with a weighted-mean $^{207}Pb/^{206}Pb$ date of 1899 ± 5 Ma. As the 2σ confidence intervals of each calculation method essentially overlap, we favor the more conservative weighted-mean $^{207}Pb/^{206}Pb$ date as the age estimate for BH10, 1899 ± 5 Ma. This age is applied to the primary magnetization of the Sourdough swarm; dike BH10 yielded typical paleomagnetic and geochemical results for the swarm.

WYOMING'S RUN

Incorporating the tectonic synthesis and new Sourdough swarm data presented above, we propose a novel hypothesis for the path of Wyoming craton toward its ultimate location within
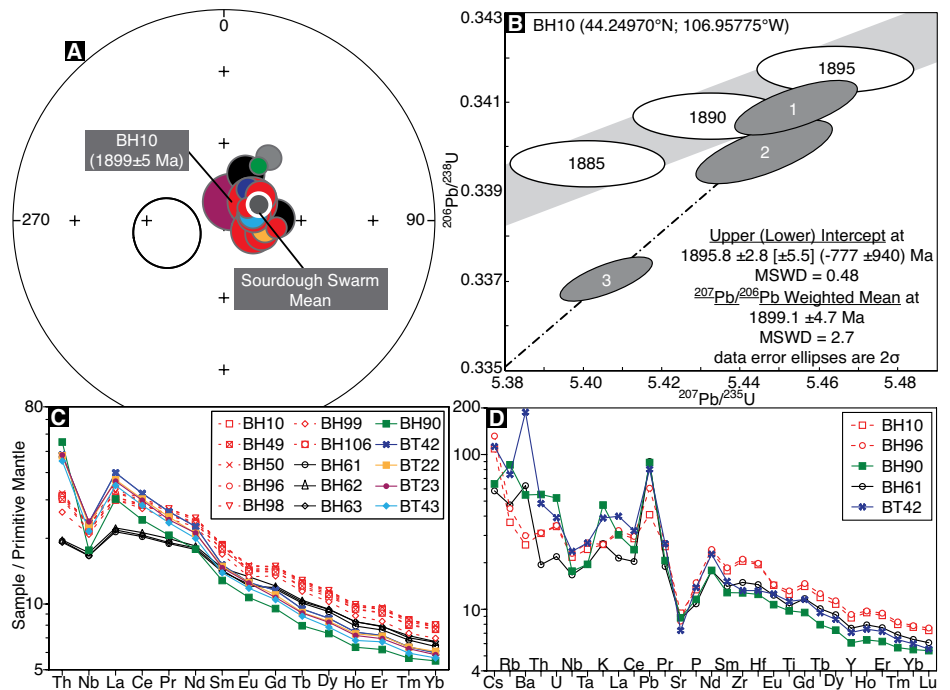
Figure 2. Paleomagnetic, geochronologic, and geochemical results for Sourdough dike swarm, Wyoming craton. A: Equal-area plot showing paleomagnetic results for 16 different mafic dikes, in local coordinates. Filled (open) ellipses indicate lower (upper) hemisphere directions; only one site (BH61) yielded negatively inclined results (i.e., upper hemisphere). Results are colored according to geochemistry (C) to show similarity in paleomagnetic results regardless of geochemical affinity. B: Concordia diagram of U-Pb (isotope dilution thermal ionization mass spectrometry) results for dike BH10 showing upper intercept date within error of preferred $^{207}Pb/^{206}Pb$ weighted-mean age of 1899 ± 5 Ma. Errors in square brackets include decay constant uncertainties. MSWD—mean square of weighted deviates. C,D: Primitive mantle–normalized trace element abundances for Sourdough dikes; C shows only immobile elements.

the North American cratonic collage. Wyoming began its independent journey after 2.15 Ga (Fig. 3A), when it was still connected to the southern margin of Superior craton as permitted by a coherent swath of 2.2–2.1 Ga paleomagnetic poles (Kilian et al., 2015). Assembly of Laurentia began with the collision of Slave and Rae cratons along the Thelon orogen at ca. 1.96 Ga (Hoffman, 1988), followed by the oblique collision of Hearne with Rae at ca. 1.9 Ga (Berman et al., 2007) at low paleolatitude (Mitchell et al., 2010) (Fig. 3B). Meanwhile, Superior occupied moderate paleolatitudes (Halls and Heaman, 2000) across the Manikewan Ocean. Our new paleomagnetic result from the Sourdough dikes also places Wyoming craton at mid-latitudes, and although numerous relative positions between Wyoming and Superior cratons are possible at ca. 1.90 Ga on the basis of the Sourdough dike paleolatitude (Fig. 3B; see caption), our favored position (position A in Fig. 3B) places them ~60° apart in arc length. This location allows the simplest drift path, with the smallest axial-plate rotation as Wyoming approached proto-Laurentia after rifting away from southern Superior (Kilian et al., 2015).

During development of the THO at 1.86–1.83 Ga, there were nearly simultaneous collisions in southern Superior (Penokean orogen) and northern Wyoming (GFTZ; Mueller et al., 2002), but there are no compelling reasons to connect these tectonically; in our model, Wyoming and Superior cratons are still separated by a wide ocean (Fig. 3C), so the collisions coincidentally overlap in age. Metamorphic ages from the Big Sky orogen (southwest Montana) and Cheyenne belt (southern Wyoming) indicate deformation from 1.78 to 1.72 Ga (Harms et al., 2004; Condit et al., 2015), which is largely absent in Superior craton and suggests their maintained separation at that time. Simultaneously, northwest Wyoming craton documents metamorphism possibly related to accretion on its western margin, which may have initiated movement toward Superior craton (Fig. 3C). The final suturing of Wyoming and Superior cratons, in our model, took place at 1.715 Ga, after the Yavapai and Penokean orogenies and before additional arc accretion occurred (e.g., Mazatzal province) along the entire southern margin of proto-Laurentia (Fig. 3D). The final assembly of Laurentia proposed herein is the precursor of supercontinent Nuna, which formed after 400 m.y. of successive cratonic amalgamations.

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Figure 3. Reconstructions through time based on paleomagnetic and geochronologic data from Wyoming (red), Superior (blue), and Slave (green) cratons; paleomagnetic poles, indicated by their 95% uncertainty circles, are color coded accordingly and labeled with their approximate ages (in Ma; Table DR3 [see footnote 1]). White arrows on cratons represent present-day north. Active sutures are colored yellow. Panels show Wyoming and Superior cratons as they rift apart in middle Paleoproterozoic time (A) only to reunite ~400 m.y. later in Laurentia (D) on opposite side of north pole. In B, allowed range of Wyoming reconstructions is plotted as gray small circle (with hypothetical positions and orientations shown with black outlines). Two reconstructions of Wyoming are labeled: our favored position (position A, in red) and "closest approach" reconstruction (position B). Latter requires overly complex series of rotations to spin Wyoming to other side of Superior prior to final amalgamation of Laurentia (D). Other possible landmasses are indicated by gray outlines, including Nuna configuration in C similar to that of Evans and Mitchell (2011). Dotted lines indicate areas of 1.74–1.65 Ga juvenile crust that accreted to or formed on southeastern Laurentia. GFTZ—Great Falls tectonic zone; THO—Trans-Hudson orogen.
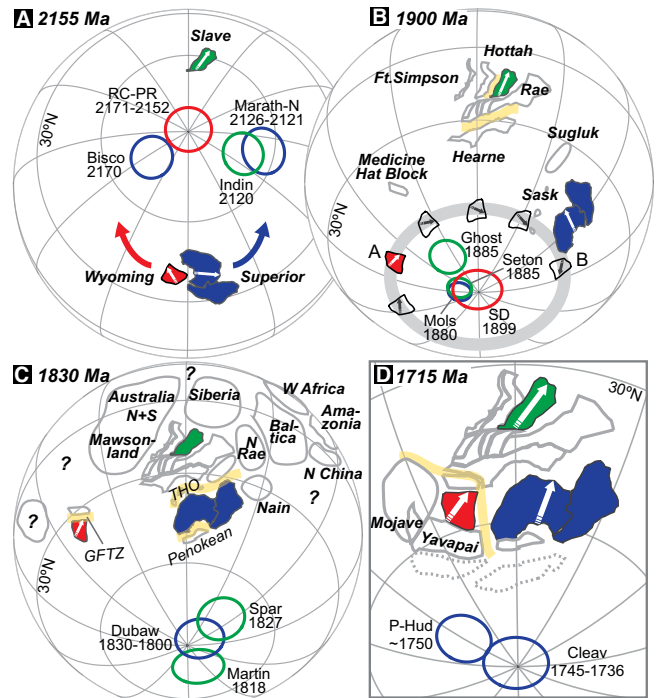
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