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PLATE TECTONICS BEFORE 2.0 Ga: EVIDENCE FROM PALEOMAGNETISM OF CRATONS WITHIN SUPERCONTINENT NUNA

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ABSTRACT. Laurentia, the core of Paleo- to Mesoproterozoic supercontinent Nuna, has remained largely intact since assembly 2.0 to 1.8 billion years ago [Ga]. For earlier times, previous paleomagnetic data on poorly dated Paleoproterozoic mafic intrusions yielded ambiguous estimates of the amount of separation between key cratons within Nuna such as the Slave and Superior. Recent developments in paleomagnetism and U-Pb baddeleyite geochronology, including new results reported herein, yield sufficiently precise data to generate partial apparent polar wander paths for both the Slave and Superior craton from 2.2 to 2.0 Ga. Our new apparent polar wander comparison confirms earlier speculations that processes similar to plate tectonics, with relative motion between the Slave and Superior cratons, were operative leading up to the final assembly of supercontinent Nuna.

Key words: Slave craton, Superior craton, Laurentia, U-Pb geochronology, paleomagnetism, plate tectonics

INTRODUCTION

Early work in Precambrian paleomagnetism and geochronology laid out the current analytical protocols for testing reconstructions and inferring the existence of plate motions in the Archean and early Paleoproterozoic (Irving and others, 1984) by comparing apparent polar wander (APW) paths (McGlynn and Irving, 1975) of Archean cratons within Laurentia. Although it was understood that constructing an APW path involved incorporating available geologic history (Dewey and Spall, 1975; Irving and Lapointe, 1975) the paleomagnetic and geochronological data were not able to support reconstruction hypotheses. Early Slave-Superior APW path comparisons were made (Cavanaugh and Seyfert, 1977), and subsequent work was careful to honor relative movement between cratons in earlier times, such as the distinction of the Slave and Rae cratons as independent drifters before amalgamation at 2.0 Ga (Cavanaugh and Nairn, 1980). Although early interpretative methods were commendably integrated with paleomagnetism, geochronological uncertainties remained substantial compared to modern standards.

The Archean cratons dispersed around the globe today were formerly independent microplates. Laurentia is home to an aggregate six cratons (fig. 1), more than any other continent with the exceptions of Africa and Eurasia. The major collisions that formed Laurentia occurred, arguably, at 1.97 Ga (Slave-Rae), 1.92 Ga (Hearne-Rae), 1.88 Ga (Slave-Hottah) 1.86 Ga (Superior-Nain), 1.85 Ga (Trans-Hudson and Penokean), 1.84 Ga (Medicine Hat-Hearne), and 1.74 Ga (Wyoming-Medicine Hat). The early Thelon suture connecting the Slave and Rae cratons put Slave near the growing

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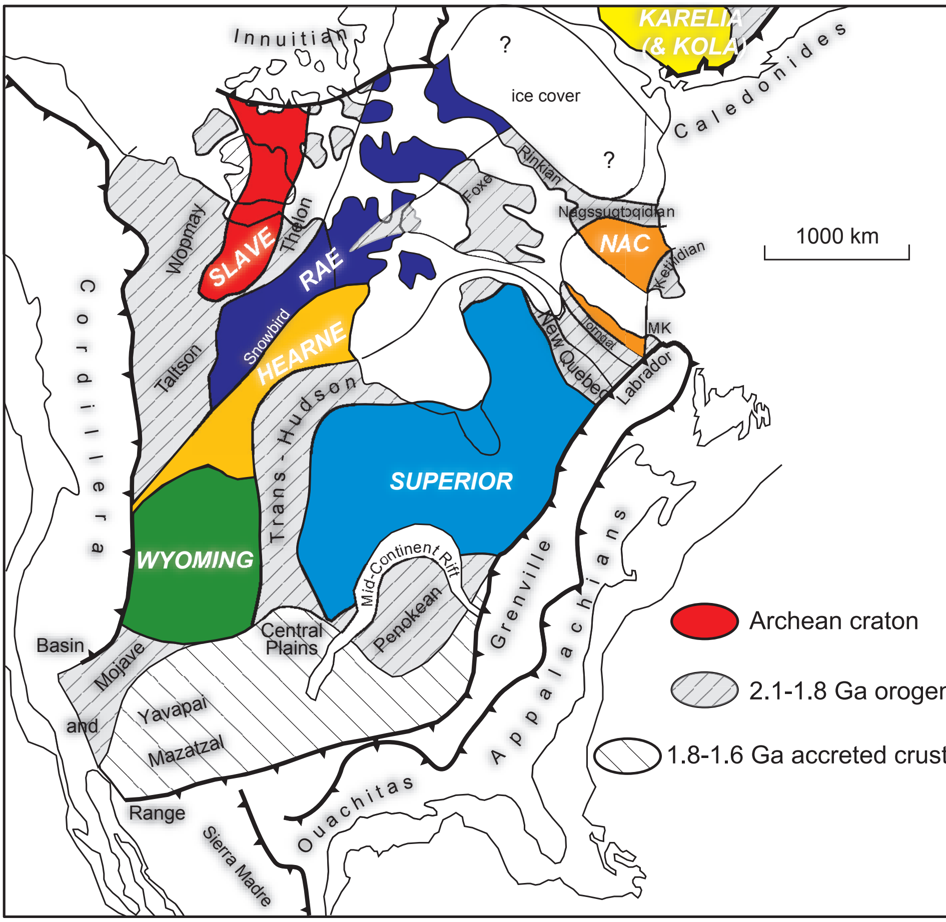

Fig. 1. Simplified geologic map of Laurentia featuring its Archean cratons. "NAC" is the North Atlantic craton, which includes the Nain province on the Labrador side. Modified from Hoffman (1988), and with Baltica placed into a configuration that is paleomagnetically viable (Evans and Mitchell, 2011).

center of the larger Nuna supercontinent (Evans and Mitchell, 2011). A strong case can be made for the Rae as the nucleus of proto-Laurentia. The Rae craton is bounded by the oldest sutures: 1.97 Ga to the NW (Thelon) and 1.92 Ga to the SE (Snowbird) (Berman and others, 2007; Martel and others, 2008; Hildebrand and others, 2010). Moreover, Rae was apparently on the upper plate for both of its bounding collisions, as well as for the younger Trans-Hudson convergence. All the other cratons were on the lower plate for terminal collision on at least one side—Superior on all sides. Dynamically, it would appear that long-lived subduction was focused beneath the Rae craton. The Slave and the Superior cratons are separated by at least three geosutures (Hoffman, 1988; Hoffman, 1997). Comparing APW paths of the Slave and Superior cratons, the "bookends" of the Laurentia continent (fig. 1), thus provides a clear geologic framework to test for pre-Nuna plate motions. Early paleomagnetic comparisons between the Slave and Superior cratons, however, were undermined by lack of age control and/or field tests for paleomagnetic reliability (Irving and Lapointe, 1975; McGlynn and Irving, 1975; McGlynn and others, 1975; Cavanaugh and Seyfert, 1977)

In the case of Superior during the pre-2.0 Ga interval, refined age control alone essentially reversed the APW path of earlier work (Buchan and others, 1993, 1994).

Recent methodological advances in both paleomagnetism and U-Pb geochronology allow the perennial question of relative cratonic movement in early geological time to be answered more definitively. Paleomagnetism has since adapted least-squares analytical techniques (Kirschvink, 1980) to unravel multiple components, and increasing emphasis has been placed on conducting field tests for primary remanence (Everitt and Clegg, 1962; Schwarz and others, 1985; Buchan, 2007). U-Pb geochronology has benefited from improved mineral separation techniques, allowing routine extraction of small amounts of baddeleyite (Söderlund and Johansson, 2002), which is a common trace mineral in unmetamorphosed mafic igneous rocks amenable to paleomagnetism. Paleomagnetic and geochronologic data can now be combined to yield datasets uniquely qualified to measure Precambrian plate motions.

We present a new precisely dated paleomagnetic pole for the 2193 Ma Dogrib dikes of the Slave craton. The Dogrib pole can be combined with those of the *ca.* 2025 Ma Lac de Gras dikes (Buchan and others, 2009) and the 2231 Ma Malley dikes (Buchan and others, 2012) to define a preliminary APW segment during 2.2 to 2.0 Ga for the Slave craton. Having an APW path for Slave, not just one or two poles, allows for comparisons at multiple well-calibrated ages with the better-resolved Superior craton APW path (Buchan and others, 2007; Evans and Halls, 2010) to be made. Our new comparison bolsters earlier speculations of divergent APW paths and confirms the suggestion that large-scale motions between Slave and Superior, and possibly other cratons, preceded assembly of Nuna, and that Slave and Superior are of unrelated ancestry (Bleeker, 2003).

GEOLOGIC BACKGROUND AND SAMPLING SUMMARY

Although the 1740 Ma Cleaver dike swarm (Irving and others, 2004) is the first intrusive event into the western margin of the Slave to be considered representative of proto-Laurentia at large, the dikes as currently mapped extend only as far as the Great Bear magmatic zone. At 1740 Ma, the Great Bear arc was part of the same plate as Slave craton, but was not part of the craton itself. Nd and Pb isotopes indicate no significant Archean component in the source of crust-derived igneous rocks in the Great Bear arc. Their source appears to be Paleoproterozoic crust of the newly accreted Hottah terrane (Hildebrand and others, 1987; Housh and others, 1989; Hildebrand and others, 2010). Kinematically, the Great Bear arc was tied to the Slave craton at 1740 Ma, but no more than it was locked to the Rae or the Hearne. What to call the composite craton (Slave-Rae-Hearne) that collided with the Superior ~1.85 Ga along the Trans-Hudson orogen? An appropriate name would be *Matonabbia*, for the Northern Indian guide, Matonabee, who led the first European (Samuel Hearne) across not one but all three cratons in 1771–1772.

Prior to Cleaver, numerous intrusions—1886 to 1884 Ma Ghost dikes, 1870 Ma Peninsular and Mara River sills, and 1901 Ma Hearne dikes, 2027 to 2023 Lac de Gras dikes, 2126 to 2108 Ma Indin dikes, 2193 Ma Dogrib dikes, and 2231 Ma Malley dikes—have been identified in the Slave craton (Bleeker and others, 2008a, 2008b; Buchan and others, 2009), only few of which, however, have both reliable geochronology and paleomagnetism (swarms depicted in fig. 2A). A cursory APW path could be drawn between poles for the Lac de Gras (Buchan and others, 2010) and Malley dikes (Buchan and others, 2012), but the untested Malley remanence is not regarded as a key pole.

Paleoproterozoic metamorphic conditions may have varied across the craton. In the autochthonous foreland of Wopmay orogen, as well as in the thin-skinned thrust-fold belt to the west, the grade of anchizonal-lower greenschist grade metamorphism is associated with the "Tree River" deformation (post-Hottah accretion, pre-conjugate transcurrent faulting) and highly variable on a length scale of 50 km

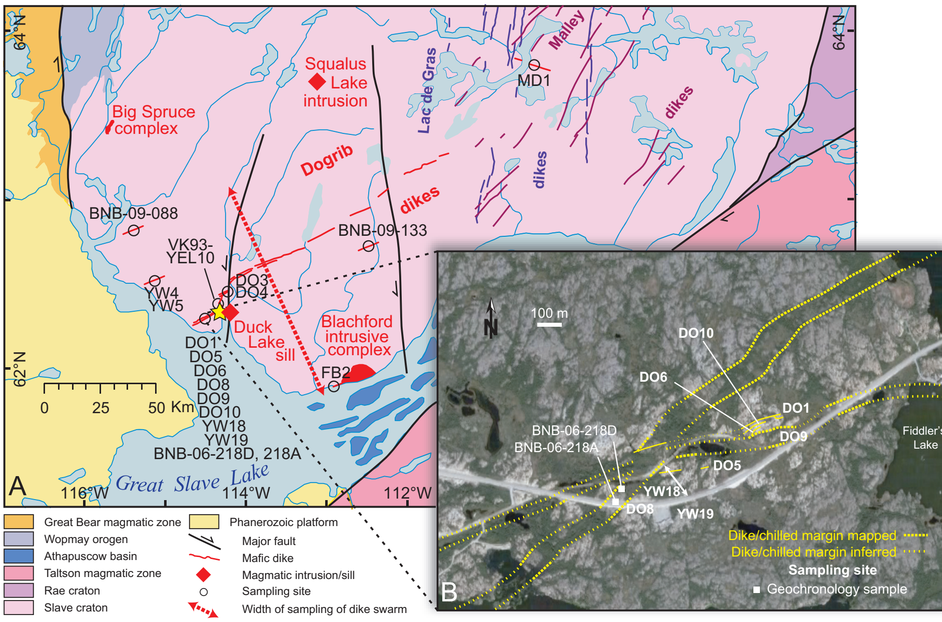

Fig. 2. Geology of Dogrib dikes and sampling sites. (A) Geologic map of magmatic events included in the *ca.* 2180 Ma Southwest Slave magmatic province (Bleeker and Hall, 2007). Modified from Buchan and others (2009). Star indicates town of Yellowknife. (B) Dike chilled margin contacts in host "Western Granodiorite" (Defeat Suite) superimposed on satellite photo of "Dogrib intersection" west of Yellowknife. Sampling sites are indicated, with descriptions and GPS locations (WGS84 datum) provided in tables 1 and 2. White arrows "YW18" indicate sampling profile in the host granodiorite for a paleomagnetic baked contact test, where "YW19" is the unbaked zone (see text and fig. 5C).

(Hoffman and others, 1988). Spatial variation in grade of metamorphism (illite crystallinity index) is strongly correlated with thick-skinned deformation (NW-SE shortening). Most locally relevant to our data, ^{40}Ar-^{39}Ar biotite and muscovite thermochronology of Archean rocks in the Yellowknife Domain indicate that regional temperatures have not exceeded ~300 °C since *ca.* 2.4 Ga (Bethune and others, 1999), suggesting the area is amenable to preserving primary thermoremanences in Paleoproterozoic dikes. Where field tests have been conducted they have been successful; for example, the primary, but as of yet under-sampled, remanence of northwest-trending Indin dikes, which crosscut the Dogrib dikes (Schwarz and others, 1985).

The Dogrib diabase intrusions comprise a relatively narrow swarm of dikes that trends east-northeast across southern Slave craton (fig. 2A). Dogrib diabase consists of approximately equal parts plagioclase and clinopyroxene, occasionally altered to mica and hornblende/chlorite, respectively (for example, fig. 3C). Just north of Yellowknife where northwest-trending, left-lateral transcurrent faults make the Dogrib dikes appear to jog, the two main large (50-100 m wide) Dogrib dikes were sampled extensively and in multiple locations for paleomagnetism by McGlynn and Irving (1975). One concern is that many measurements on only a few dikes may not average secular variation of the geomagnetic field (Carlut and others, 1999). Also, because sampling was limited to one structural domain (left-lateral) of a conjugate system, the consistent early Dogrib result did not assuage the concern that transcurrent faulting may have caused minor vertical-axis rotations to occur within the swarm. All the dikes (and blocks) of previous sampling could easily have experienced roughly the same rotation. Consistency would not be a measure of reliability. The only true test is to sample

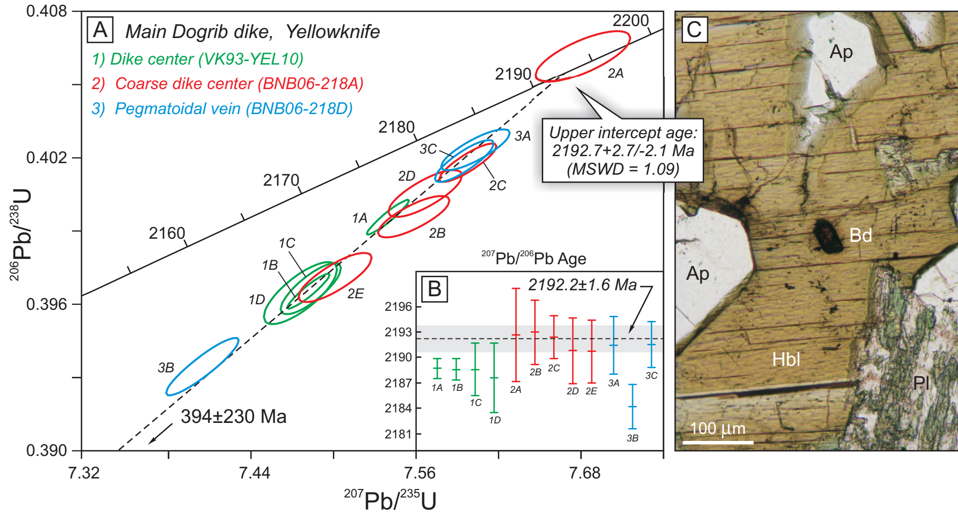

Fig. 3. U-Pb geochronologic results for the largest Dogrib dike. (A) Concordia diagram for baddeleyite from the center of the largest Dogrib dike (samples 1 and 2) and from a late-stage pegmatitic vein in the marginal zone (sample 3) showing upper and lower intercept ages for all fractions excluding 3B. (B) Plot of ^{207}Pb/^{206}Pb ages showing weighted average for four fractions 2A, 2C, 3A and 3C. See table 2 for geochronologic data. (C) Photomicrograph depicting a typically-sized baddeleyite (Bd) crystal included in late-magmatic hornblende (Hbl); also visible are chlorite-altered plagioclase (Pl), and apatite (Ap).

opposite domains (right- and left-lateral) or domains with and without faults. We re-sampled these two main dikes and 11 others—14 dikes in total including one from MacKay Lake (Buchan and others, 2012)—in an attempt to average geomagnetic secular variation and address the possibility of internal structural corrections that may apply. Of the newly sampled dikes, five are possible offshoots (or "companion dikes") of the two main dikes, but five come from more distant localities: Stagg Lake dike (BNB-09-088) to the northwest, Amacher Lake dike (BNB-09-133) to the northeast, Francois Bay dike (R10FB2) to the east, and two dikes north of the highway >30 km west of Yellowknife (R10YW4 and R10YW5) (fig. 2A; table 1). The sampled dikes cover a >100 km wide swath of the Dogrib swarm, and must represent at least seven independent intrusions or cooling units (that is, not including companion dikes).

Detailed mapping west of Fiddler's Lake (fig. 2B) reveals that the two main Dogrib dikes [see also Henderson (1985)] intersect each other at a low angle. Although the two dikes can be shown to have diagnostic widths, arguing for independent intrusion events, their relative ages cannot be discerned, which prevents us from conducting a dike-on-dike baked contact test (as we will see, because the dikes preserve the same geomagnetic polarity, such a test would have proven futile). The straightforward, low-angle geometry at the "Dogrib intersection" nonetheless is ideal for sampling a baked contact test profile into adjacent Archean country rock (fig. 2B). The host Defeat Suite plutons were the first tonalite-granodiorite plutons to intrude the *ca.* 2670 to 2660 Ma Burwash Formation, extensive turbidites blanketing the Yellowknife greenstone belt. Restricted to southern Slave craton, the Defeat suite spans several pulses from *ca.* 2630 to 2620 Ma, including the "Western Granodiorite" plutons that intruded into the basal Yellowknife greenstone belt west of Yellowknife, the 2628 ± 3 Ma Wool Bay diorite east of Yellowknife, and a small biotite tonalite stock yielding an age of 2624 ± 4 Ma at Watta Lake (Davis and Bleeker, 1999).

In order to establish whether the unbaked remanence in the baked contact test is consistent with expectations for the Defeat suite, we sampled paleomagnetic sites in

Table 1

Paleomagnetic sampling sites and directions

ID	Lat (°N)	Long (°E)	Dec (°)	Inc (°)	a95 (°)	n/N	k	Plat (°N)	Plong (°E)	A95 (°)	LN2 %	T_{unbl} (°C)
Dogrib dikes												
BNB-09-088	62.9254	244.4600	282	33	7	5/5	114	22	153	6	10	578
BNB-09-133	62.9069	247.4746	320	51	7	4/4	137	50	125	8	31	561
R10YW1	62.4604	245.4731	287	39	3	7/7	297	27	151	3	19	571
R10YW4	62.6465	244.7553	312	37	5	8/8	103	37	125	5	42	566
R10YW5	62.6465	244.7553	323	28	4	6/6	186	36	110	4	20	566
R08DO1	62.4605	245.4701	301	21	1	20/20	581	23	133	1	17	560
R08DO10	62.4600	245.4694	298	34	8	5/5	76	29	139	7	16	562
R08DO3	62.5979	245.6423	285	59	19	7/8	30	42	165	13	22	560
R08DO4	62.5931	245.6531	300	14	3	8/8	333	20	132	2	-	560
R08DO5	62.4581	245.4607	295	24	4	8/8	175	23	139	3	26	568
R08DO6	62.4600	245.4692	294	38	1	16/16	615	30	144	1	16	565
R08DO8	62.4567	245.4555	310	44	5	13/15	69	41	131	5	29	552
R08DO9	62.4595	245.4700	308	20	11	11/11	16	26	125	9	38	564
R10FB2	62.0347	247.1086	296.3	28	8	11/11	39	26	141	7	55	571
MD1	63.9555	249.7770	305	40	10	5/5	62	35	138	9	-	-
Defeat Suite "Western Granodiorite", "Pyroxenite", and "Wool Bay Diorite"												
R09YW19	62.4567	245.4630	2	-55	9	8/8	31	8	244	12	10	572
R08WG	62.4578	245.4434	8	-47.9	3	11/11	215	2	238.69	3	20	572
R08DS1	62.4722	245.6120	344	-37	8	6/8	65	-6	261	7	7	564
R08WGP	62.4861	245.2371	177	60	7	25/27	17	13	248	9	21	516
R08WBD2	62.3201	245.7668	18	-33	6	8/8	82	-8	229	5	5	557

Table 1
(continued)

	Trend ( )	Width (m)	Locality	Notes
Dogrib dikes				
BNB-09-088	072	~80-90	Stagg Lake	70 km northwest of main Dogrib dike
BNB-09-133	055-060	~40	Amacher Lake	Large columnar joints, 18-20 km south of main dated Dogrib dike
R10YW1	075	0.45	West of Fiddler's Lake	Crosscut by a 0.5-.0.6 m northeast-trending diabase dike
R10YW4	065	5.5	North of Highway 3	Plagioclase glomerocrysts
R10YW5	~065	0.29	North of Highway 3	Companion dike; plagioclase phenocrysts; vesicles filled with chlorite
R08DO1	085	1.5-2.5	West of Fiddler's Lake	Crosscut by a 0.24-m-wide northeast-trending diabase dike
R08DO10	065	0.50	West of Fiddler's Lake	Companion dike; 3 m north of R08DO6
R08DO3	~065	60-90	East of Ryan Lake	One of the two main Dogrib dikes
R08DO4	080	1	Milner/Ryan Lakes	Crosscuts metagabbro
R08DO5	070	0.97	West of Fiddler's Lake	Companion dike; >48 m south of the Dogrib intersection
R08DO6	065	1.7	West of Fiddler's Lake	Companion dike; 16.7 m north of R08DO9
R08DO8	~065	60-90	West of Fiddler's Lake	One of the two main Dogrib dikes
R08DO9	~065	50	West of Fiddler's Lake	One of the two main Dogrib dikes
R10FB2	062	90-100	Francois Bay	Both marginal and central dike sampled; once mapped as Caribou Lake gabbro
MD1	287	40	MacKay Lake	From Buchan and others (2012)
Defeat Suite "Western Granodiorite", "Pyroxenite", and "Wool Bay Diorite"				
R09YW19			West of Fiddler's Lake	Unbaked site for Dogrib contact test; across road from the Dogrib intersection
R08WG			North of Highway 3	Two phases of Western Granodiorite; 10.4 km west of Highway 2/3 intersection
R08DS1			Jack Fish pluton	Medium-grained granodiorite; just west of Highway 2/3 intersection
R08WGP			North of Highway 3	Pyroxenite layer in Western Granodiorite; 21.2 km west of Highway 2/3 intersection
R08WBD2			East Yellowknife Bay	Medium-grained, porphyritic diorite; near Duck Lake Sill in Wool Bay Diorite

Notes: Calculated mean paleomagnetic directions in this study and figure 5. ID = identification of sample number used in text and figures, Lat = latitude, Long = longitude, Dec = declination, Inc = inclination, a95 = radius of circle of 95% confidence, n/N = success ratio of samples collected, k = precision parameter, Plat = pole latitude, Plong = pole longitude, A95 = radius of circle of 95% confidence, LN2 = percentage of natural remanent magnetization lost during liquid nitrogen immersion, T_{unbl} = average unblocking temperature.

several different phases within the Defeat Suite. Broad similarity in paleomagnetic direction is found and helps support the baked contact test. Nonetheless, even though a mean direction is provided, both the limited sampling and the possibility that plutons have rotated about vertical axes obfuscate the calculation of a mean Archean paleomagnetic pole for the Slave craton at present. Also, the Dogrib dike contact test only serves as a positive "inverse" test for the Defeat Suite, meaning the Defeat Suite remanence is not proven to be primary, only acquired before Dogrib.

U-Pb GEOCHRONOLOGY

Baddeleyite crystals consist of flat, unaltered, tabular brown prisms, ~50 to 250 μm long by ~30 to 90 μm wide; they were not abraded prior to analysis. U-Pb analyses were carried out at the Geological Survey of Canada laboratory. Isotope dilution and thermal ionization mass spectrometry (ID-TIMS) for measuring U-Pb isotopes are based on techniques reported by Krogh (1973) with details and modifications outlined in Parrish and others (1987). Residual common Pb was subtracted using compositions estimated from the Stacey and Kramers (1975) model. Decay constants are those of Jaffey and others (1971). Data reduction and method of propagation of analytical uncertainties followed the numerical procedure of Roddick (1987). All errors quoted in the text and table 2 and error ellipses in the concordia diagrams are given at the 95 percent confidence level.

Isotopic analyses of baddeleyite grains from sample 1 were completed in 1995 with Pb blanks of 10 picogram, whereas those from samples 2 and 3 were analyzed in 2010 with Pb blanks of 1.0 picogram. Baddeleyite grains from sample 1 were weighed on a balance, whereas weights for samples 2 and 3 were computed using photographic imagery assuming a crystal depth aspect ratio of 0.2. Grains from sample 1 were separated using standard heavy mineral and magnetic susceptibility techniques for zircon separation at the Geological Survey of Canada. Grains from the other two samples were extracted at the Institute of Geology, University of Lund, Sweden, using the small sample "water based" technique of Söderlund and Johansson (2002).

U-Pb isotopic data are presented in table 2 and shown on a standard concordia diagram in figure 3A. Twelve fractions of baddeleyite, from the three different samples, form a linear array with individual fractions ranging from concordant to 2.5 percent discordant. The most discordant analysis (3B) has a slightly younger $^{207}Pb/^{206}Pb$ age compared to the other fractions and is excluded from linear regression analysis that yields upper and lower intercept ages of 2192.7 +2.7/−2.1 Ma and 394 ± 230 Ma, respectively, with a mean square of weighted deviates of 1.09. The four least-discordant fractions (2A, 2C, 3A and 3C) yield a weighted mean $^{207}Pb/^{206}Pb$ age of 2192.2 ± 1.6 Ma (fig. 3B). In view of the evidence for Pb loss slightly predating recent time, an age and uncertainty of 2193 ± 2 Ma are assigned to baddeleyite formation during late-stage crystallization of this high level mafic dike.

The larger of the two main Dogrib dikes (~80 m wide), well exposed in a road cut ~250 m southwest of the intersection locality west of Fiddler's Lake (fig. 2B), yielded baddeleyite from three different samples, yielding a precise age of 2193 ± 2 Ma (fig. 3; table 2), confirming preliminary analyses (Bleeker and others, 2007). Dogrib dikes are thus part of the *ca.* 2180 Ma Southwest Slave magmatic province (fig. 2A), along with the Big Spruce complex (2193 $^{+16}/_{-10}$ Ma), Duck Lake sill (2181 ± 2 Ma), Squalus Lake intrusion (2180 ± 1 Ma), and Blachford Lake igneous complex (*ca.* 2180 Ma) (Bleeker and Hall, 2007; Buchan and others, 2010).

PALEOMAGNETISM

Oriented paleomagnetic cores 2.54 cm in diameter were drilled on site using a portable, gasoline-powered, water-cooled diamond-tipped coring drill. Sun-compass observations were made whenever possible to check the magnetic compass, and to

Table 2

U/Pb geochronology sampling sites and results

Fraction[a]	Weight[b] (mg)	U (ppm)	Pb[c] (ppm)	Pb[d] (pg)	Isotopic ratios $^{206}Pb^{e}/^{204}Pb$	$^{208}Pb^{e}/^{206}Pb$	$^{207}Pb^{e}/^{235}U$	$^{206}Pb^{e}/^{238}U$	$^{207}Pb^{e}/^{206}Pb$	Ages (Ma) U-P ^{235}U	$^{206}Pb^{f}/^{238}U$	$^{207}Pb^{f}/^{206}Pb$	Disc[h]
1) VK93-YEL10: Dogrib dike (Z3669; 62.5169°N 114.3815°E)													
A	13	228	92	1	7087	0.04	7.538±0.10	0.3993±0.09	0.13693±0.03	2177.5±1.8	2165.6±3.3	2189±1	1.24
B	11	144	57	9	4283	0.03	7.480±0.10	0.3962±0.09	0.13692±0.04	2170.6±1.8	2151.6±3.3	2189±1	1.99
C	10	140	56	21	1036	0.04	7.482±0.15	0.3963±0.13	0.13692±0.09	2170.8±2.6	2152.1±4.8	2189±3	1.96
D	11	149	60	25	761	0.04	7.474±0.18	0.3961±0.16	0.13684±0.12	2169.9±3.2	2151.2±5.8	2188±4	1.95
2) BNB-06-218A: coarse-grained diabase from center of the largest (older) Dogrib dikes, west of Yellowknife (Z10251)													
A (3)	1	184	76	8	598	0.04	7.680±0.22	0.4058±0.13	0.13725±0.16	2194.2±4.0	2195.8±4.8	2193±6	-0.17
B (8)	1.5	118	48	5	819	0.02	7.557±0.17	0.3993±0.11	0.13727±0.11	2179.7±3.1	2165.7±3.9	2193±4	1.47
C (7)	1.5	138	56	4	1410	0.05	7.596±0.14	0.4015±0.10	0.13722±0.07	2184.4±2.5	2175.9±3.6	2192±3	0.89
D (7)	1.5	82	32	3	1030	0.04	7.565±0.18	0.4002±0.12	0.13709±0.11	2180.7±3.2	2170.0±4.4	2191±4	1.12
E (9)	1.5	88	34	3	908	0.03	7.499±0.18	0.3968±0.13	0.13708±0.11	2172.9±3.2	2154.2±4.6	2191±4	1.96
3) BNB-06-218D: very coarse (pegmatitic) veins from the same dike (Z10252)													
A (12)	2.5	156	64	10	1028	0.03	7.601±0.16	0.4020±0.10	0.13714±0.10	2185.0±2.9	2178.3±3.9	2191±3	0.71
B (10)	2.5	150	60	6	1554	0.04	7.403±0.18	0.3931±0.15	0.13657±0.07	2161.3±3.2	2137.3±5.5	2184±3	2.52
C (7)	2.5	108	44	3	1364	0.03	7.593±0.14	0.4016±0.11	0.13715±0.08	2184.1±2.5	2176.2±4.0	2192±3	0.82

Notes: U-Pb ID-TIMS baddeleyite data. [a] Number of grains in brackets, [b] Error on weight = ±1 mg, [c] Radiogenic Pb, [d] Total common Pb on analysis corrected for fractionation and spike, [e] Measured ratio corrected for spike and Pb fractionation of 0.09 ± 0.03 percent per AMU, [f] Corrected for blank Pb and U, common Pb, errors quoted are 2 in percent, [g] Age errors quoted are 2 in Ma, [h] Discordance in percent along a discordia to origin.

independently measure the local magnetic deviation, which, at ~17°E, is indistinguishable from the International Geomagnetic Reference Field model for the sites. Remanent magnetization measurements were made with a 2G Enterprises™ DC-SQuID magnetometer with background noise sensitivity of 5×10^{-12} Am^2 per axis at Yale University. The magnetometer is equipped with computer-controlled, on-line AF demagnetization coils and an automated vacuum pick-and-put sample-changing array (Kirschvink and others, 2008). Samples and instruments are housed in a magnetically shielded room with residual fields <100 nT throughout the demagnetization procedure and <5 nT in the measurement sense region.

After measurement of natural remanent magnetization (NRM), all samples were demagnetized cryogenically in a low-magnetic field-shielded liquid nitrogen bath in an attempt to help unblock larger multi-domain magnetite grains by "zero-field" cycling through the Verwey transition near 120 K (Muxworthy and Williams, 2006). Next, random magnetic field components possibly ascribable to sample transportation and handling overprints were removed from all samples with incremental alternating field demagnetization at 2, 4, 6, 8, and 10 mT. Finally, all samples were thermally demagnetized in ~25 steps, starting at 100 °C and going up to 578 °C (or until thoroughly demagnetized or unstable) in a magnetically-shielded furnace (±2 °C relative error) in a flowing nitrogen atmosphere. After each demagnetization step, automated three-axis measurements were made in both sample-up and sample-down orientations, and samples with circular standard deviation >10° were rerun manually. Magnetic components were computed for each sample using principal component analysis (Kirschvink, 1980) as implemented in PaleoMag OS X (Jones, 2002). Paleomagnetic poles from various previous works and this study are compiled in table 3 and compared using the software program Paleomac (Cogne, 2003).

Dogrib dikes are stably magnetized. Dogrib natural remanent magnetizations are composed of a strong remanent and a weak induced magnetization. Liquid nitrogen demagnetization, which can be considered a proxy for the percentage of natural remanent magnetization carried by multi-domain magnetite (Halgedahl and Jarrard, 1995), removes 26 ± 13 percent of the original intensities. A few samples at site R08D09 with abnormally high intensities indicative of a lightning strike are excluded from the mean calculation. A handful of samples from two dikes (R08DO9, BNB-09-133) gave southeast and moderately-down overprints, similar to observations by McGlynn and Irving (1975) on samples collected near dike margins. These southeast and down components likely represent *ca.* 1.75 Ga chemical overprints originating from fluid-flow following the Hudsonian orogeny (Irving and others, 2004). For the most part, however, Dogrib dikes carry a single-component, single-polarity remanence directed northwest and shallow-to-moderately-down that decays directly to the origin and is thus interpreted as the characteristic remanence. Unblocking temperatures are sharply defined at 564 ± 6 °C and suggest magnetite, with minor titanium contents, as the paleomagnetic carrier (figs. 4A-4C; table 1). Although originally mapped as Caribou Lake gabbro (Davidson, 1978), a 90 to 100 m wide dike to the southwest of the Blachford intrusive complex (R10FB2) shares a similar trend and paleomagnetic direction to those of the Dogrib dikes, representing the south eastern extent of the swarm. A northwest-trending dike at Mackay Lake, which also yields a characteristic Dogrib remanence (Buchan and others, 2012) and represents the northern extent of the swarm, would suggest a possible convergence of Dogrib dikes somewhere along the eastern (not western) margin of the Slave craton (Bleeker and others, 2012). The mean direction for 14 sites in approximately 14 unique Dogrib dikes is $D = 302°$, $I = 33°$ ($\alpha_{95} = 7$, $k = 34$), where D and I are declination and inclination, respectively, α_{95} is the radius of the 95 percent confidence circle, and k is the precision parameter (fig. 5A). The corresponding paleomagnetic pole is located at 31°S, 45°W ($A_{95} = 7°$, where

Table 3

Paleomagnetic poles for the Slave and Superior cratons (2.2-2.0 Ga)

Rock unit (remanence)	Age (Ma)	±	ID	Plat	Plong	A95	Reference
Minto dikes	1998	2	Min	30	183	13	Buchan and others (1998)
							Evans and Halls (2010)
Lac de Gras dikes	2029-2023	-	LdG	12	268	7	Buchan and others (2009)
Lac Esprit dikes	2069	1	LEs	53	181	6	Buchan and others (2007)
Fort Francis dikes	2076	4	FF	43	185	6	Halls (1986)
							Evans and Halls (2010)
Cauchon dikes	2091	2	Cau	54	181	8	Halls and Heaman (2000)
							Evans and Halls (2010)
Marathon dikes (reversed polarity)	ca. 2105	-	MaR	55	182	8	Buchan and others (1996)
							Halls and others (2008)
Marathon dikes (normal polarity)	2126	1	MaN	45	198	8	Buchan and others (1996)
							Halls and others (2008)
Biscotasing dikes	ca. 2170	-	Bis	20	232	7	Halls and others (2004)
Senneterre dikes	2216	6	Sen	-13	297	6	Buchan and others (1993)
Nipissing dikes and sills (N1)	2217	4	Nip	-16	286	10	Buchan (1991)
							Buchan and others (2000)
Dogrib dikes	2193	2	Dog	-31	315	7	this study
Malley dikes	2231	2	Mal	-51	310	7	Buchan and others (2012)

Notes: ID, identification for figure 6, Plat = pole latitude, Plong = pole longitude, A95 = circle with radius of 95% confidence. Superior poles are in western reference frame (calculated by Evans and Halls, 2010).

See text for discussion of selected polarities.

A_{95} is the radius of the 95% confidence circle). We note our Dogrib direction is essentially identical to that of McGlynn and Irving (1975); but by sampling the swarm more completely, we are able to more precisely quantify the uncertainty due to geomagnetic secular variation.

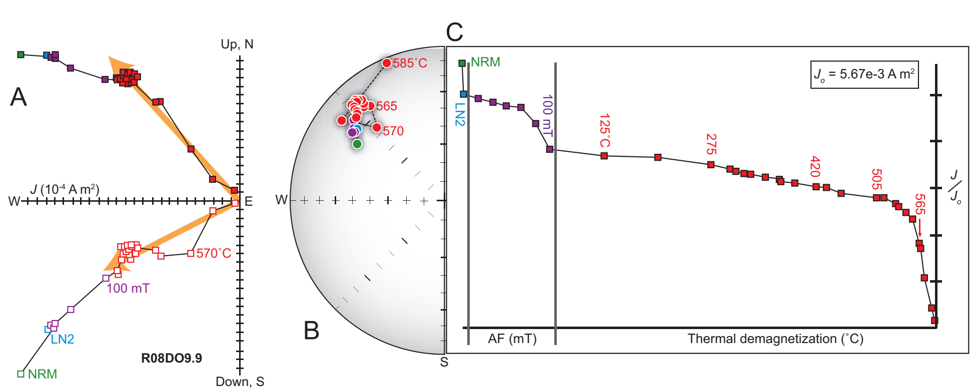

Fig. 4. Dogrib dikes demagnetization behavior. (A-C) Representative demagnetization behavior for a Dogrib dike (R08DO9.9): (A) orthogonal plot, (B) equal-area net, and (C) J_o/J intensity diagram.

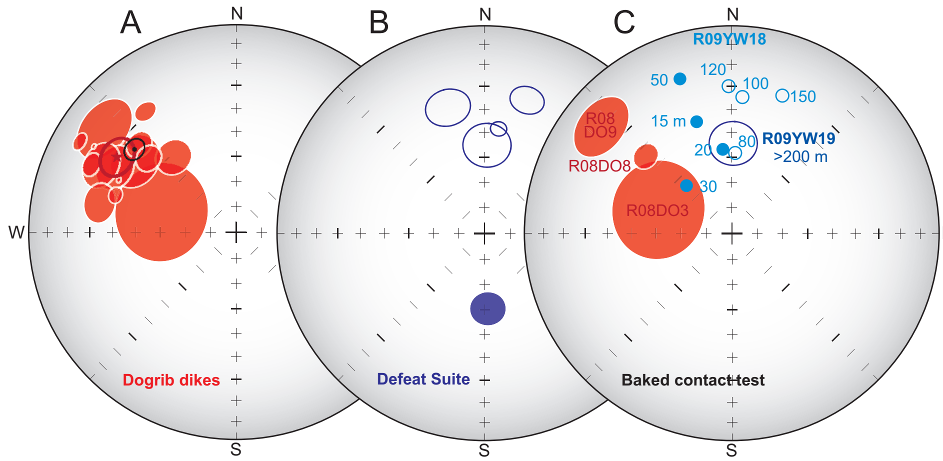

Fig. 5. Paleomagnetic directions. (A) Equal-area net of site averages from 2193 Ma Dogrib dikes (table 1), where the mean paleopole (star) is dark red and virtual geomagnetic poles are light red. In black, we include the mean from the previous work of McGlynn and Irving (1975) on the paleomagnetism of Dogrib dikes in the Yellowknife Domain, which is notably as accurate as our mean even without the application of the least-squares analytical routine (Kirschvink, 1980). The apparently increased precision of the early work compared to ours we attribute to an under-sampling of the true range of geomagnetic secular variation. See text for discussion. (B) Equal-area net of site averages of various phases of the *ca.* 2630–2620 Ma Defeat intrusive suite (table 1). (C) Equal-area net of positive baked contact test for Dogrib remanence into Defeat Suite granodiorite with baked and partially remagnetized zones (light blue; R09YW18; sample distance from Dogrib dike labeled in meters) and unbaked zone (dark blue; R09YW19 over 200 meters away). See text and figure 2B for details.

To test whether the characteristic remanence was acquired at the time of cooling, a baked contact test (Everitt and Clegg, 1962; Schwarz and others, 1985) was sampled along a profile south of the "Dogrib intersection" into the Defeat Suite "Western Granodiorite" pluton (fig. 2B). Approximately 250 m away from the Dogrib dikes (that is, >2-3× the dike width), in the unbaked zone, the Defeat granodiorite preserves a characteristic remanence broadly similar to those of other phases of Defeat Suite sampled elsewhere across the southern Slave Province (D = 002°, I = −47°, k = 30, α_{95} = 14°, n = 5 sites; table 1; fig. 5B). In a profile ranging from 15 to 150 meters from the "Dogrib intersection," evidence for partial remagnetization generally diminishes farther from the Dogrib dikes, where Defeat granodiorite remanences are almost completely remagnetized with the Dogrib direction closest to the dikes and arc over to a direction indistinguishable from the unbaked Defeat Suite with increasing distance from the large Dogrib dikes (fig. 5C). We do note with interest that the remanences along the profile jog back and forth between the endmember directions and do not follow perfectly the expected order according to distance. Possible explanations for this inconsistency could be host rock heterogeneity or, more likely, the fact that the relict remagnetization profile is actually the composite of two separate Dogrib intrusions of slightly different widths and orientations. In sum, successful identification of the baked, hybrid, and unbaked zones constitutes a complete positive baked-contact test, confirming that the Dogrib dike remanence is primary and may be used for paleogeographic purposes at the time of crystallization.

DISCUSSION

The 2193 Ma Dogrib dikes pole can be combined with those of the *ca.* 2025 Ma Lac de Gras dikes (Buchan and others, 2010) and the 2231 Ma Malley dikes (Buchan and others, 2012) to allow a robust comparison of Slave APW with that of Superior

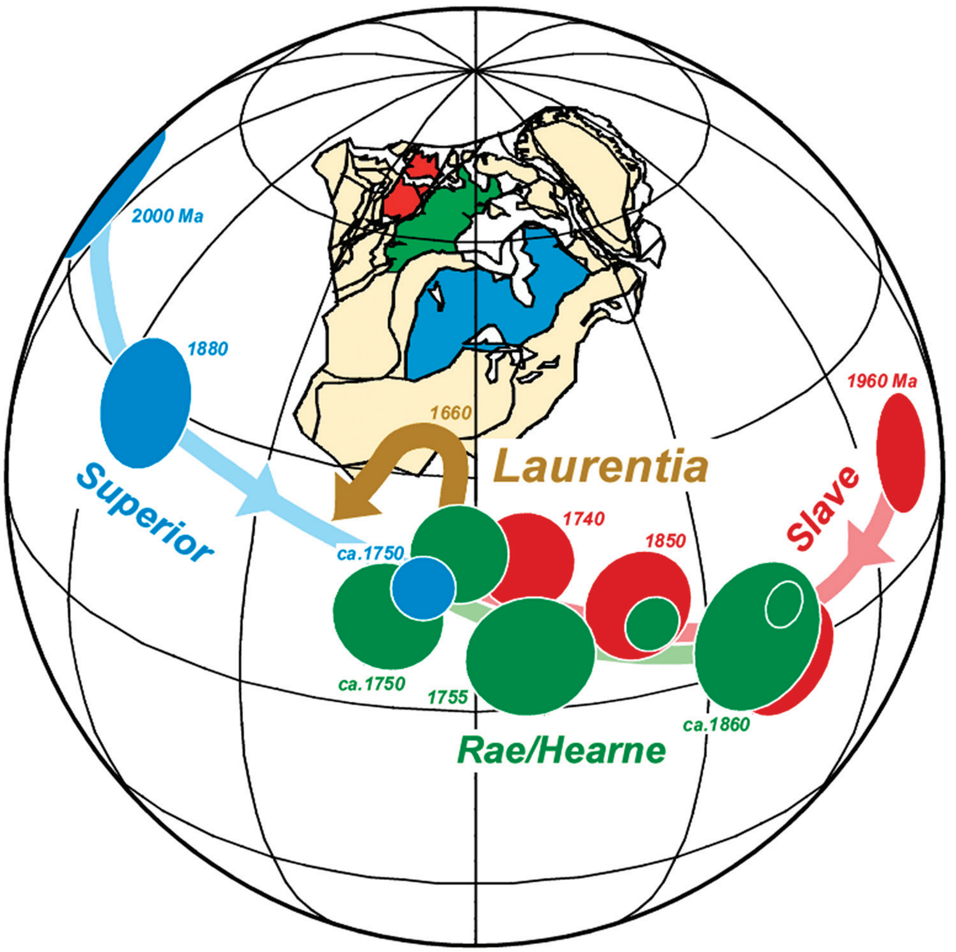

Fig. 6. APW path comparison and relative reconstruction of Slave and Superior cratons for 2.2–2.0 Ga where APW paths are plotted in present (North American) coordinates and need not be overlain and directly compared (fig. 7B). According to this interpretation, common APW signals are fortuitous and interpreted as tectonic motions (of incidentally similar amplitude and rate) and not as TPW. See text for comparison with the preferred interpretation presented in figure 7B.

(Buchan and others, 2007; Evans and Halls, 2010). This comparison is only valid under the assumption that the two paths contain a common APW signal, either 1) as part of a large single plate, or 2) due to true polar wander dominating the APW signal. A third possibility, based on just these data alone, is that the two paths have nothing in common and that their similar arc lengths over a similar amount of time are purely coincidental plate motions of similar latitudinal magnitude and rate. As an alternative to the assumption of common APW, figure 6 portrays the poles plotted in present-day coordinates (for example, Dunsmore and Symons (1990), albeit with a less reliable selection of available well-dated poles), where the APW paths appear to converge by *ca.* 1750 Ma. According to such an interpretation, the APW paths should not be directly compared until that final age of amalgamation. Instead assuming a common APW signal as we do herein, Buchan and others (2010, 2012) previously noted that the Lac de Gras and Malley poles from the Slave craton both plot off the Superior APW path,

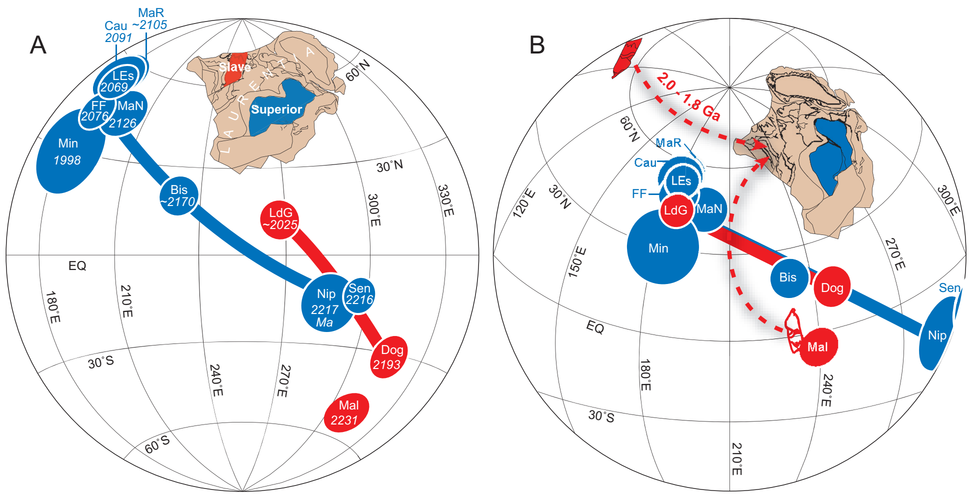

Fig. 7. APW path comparison and relative craton reconstruction of Slave and Superior cratons for 2.2–2.0 Ga. (A) The Superior craton APW path (blue) modified from Buchan and others (2007) by Evans and Halls (2010) to restore internal deformation (western reference frame used) and the Slave craton APW path (red) including poles for Lac de Gras dikes (Buchan and others, 2009) and Dogrib dikes (this study). Malley is not yet a key pole. Poles are in present-day coordinates (table 3). (B) Reconstruction of Slave relative to the Superior craton (using an Euler pole of 52°N, 356°E, −79°) which superimposes APW paths as shown. Also shown as a red outline (using an Euler pole of 35°S, 055°E, 176°) is the preferred reconstruction of Slave relative to the Superior craton where the polarity of the Dogrib and Malley dikes have been reversed.

hinting at relative movements between the two cratons before the *ca.* 2.0 to 1.8 Ga Nuna assembly (Hoffman, 1988) and thus implying that pre-Nuna APW paths should be developed independently for each constituent craton (Cavanaugh and Seyfert, 1977). The new Dogrib dikes pole similarly plots off the contemporary Superior APW path (fig. 7A), confirming that separation of these cratons is long-lived and that no convergence of poles occurred anytime during 2.2 to 2.0 Ga, immediately before assembly of Nuna was initiated with the Thelon suture at 1.97 Ga (Bowring and Grotzinger, 1992).

When we reconstruct the new Slave APW path relative to that of Superior, the separation between cratons is substantially larger than previously speculated (McGlynn and Irving, 1975). The closest age agreement between APW paths (not just individual pole comparisons) yields a ~90° separation between the cratons (fig. 7B). The older and untested Malley dikes pole from Slave tentatively suggests that this reconstruction does not hold farther back than 2.2 Ga, before which APW paths may diverge. Polarity of the Slave APW is suggested by trade wind orientations which constrain a northern hemisphere paleogeography (Hoffman and Grotzinger, 1993). Reconstructing Slave according to the other polarity option requires APW oscillations that are less parsimonious than the simple solution displayed in the figure. Although the polarity of the Superior craton at 2.2 to 2.0 Ga is unknown, because its APW path is well sampled only two reconstructions are possible. Irrespectively, both of the viable polarity options for the Superior APW path imply a similar distance from Slave (fig. 7B). New time-constrained paleomagnetic evidence from 2.2 to 2.0 Ga, therefore, shows that plate tectonic processes were operational prior to assembly of the Nuna supercontinent, earlier than previous evidence for relative motion back to *ca.* 1.8 Ga (Evans and Pisarevsky, 2008).

CONCLUSION

Combined U-Pb geochronologic and paleomagnetic study of the Dogrib dikes yields a well-dated pole for the Slave craton at 2193 Ma. The new age identifies a unique magmatic event on the craton. The new paleomagnetic pole is identical to early work, but more dikes have been sampled. The length and width of the Dogrib swarm are now mapped in more complete detail, which allows for proper paleomagnetic averaging of geomagnetic secular variation. The new result better estimates paleomagnetic uncertainty. Furthermore, the Dogrib pole is now proven to be primary by a detailed positive baked contact test.

A long-sought comparison between the Slave and Superior cratons can now be made before 2 Ga. Suitable for paleogeographic use, the Dogrib pole helps trace a crude APW segment for the Slave craton from *ca.* 2.2 to 2.0 Ga. The Superior craton APW path for the same period of time is well developed. We find that irrespective of polarity freedom, all reconstructions leave a large ~90° separation between Slave and Superior cratons, implying large-scale tectonic motions preceded the suturing of Laurentia. The large gulf between Slave and Superior cratons before 2 Ga could bring into question the likelihood of a "Kenorland" supercontinent (Williams and others, 1991), but the reconstruction comparison must be extended further back in Paleoproterozoic time to investigate this question.

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