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Coronation loop resurrected: Oscillatory apparent polar wander of Orosirian (2.05–1.8 Ga) paleomagnetic poles from Slave craton

Ross N. Mitchell[a,*], Paul F. Hoffman[b,c], David A.D. Evans[a]

[a] *Department of Geology & Geophysics, Yale University, 210 Whitney Ave, New Haven, CT 06511, USA*
[b] *Department of Earth & Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, MA 02138, USA*
[c] *School of Earth and Ocean Sciences, University of Victoria, Box 1700, Victoria, BC, Canada V8W 2Y2*

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ABSTRACT

The Coronation loop is a 110° arcuate sweep of 15 paleomagnetic poles with ages of ca. 1950–1850 Ma, derived from contemporaneous basins on the western (Coronation), southern (Great Slave) and eastern (Kilohigok) margins of the Slave craton in the northwestern Canadian shield. Although the paleomagnetic results are either demonstrated as primary or most parsimoniously interpreted as such, it is likely they were subsequently rotated shortly after deposition during conjugate transcurrent faulting along the conjugate McDonald (Great Slave) and Bathurst (Kilohigok) strike-slip fault systems. No rotation is expected of poles from the epicratonic Coronation margin. Previous analyses have debated the amounts of local rotations in the other basins, with one end-member view that the spread in paleomagnetic poles is entirely due to local rotations. Here we propose that, relative to the principal axis of compression for conjugate faulting, the far-field Bathurst and McDonald fault systems have rotated (equally and oppositely) 12° to widen an original 60° geometry to the present-day 84° angle. We rotate pre-1840 Ma poles from the immediate (~50 km) environs of these faults 12° CCW (Bathurst) and CW (McDonald). This simple structural retrodeformation brings time-correlative poles from the Kilohigok and Great Slave basins into agreement. As independent support for this modest amount of local rotations, paleocurrent measurements from the Great Slave basin, from sections interspersed among paleomagnetic sampling localities and elsewhere, indicate that large vertical-axis rotations have not taken place. Our restoration of the Coronation loop to Slave's cratonic reference frame slightly increases its angular sweep and implies rapid polar wandering that is irreconcilable with plate tectonic rates of motion. We interpret the Coronation loop as a signal of rapid, oscillatory true polar wander (TPW), which suggests that Archean-Paleoproterozoic supercratons modulated mantle topology in much the same manner as recent supercontinents Rodinia and Pangea.

1. Introduction

The Coronation loop (McGlynn and Irving, 1978) refers to a large sweep of Orosirian (2.05–1.80 Ga) paleomagnetic poles from the Slave craton (Fig. 1). The poles were obtained from redbed and volcanic rocks on the western (Coronation or Epworth basin), eastern (Kilohigok, formerly Goulburn, basin) and southern (Great Slave basin) margins of the craton (Fig. 2, Table 1). The Coronation loop was originally interpreted as the paleomagnetic signature of the Wopmay orogeny that affected the Coronation basin (McGlynn and Irving, 1978).

Although the raw paleomagnetic data sweep a 110° coplanar arc, a recent interpretation considers only a much tighter population of poles as primary and truly cratonic (Irving et al., 2004). The interpreted arc of Irving et al. is 60° shorter than the unfiltered Coronation loop, disregarding the oscillatory subloops inherent in the raw data (McGlynn and Irving, 1978). Irving et al. (2004) attribute poles at the ends of the Coronation loop to vertical-axis structural rotations of primary remanences during orogenic deformation. Vertical-axis rotations endemic to conjugate transcurrent faulting (Freund, 1970; Freund, 1974; Ron et al., 1984) are widespread in Wopmay orogen and related conjugate Bathurst and McDonald fault systems (Hoffman, 1980; Hoffman and Hall, 1988). However, Irving et al. (2004) did not attempt to make structural corrections (retrodeformations) on a site-by-site basis to test their attribution.

Here we reconsider the Coronation loop in light of plausible site-by-site structural corrections related to conjugate transcurrent faulting. We use published sedimentary paleocurrent data as an additional test of proposed differential vertical-axis rotations within the Great Slave basin (Bingham and Evans, 1976; Irving et al., 2004). We find that structural correction actually increases the amplitude of the Coronation loop, and we consider how it may

* Corresponding author. Tel.: +1 203 788 4149.
E-mail address: ross.mitchell@yale.edu (R.N. Mitchell).

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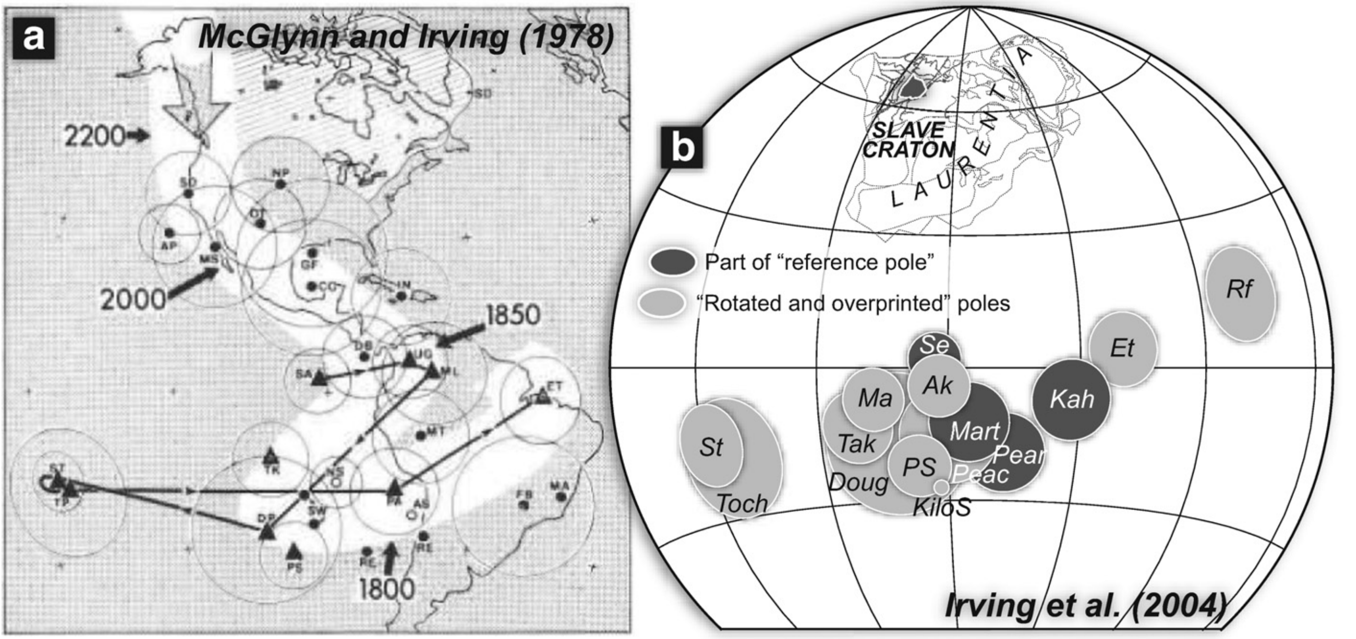

Fig. 1. The Coronation loop over the years. (a) Original conception of the Coronation loop (McGlynn and Irving, 1978). Note the Great Slave Supergroup poles, restored to a cratonic reference frame herein along with correlates: ST, Stark Formation; TP, Tochatwi Formation; DP, Douglass Peninsular; PS, Peninsular sill; TK, Takiyuak Formation; PA, Pearson Formation; ET, Et-Then Group. See original paper for identification of other (some outmoded) poles shown. (b) More recent interpretation (Irving et al., 2004) of the Coronation loop poles as either indicative of a stationary “reference pole” direction or of varying amounts and senses of rotation and/or overprinting.

have developed. We conclude that the rates and style of motions implied by the Coronation loop are best explained by rapid true polar wander (TPW).

2. Stratigraphy and correlation

Over half of the Orosirian paleopoles for the Slave craton that define the Coronation loop come from the Great Slave basin (Fig. 2), so we take a moment to sketch its stratigraphy in broad outline (Fig. 3; and, in Section 3, its paleocurrent indicators). The sedimentary, igneous and structural history of the basin is quite intricate (Bowring et al., 1984; Hoffman, 1970; Hoffman et al., 1977; Johnson, 1990; Ritts and Grotzinger, 1994), so the account that follows is highly generalized.

The oldest parts of the basin fill comprise southwesterly directed fluvial and shallow-marine clastic rocks of the (autochthonous) Sosan and (allochthonous) Wilson Island Groups (Johnson, 1990), the former being locally underlain by a variegated rift-basin sequence named the Union Island Group composed of sandy dolostone, organic-rich and maroon slates, and pillow basalt (dated correlative units are included in Table 1; Davis et al., 2004; Hoffman et al., in press; Roscoe et al., 1987). The Wilson Island Group contains bimodal volcanics dated at 1928 ± 11 Ma in its lower part, and it is intruded by an epizonal granite suite dated at 1895 ± 8 Ma (Bowring et al., 1984). (This paper only cites U–Pb ages and if no precision is provided the age has only heretofore been published in abstract without error bars.) The Sosan and Wilson Island clastics are interpreted as coextensive with the Bear Creek foredeep of the Kilohigok basin (Grotzinger and McCormick, 1988; McCormick and Grotzinger, 1992) and contemporaneous with collisional indentation of the Slave craton into the Taltson-Thelon magmatic zone (Johnson, 1990).

Flexural subsidence toward the southeast caused a major transgression and deposition of a sequence of red shale, red concretionary shale and green concretionary shale named the Kahochella Group, which is correlated with a similar shale-dominated sequence named the Recluse Group in the Coronation basin. A tuff dated at 1882 ± 4 Ma (Bowring and Grotzinger, 1992) exists near the base of the Recluse Group, and the shale sequence passes westward into axial turbidites of the collisional foredeep in front of the Hottah terrane (Hoffman, 1987b). The Recluse Group is correlated by sequence stratigraphy with the Peacock Hills Formation of the Kilohigok basin (Grotzinger and McCormick, 1988; Hildebrand et al., 2010; Hoffman and Grotzinger, 1993). Turbidites spilled from the collisional foredeep into the axial part of the Great Slave basin, contemporaneous with the construction of a carbonate platform, the Pethei Group, on the adjacent Slave craton (Sami and James, 1993). The Pethei Group has correlatives in the Coronation and Kilohigok basins, respectively named the Cowles Lake and Kuuvik Formations (Table 1).

In all three basins, the carbonate platforms and equivalent basinal strata are overlain by evaporite solution-collapse breccias (Cecile and Campbell, 1977; Hoffman et al., 1977; Hoffman and Grotzinger, 1993; Pope and Grotzinger, 2003), which grade into red lithic arenites of non-marine origin and westerly provenance, named the Takiyuak (Coronation), Tochatwi (Great Slave) and Brown Sound (Kilohigok) Formations (Table 1). In the Great Slave basin, the red lithic arenite is overlain by evaporitic ($CaSO_4$ + NaCl) siltstone and flood basalt (Pearson Formation), while the eastern Coronation and western Kilohigok basins were intruded by mafic Mara Sills dated at ca. 1870 Ma (Davis and Bleeker, 2007).

In the Great Slave basin, the axial and cratonic margin facies were telescoped by northwest-directed thrusting (Hoffman, 1980; Hoffman et al., 1977). A short time later they were intruded by quartz-diorite to quartz-monzonite laccoliths of the Compton Intrusive Suite (Badham, 1981; Hoffman et al., 1977). The laccoliths are broadly similar in age (1865 Ma), composition (calc-alkaline) and style of mineralization (U–Ag–magnetite–apatite veins) to early synvolcanic plutons of the subduction-related Great Bear magmatic zone of Wopmay orogen (Hildebrand et al., 1987, 2010).

The Compton laccoliths and all older rocks of the Great Slave basin are overlain unconformably by alluvial fanglomerate and fluvial sandstone of the Et-then Group, which was deposited contemporaneously with the McDonald Fault system (Hoffman

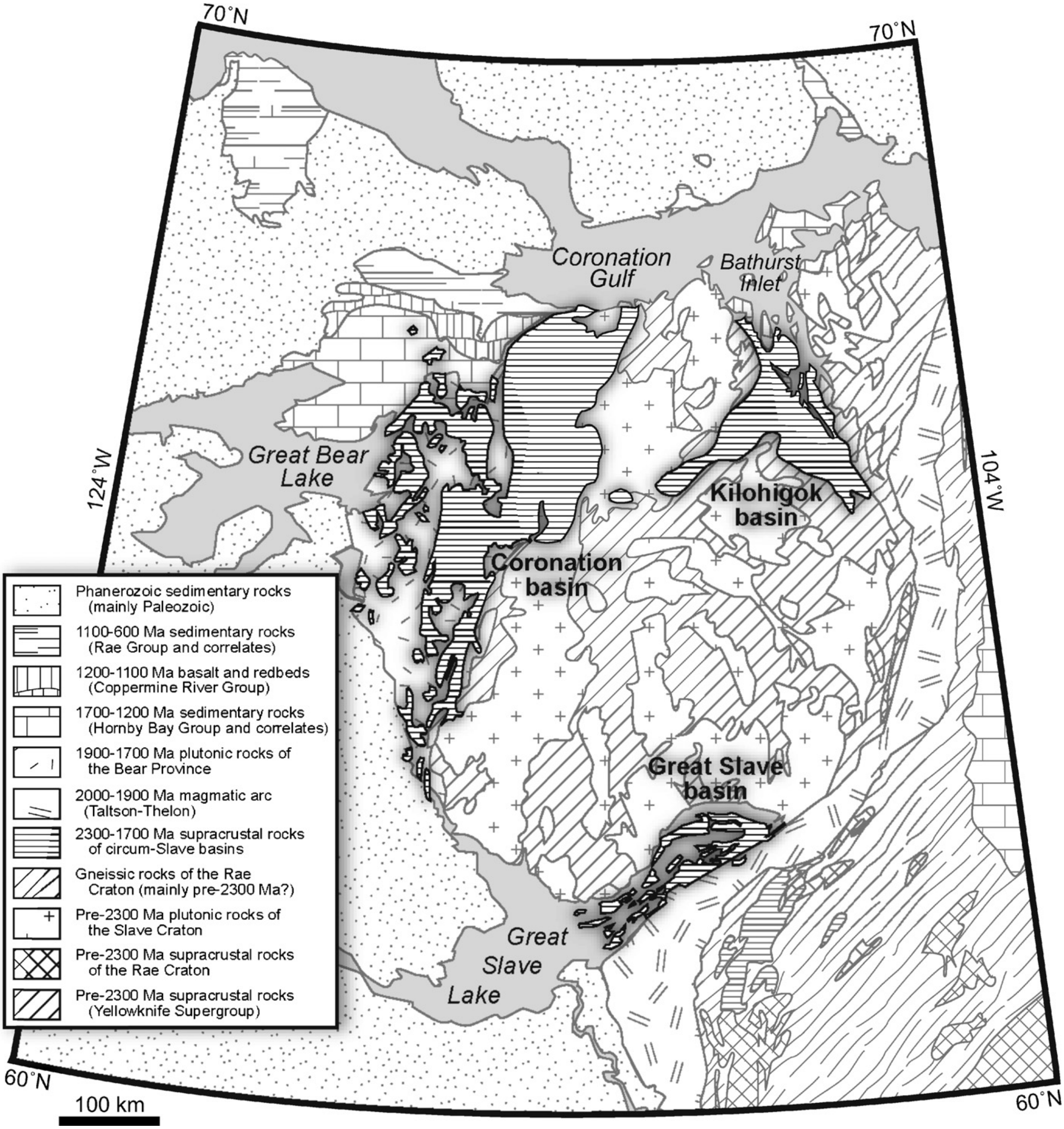

Fig. 2. Simplified geologic map of the northwestern corner of the Canadian Shield showing the three Orosirian, circum-Slave basins: Great Slave basin (of the Great Slave Supergroup) in the East Arm of Great Slave Lake, Kilohigok basin (formerly the Goulburn basin) south of Bathurst Inlet, and Coronation basin (formerly the Coronation Geosyncline) south of Coronation Gulf. Modified from Hoffman (1973).

et al., 1977; Ritts and Grotzinger, 1994). The Et-then Group is homologous with the fault-bounded Tinney Cove Formation of the Kilohigok basin (Campbell, 1978).

3. Paleocurrent test of local rotations within the Great Slave basin

Bingham and Evans (1976) observed that statistically indistinguishable paleopoles from the Stark (St) and Tochatwi (Toch) Formations fall to the west of those from correlative units outside the Great Slave basin, and from older and younger units within the basin (Fig. 1). They noted that 60° of anticlockwise-restored vertical-axis rotation would bring the two poles into agreement with the rest. They went on to suggest that a local clockwise structural vertical-axis rotation was responsible for the discrepant poles. Irving et al. (2004) follow this interpretation.

Bingham and Evans (1976) justified their suggestion by noting that poles to sedimentary layering in their tightly folded study area, north of the village of Snowdrift, define a girdle fabric, the subhorizontal axis of which trends ENE (108°), compared with the ENE

Table 1
Circum-Slave Paleoproterozoic basin correlation chart.

Wopmay orogen	Coronation basin	Great Slave basin	Kilohigok basin	Thelon orogen
Cleaver dikes (**1740 ± 5 Ma**)[a]				
Conjugate Fault system (Nahanni-Hottah collision)	Conjugate Fault system Unnamed	Macdonald Fault system ET-Then Group Preble Fm *Murky Fm*	Bathurst Fault system Tinney Cove Fm T_2 member T_1 member	Bathurst Fault system
Great Bear arc (**1878 – 1842 Ma**)[b]		Compton laccoliths (**1865 ± 15 Ma**)[c]		
	Peninsular sills (**1870 Ma**)[d]	*Pearson Fm basalts*	Mara River sills (**1870 Ma**)[d]	
	Takiyuak Fm Unnamed breccia	Christie Bay Group *Tochatwi Fm* *Stark Fm*	Amagok Fm Brown Sound Fm Omingmaktook Mb	
	Cowles Lake Fm	Pethei Group Pekanatui Fm Blanchet Fm McLean Fm *Douglas Peninsula Fm*	Kuuvik Fm	
Calderian foredeep (Hottah-Slave collision)	Recluse Group Morel sills Kikerk Fm (Asiak Fm) Fontano Fm (**1882 ± 4(1) Ma**)[e,f]	Kahochella Group Charlton Bay Fm McLeod Bay Fm Gibraltar Fm	*Peacock Hills Fm*	
	Ghost dikes (**1884 Ma**)[d]	*Seton Fm volcanics*	Bear Creek Group Quadyuk Fm	Bear Creek foredeep (Rae-Slave collision)
	Tree River Fm	Sosan group *Akaitcho River Fm* Kluziai Fm	*Mara River Fm* Burnside River Fm Link Fm	
Passive Margin	Epworth Group Rocknest Fm Odjick Fm	Duhamel Fm Hornby Channel Fm Wilson Island Group	Beechey Fm *Rifle Fm* (**1963 ± 6 Ma**)[e] Hackett Fm (**1969 ± 1 Ma**)[e]	
Initial rift	Cloos Nappe Stanbridge dolostone Drill arkose Vaillant basalt (**2015 ± 1 Ma**)[f]	Union Island Group	Kimerot Group Peg Fm Kenyon Fm (age relations uncertain) Booth River Complex (**2023 ± 3** and **2026 ± 1 Ma**)[g] Lac de Gras dikes (**2023 ± 2** and **2027 ± 4 Ma**)[h]	Passive Margin
Archean basement of Slave craton				

Notes: Italicized units have paleomagnetic poles that help define the Coronation loop. Geochronological constraints are in bold numbers.
[a] Irving et al. (2004).
[b] Hildebrand et al. (2010).
[c] Bowring et al. (1984).
[d] Davis and Bleeker (2007).
[e] Bowring and Grotzinger (1992).
[f] Hoffman et al. (in press).
[g] Roscoe et al. (1987) and Davis et al. (2004).
[h] Buchan et al. (2009).

(065°) trend of structures in the Great Slave basin as a whole. A local 43° (i.e. 108–65°) vertical-axis rotation would account for most of the needed 60° clockwise rotation.

Various deformation events could have caused the inferred vertical-axis rotation. The oldest was the evaporite solution-collapse that formed the Stark megabreccia. However, this seems unlikely because the Stark and Tochatwi Formations are relatively coherent structurally within the study area of Bingham and Evans (1976). Moreover, solution-collapse of the Stark Formation would not likely rotate both poles (St and Toch) uniformly as observed (Fig. 1). The next deformation was the northwest-directed thin-skinned thrusting responsible for the tight folds in the study area, which are developed above a thrust flat at the base of the Christie Bay Group (Fig. 2). Vertical-axis rotation could have occurred, for example, if the study area lay above an oblique thrust ramp. This possibility remains entirely hypothetical. Local

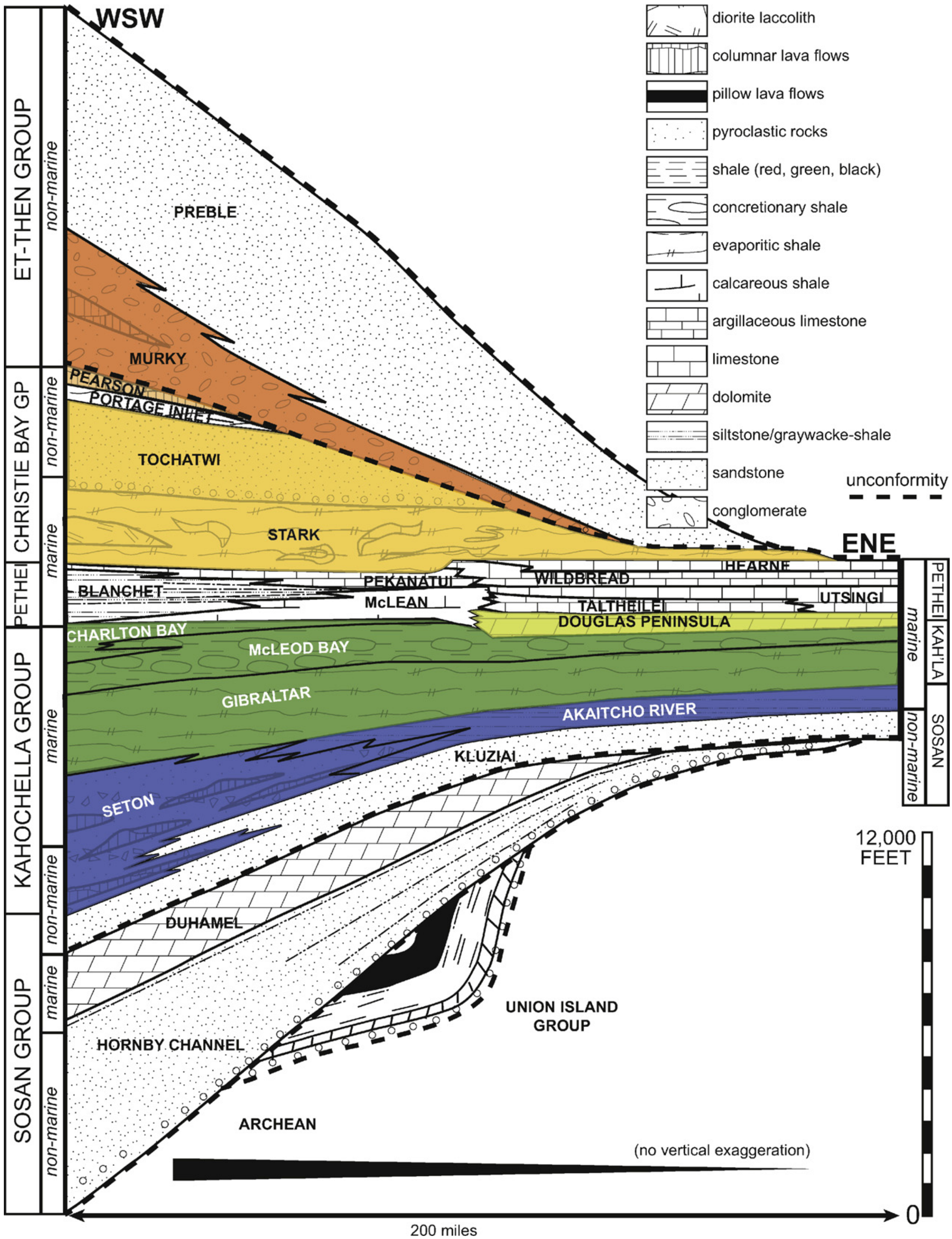

Fig. 3. Stratigraphic cross-section of Proterozoic Formations from the northeast to the southwest end of the East Arm Fold Belt (modified from Hoffman, 1969). Spectrum-colored units have yielded paleomagnetic poles that define the Coronation loop. These same color associations remain in subsequent figures in order to illustrate superposition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

clockwise vertical-axis rotations could have occurred within the right-lateral McDonald Fault system. However, the study area lies 15 km outside the fault zone and structures closer to the fault zone in the same area have normal (~065°) trends. Localized deformation also occurred when the Compton laccoliths were emplaced, after thrusting but before transcurrent faulting. The deformation stems from the elliptical shapes of the laccoliths and their displacive mode of emplacement by magmatic inflation from floors

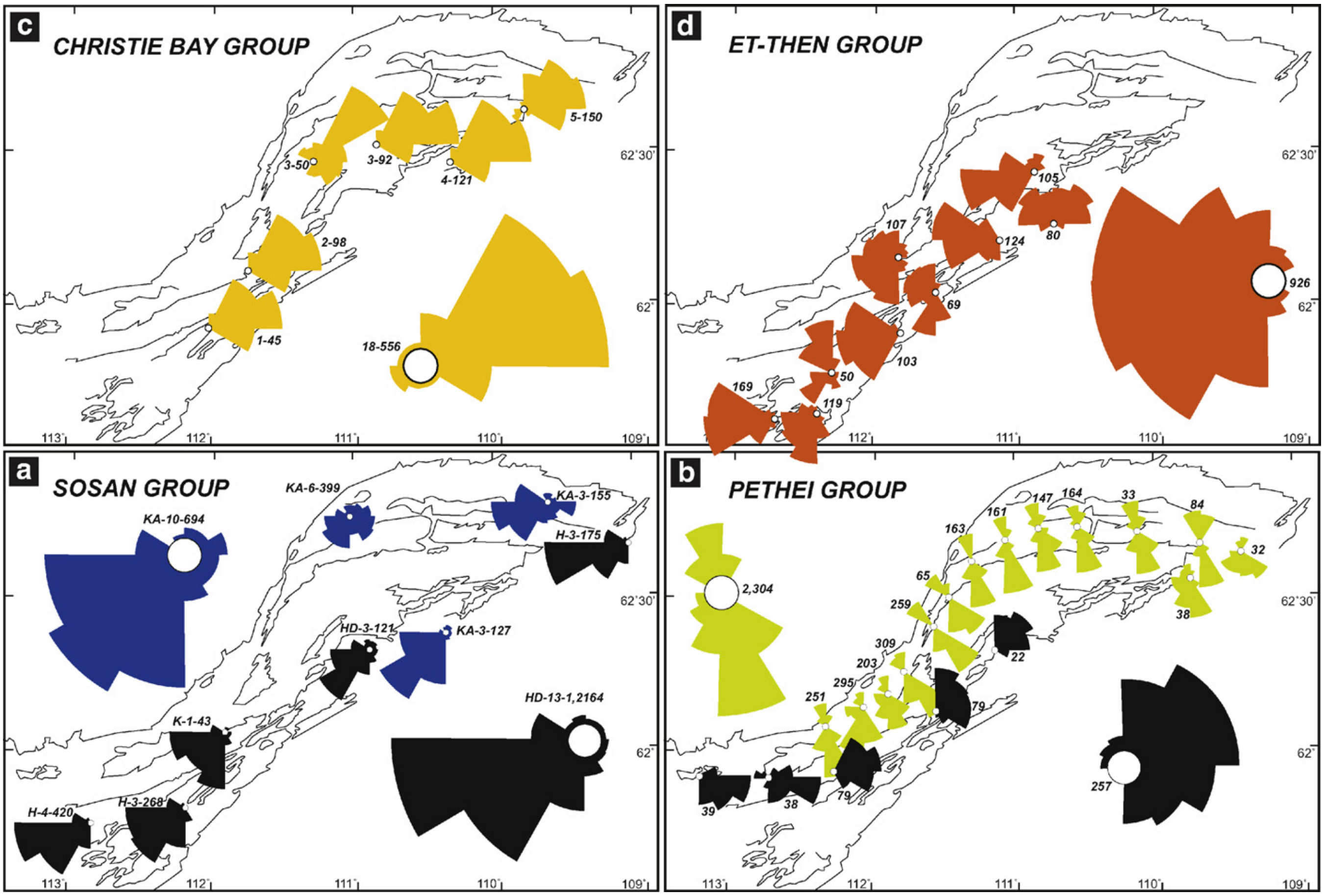

Fig. 4. Summary of over 12,000 measured paleocurrent indicators in the four major sandstone units (a) Sosan, (b) Pethei, (c) Christie Bay, and (d) Et-Then Groups and (b) carbonate platform Pethei Group of the Great Slave Supergroup in the Great Slave basin. Pethei Group has both basin and platform paleocurrent indicators. Large rose diagrams are summaries of all sites in each panel. Single number indicates number of measurements. Two numbers indicate, first, number of sites, second, number of measurements. Same color associations as Fig. 3. Modified from Hoffman (1969). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

typically controlled stratigraphically by the contact between the Pethei and Christie Bay Groups. In particular, the large laccolith on the mainland west of Snowdrift quite possibly extends northward beneath Et-then Group cover toward the study area, where no laccolith exposure exists.

Paleocurrent data (Hoffman, 1969) from the Tochatwi Formation (Fig. 4), assumed to be originally aligned within the formation and basin, allow a quantitative test of the proposed vertical-axis rotation, which would, if present, rotate paleocurrent azimuths away from even broad agreement. The data are based on large-scale planar crossbeds which, because the folds are subhorizontal, were tilt-corrected simply by rotation around the strikes of bedding. In Fig. 4, paleocurrent directions from the study area of Evans and Bingham (1976) correspond to individual rose diagrams 3–92 (their F-section) and 4–121 (their N-section). The mean direction for those sites is rotated clockwise relative to the overall Tochatwi data-set (556 crossbeds from 18 sites), but the amount of rotation is small (Fig. 4). It is a far cry from the 60° required to bring the Stark and Tochatwi paleopoles into compliance (Bingham and Evans, 1976; Irving et al., 2004). Von Mises statistics (pp. 88–89 in Fisher, 1993) show quantitatively that those paleocurrents from the paleomagnetic sample locations of Evans and Bingham (1976) are statistically indistinguishable from those within distant sites (Table 2). We conclude that the separation of the Stark and Tochatwi

Table 2
Von Mises statistics of Tochatwi Formation paleocurrents.

Section	*N* (mode)	kappaML	Mean az°	±	Rose (H69)
84 North East Stark Lake	26	7.2	049	9	4–121
109 Christie Bay (Northeast of Redcliff Island)	38	4.9	049	9	3–50
83 Stark Lake	**43**	**6.4**	**054**	**7**	**4–121**
03 Pointe-a-Tuer	34	4.0	057	10	1–45
107 Tochatwi Bay (South of Wildbread Bay)	29	8.8	057	7	5–150
108 Tochatwi Bay	28	6.6	058	9	5–150
105 East of Pearson Pt	**41**	**22.4**	**059**	**4**	**3–92**
102 Pearson Point	**48**	**14.0**	**072**	**4**	**3–92**
111 East end Tochatwi Bay	36	10.0	074	6	5–150
113 Isl. in Tochatwi Bay (S of Wildbread Bay)	22	33.1	076	4	5–150
106 Christie Bay (South of Fortress Island)	25	8.2	085	8	3–92

Notes: Bold sections are proximal to paleomagnetic sampling sites; kappaML is measure of precision (Fisher, 1993); mean az° is mean azimuth; (±) 95% confidence; rose (H69) refers to rose diagrams in Fig. 7 of Hoffman (1969).

paleopoles from others in the Coronation loop is not a trivial consequence of local rotations at the sampling localities.

4. Conjugate transcurrent faulting and vertical-axis rotations

Most paleomagnetic studies hoping to resolve vertical-axis rotations first designate a reference pole with which to compare anomalous, possibly rotated paleomagnetic poles (c.f., chapter 11 of Butler, 1992). The reference pole approach is applied successfully to neotectonic and younger Phanerozoic tectonic settings with short time scales ($\ll$100 million years) and well-sampled apparent polar wander (APW) paths. Such applications satisfy a central assumption of the reference pole method: that non-detectable amounts of APW took place between the age of the reference pole and the age of the anomalous pole(s).

The Orosirian period (2050–1800 Ma) is not likely to be characterized by a single reference pole—an average plate motion rate of ~3 cm/yr would generate a minimum of 75° apparent polar wander. Furthermore, its 250-million year duration is sampled at much lower resolution than those of more recent times. Instead of the reference pole method, we conversely let structural kinematics determine the senses and magnitudes of vertical-axis rotations with respect to non-rotated parts of Slave craton.

4.1. Conjugate transcurrent faulting in Wopmay orogen

A conjugate system of vertical NE-right-slip and NW-left-slip fault domains accommodated as much as 15% west–east shortening and north–south extension in Wopmay orogen (Hoffman, 1980; Hoffman and Hall, 1988; Hoffman et al., 1983; Tirrul, 1992). Conjugate faulting post-dates the youngest intrusions of the Great Bear magmatic arc, dated ~1840 Ma (Hoffman and Bowring, 1984), and pre-dates the 1740-Ma Cleaver dike swarm (Irving et al., 2004). The tentative cause of the horizontal plane strain is the terminal collision in the Wopmay orogen, located in the subsurface between the Great Bear and Fort Simpson magmatic arcs via aeromagnetic and gravity field interpretation, deep seismic reflection sounding, and drill-core U–Pb zircon dating (Cook et al., 2005; Cook et al., 1999; Hoffman, 1980; Hoffman, 1987a).

Conjugate transcurrent faults accommodate slip by means of block rotation (Fig. 5a) (Freund, 1970; Freund, 1974). Blocks (and faults) rotate around the vertical toward the principal axis of extension. The amount of rotation (r) is related to fault-displacement (d) and spacing (w) according to the following relation (Freund, 1970):

$$\sin r = \frac{d[\cos i \cdot \cos(i+r)]}{w}$$

where i is the initial or failure angle of the fault set. Right- and left-slip faults are generally segregated into domains. Toward domain boundaries, faults lose slip in different ways: by loss of rotation (sigmoidal faults), by multiple splays, or by conjugate branching. Fault rotation does not exceed 45°. After blocks have rotated 45° additional strain is accommodated by new fault sets at the angle (i) favored for slip (Fig. 5b) (Nur et al., 1986). The aforementioned work finds examples of such large rotations, such as the Sistan fault in southeast Iran. Where rheological layering is steeply inclined, layer-parallel shear zones develop when layers rotate into orientations favorable for conjugate slip. This is well displayed in the western part of the Coronation basin (Hoffman and Tirrul, 1994).

In Wopmay orogen, right-slip domains greatly predominate over left-slip domains (Fig. 5c), yet in the foreland thrust-fold belt where fault behavior is well constrained, right- and left-slip domains have rotated symmetrically with respect to the principal irrotational axis of compression (σ_1), oriented 266–086° (Fig. 5e) (Tirrul, 1992). This is confirmed by symmetrical clockwise and anticlockwise rotations of pre-fault (Calderian) thrusts and folds relative to their non-rotated orientation in the northeastern part of the thrust-fold belt, where transcurrent faults are absent (Hoffman and Tirrul, 1994).

4.2. Conjugate Bathurst and MacDonald fault systems

Gibb (1978) proposed that the Bathurst (left-slip) and McDonald (right-slip) fault systems (Fig. 5d) form a conjugate pair related to plane indentation associated with collision between the Slave and "Churchill" (Rae + Hearne) cratons (see also Tirrul and Grotzinger, 1990). As the indentor was assumed to be rigid, no rotation of the fault systems was envisioned. Hoffman (1980) speculated that the conjugate pair developed as a far-field consequence of terminal collision in Wopmay orogen, and triggered the Dubawnt volcanism beyond the apex of the indentor (Fig. 5d). The age of the Dubawnt Supergroup of 1.84–1.75 Ga (Rainbird and Davis, 2007) snugly fits the age constraints on conjugate faulting in Wopmay orogen of 1.84 and 1.74 Ga (see above).

Slave-Rae collision and indentation gave rise to the lower clastics of the Great Slave Lake basin (Wilson Island and Sosan Groups) and correlatives in the Kilohigok and Coronation basins (Table 1), which were derived from its erosion (Fig. 4a). Conjugate faulting occurred later, after Wopmay orogen had become the major source of clastic input into the Great Slave basin (Fig. 4b and c). However, crustal thickening in the Taltson-Thelon orogen is indicated by provenance studies and sediment transport directions in the fluviatile upper Et-Then Group (Fig. 4d) and Tinney Cove Formation (Campbell, 1978), which were deposited contemporaneously with the McDonald and Bathurst Fault systems, respectively. Non-plane strain reactivation of the 130+ Myr-old (1.97 Ga) Slave-Rae collision zone at the time of Bathurst–McDonald conjugate faulting (1.84–1.74 Ga) is independently supported by a strong mode of 2.0–1.9-Ga detrital zircon ages diagnostic of the Taltson-Thelon magmatic zone in the middle–upper (Whart sequence) Dubawnt Supergroup (Rainbird and Davis, 2007). Accordingly, far-field consequences of the terminal Wopmay collision include both conjugate faulting and dip-slip reactivation of the Slave-Rae collision zone.

The present azimuth of the Bathurst Fault system is 328°, and that of the McDonald Fault system is 244° (Fig. 5d). The 84° angle between them is larger than ~60° expected from Coulomb theory (Anderson, 1951), implying ~24° of outward rotation between the two fault systems. Can we assume that they rotated symmetrically like the conjugate fault domains in Wopmay orogen (Fig. 5e)? Estimates of left-slip on the Bathurst Fault system are 48 km, based on brittle offsets of aeromagnetic anomalies (Henderson et al., 1990; Thomas et al., 1976), and 115 km from tectonostratigraphic restoration of the Kilohigok basin, incorporating brittle and ductile deformation on the Bathurst Fault system (Tirrul and Grotzinger, 1990). Estimated right-slip on the McDonald Fault system (Fig. 5f) is 70 or 125 km, based on magnetic anomalies (Thomas et al., 1976), and 70–90 km from geological restorations across the McDonald-Wilson Fault strand (Hoffman et al., 1977). The large uncertainty for the McDonald Fault system stems from its subparallel orientation with respect to older structures used as piercing points to estimate displacement. In any event, the relationship between fault slip and fault rotation is less quantitative for solitary faults than for fault domains, because rigid-block behavior does not strictly apply in the former case. If the two fault systems experienced equal rotation, the principal axis of compression would have been oriented 286°, which is 20° clockwise of the same principal axis in Wopmay orogen (Fig. 5c and d). Alternatively, if the principal axis is

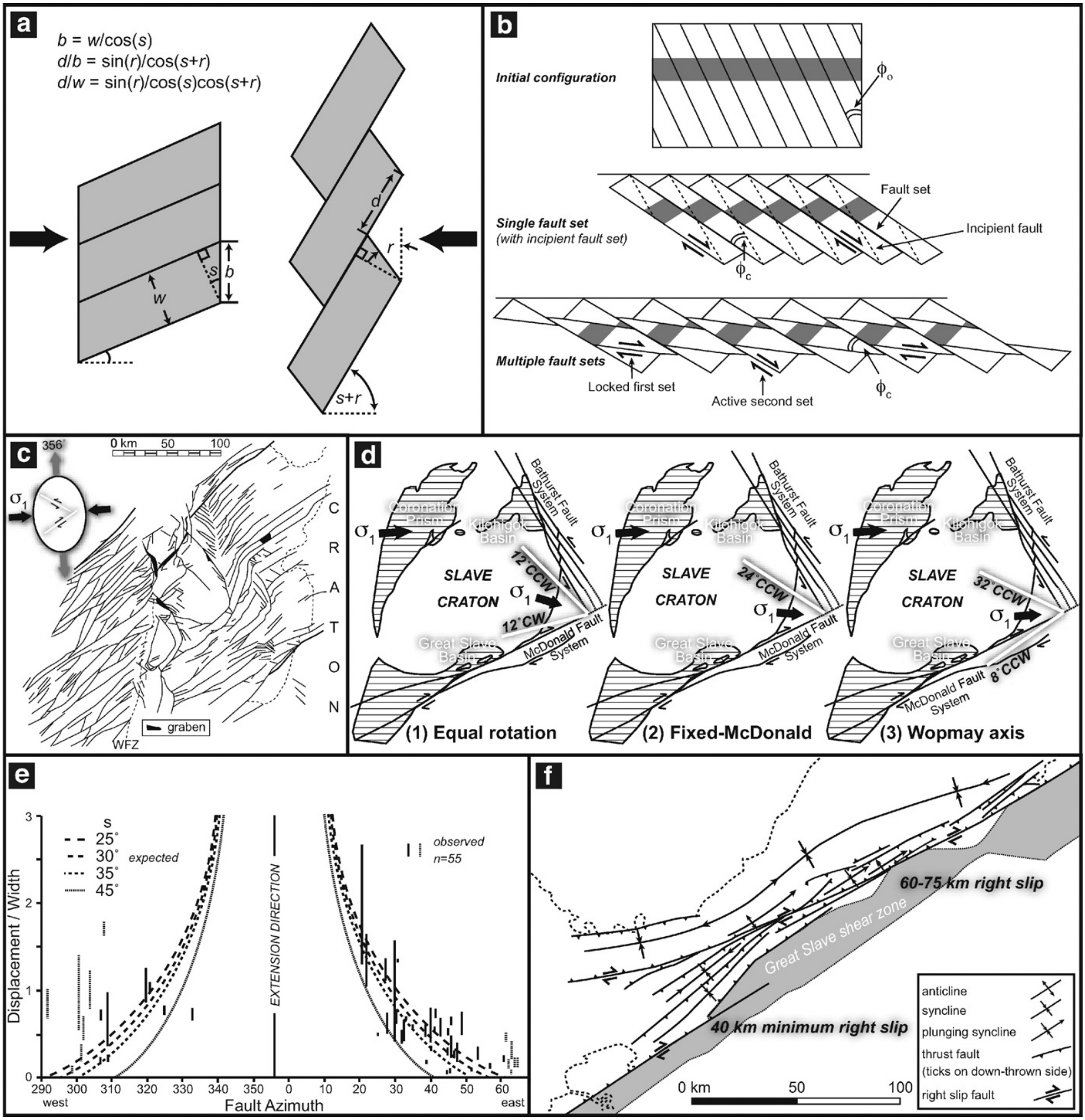

Fig. 5. (a) Conjugate transcurrent faulting by vertical-axis rotation of rigid blocks, manifesting horizontal plane strain. R. Tirrul modified after Freund (1970, 1974). Note fixed relation between fault spacing (w), displacement (d) and fault-block rotation (r). (b) Development of second fault set required to accommodate block rotations greater than 45° (Nur et al., 1986). (c) Conjugate NE right-slip and NW left-slip faults in northern Wopmay orogen, NW Canadian Shield (Hoffman, 1980, 1989). Mean extension direction is oriented 176–356°. Dotted line is the erosional limit of Paleoproterozoic sedimentary cover on Archean cratonic basement. (d) Regional tectonic setting of conjugate transcurrent in northern Wopmay orogen. Box indicates area of (c). (e) Measured displacement/width ratios as a function of fault azimuth in Wopmay orogen, compared with predicted values for s = 25°, 30°, 35° and 45°, where angle s is defined in (a), after R. Tirrul (unpublished). (f) Left-stepping, right-slip McDonald Fault System, east arm of Great Slave Lake, NW Canadian Shield. Dotted line is the present shoreline. Note that teeth on thrust (oblique reverse) faults are unconventionally drawn on down-thrown side.

assumed to have been the same as in Wopmay orogen, 266°, then the Bathurst Fault system rotated 32° (328° − [266 + 30]°) clockwise and the McDonald Fault system rotated clockwise also, but only by ∼6° (244° − [266 − 30]°).

Why would one system rotate much more than the other? It is conceivable that asymmetric rotation was favored by heterogeneous crustal rheology. The McDonald Fault system occupies and parallels the Great Slave Lake shear zone (Hoffman, 1987a), a 25-km-wide zone of continuous mylonite and protomylonite forming a segment of the Taltson-Thelon magmatic zone of the Slave-Rae collision zone (Fig. 5d). In contrast, the Bathurst Fault system transects the collision zone at a 45–55° angle. As fault slip is easier if directed parallel to a crustal-scale mylonite fabric than oblique to it, less work may have been expended if the total rotation was taken

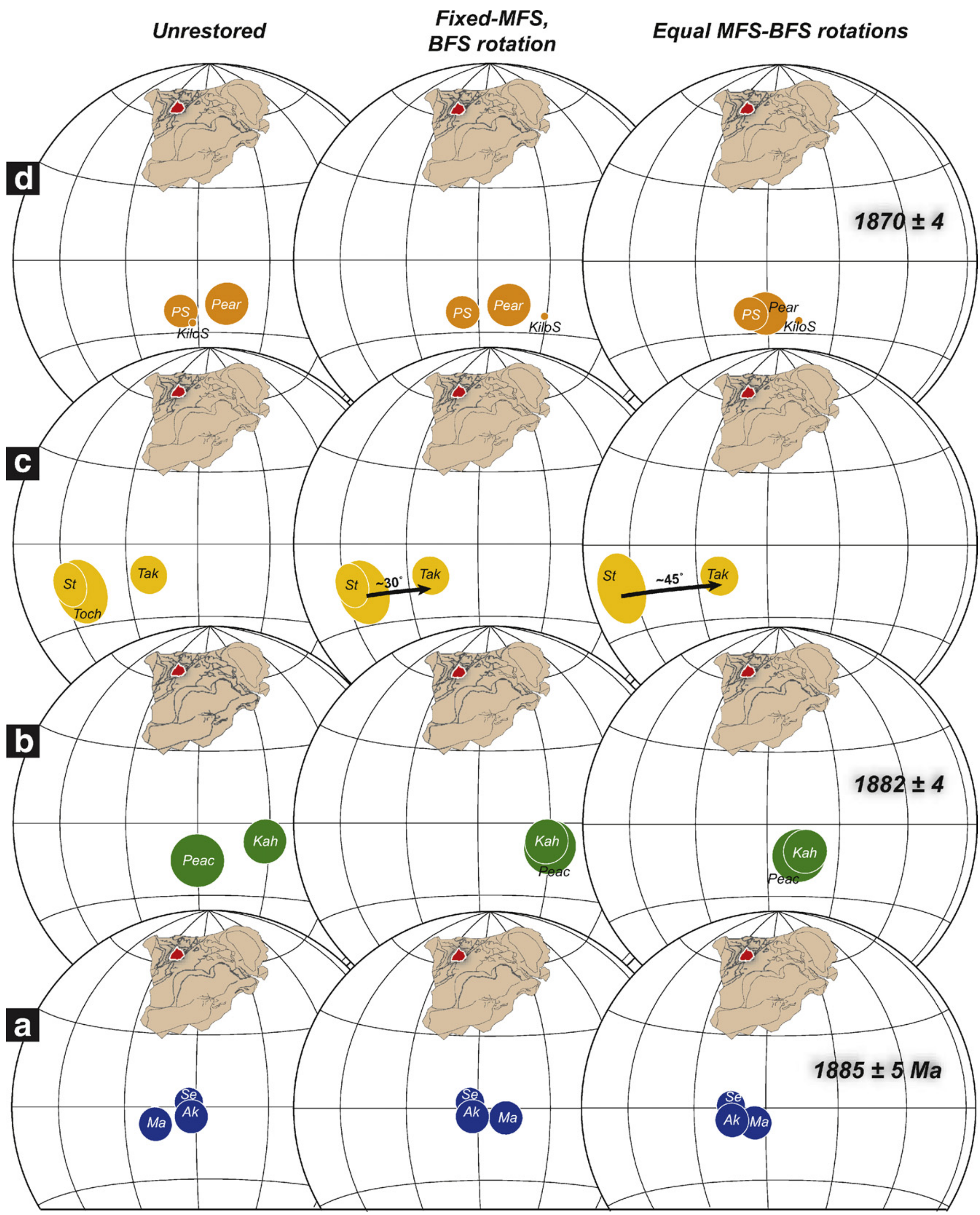

Fig. 6. Paleomagnetic correlations according to (left) unrotated poles, (middle) fixed-McDonald kinematic model, and (right) equal rotation kinematic model. Correlation of poles from the (a) pre-flysch, (b) flysch, (c) molasse, and (d) basaltic phases in superposition (Fig. 3). (a–c) Correlations between poles from the Great Slave and Kilohigok basins. (d) Correlation between poles from the Great Slave and Epworth basins. See Table 1 for stratigraphic correlations, Table 3 for abbreviations, Table 4 for mean calculations for panels (a–c), and text for detailed discussion. Same color associations as Fig. 3. Slave craton is red and lines on Laurentia outline Precambrian geologic boundaries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

up by the Bathurst Fault system and the McDonald Fault system remained pinned in a rheological weak slot. Alternatively, rotation would affect the fault system and the mylonite zone equally, so fault-slip should remain parallel to the mylonite fabric as rotation progressed.

When a transcurrent fault rotates away from σ_1, the normal stress on the fault plane increases. When normal stress is low, transcurrent fault segments "step" sympathetically with sense of displacement (i.e. right-slip faults step right). Fault-tip stress fields favor the formation of rhombochasms (Carey, 1958), a.k.a. 'pull-apart' basins, connecting fault segments. When normal stress is high, fault segments step antithetically (i.e. right-slip faults step left) and are connected by sets of steeply dipping, oblique-slip, reverse (thrust) faults. This latter is the style observed in the Great Slave basin, best illustrated by the set of SW-NE reverse faults in the Simpson Island–Preble Island area linking the LaLoche and McDonald fault segments of the McDonald Fault system (Fig. 5e). Accordingly, the structural style of the McDonald Fault system is more consistent with anticlockwise rotation than with clockwise or non-rotation. This direction of rotation favors the equal rotation model (Fig. 5d).

4.3. *Contemporaneous paleomagnetic poles as structural indicators*

In Section 5 we explore how the possible structural models summarized next restore (or not) contemporaneous poles from the Bathurst and McDonald environs. Since both or one of the fault systems may have rotated, the aforementioned reference pole method generally does not apply. One paleomagnetic pole for the Takiyuak Formation (Irving and McGlynn, 1979) is, nonetheless, from the autochthonous part of the Coronation basin in an area where the azimuths of right-slip faults is ~244° (Hoffman and Tirrul, 1994). This is less than 30° from σ_1, consistent with small slip (observed) and little rotation (inferred) on these faults. The Takiyuak Formation is correlative with the Tochatwi Formation (Table 1) of the Great Slave basin (Hoffman, 1973): both are red lithic sandstones of westerly derivation forming the stratigraphically highest, non-marine, part of the Calderian foredeep (Hoffman, 1987b), related to the Slave-Hottah arc collision in Wopmay orogen (Hildebrand et al., in press). Both formations gradationally overlie the solution-collapse megabreccias (Stark Formation and correlatives) that occur in all three basins (Hoffman and Grotzinger, 1993). Relative to the Takiyuak pole, the Tochatwi paleomagnetic pole (Evans and Bingham, 1976) is rotated ~30° in a clockwise direction (Fig. 6c). This paleomagnetic correlation would imply clockwise, not anticlockwise, rotation of the McDonald Fault system (recall, however, that paleocurrent data contra-indicate significant differential vertical-axis rotation of the Tochatwi Formation within the basin).

4.4. *Alternative kinematic models*

The above discussion leaves the kinematic development of the Bathurst–McDonald conjugate system in a fixed external reference frame unresolved. Let us summarize some simple alternative models.

(1) *Equal rotation*: The two fault systems rotated equally and oppositely (12° each), opening the angle between them from 60° to 84°. The principal axis (286°) is rotated 20° clockwise relative to that observed in Wopmay orogen (266°).

(2) *Fixed-McDonald*: The orientation of the McDonald Fault system was held fixed while the 24° angle of opening was taken up entirely by clockwise rotation of the Bathurst Fault system.

Table 3
Paleomagnetic poles defining the Coronation loop from the Slave craton.

Basin	Group	Formation (remanence)	ID	Age (Ma)	Unrotated Fixed-MFS				Equal rotation			N	Ref
					Plat	Plong	Plat	Plong	Plat	Plong	A95		
Kilohigok		Kilohigok sill	KiloS	1870 ± 4	–27	268	–21	295	**–25**	**282**	0	1	1
Kilohigok		Peacock Hills	Peac	1882 ± 4	–15	270	–10	295	**–13**	**283**	11	15	1
Kilohigok		Mara	Ma	1885 ± 5	–7	253	–5	277	**–6**	**266**	7	28	1
Kilohigok		Rifle	Rf	1963 ± 6	14	341	–24	185	**19**	**353**	9	22	1
Epworth		Peninsula sill	PS	1870 ± 4	**–22**	**263**	–	–	–	–	7	7	2
Epworth		Takiyuak	Tak	ca. 1885–1870	**–13**	**249**	–	–	–	–	8	17	1, 2
Great Slave	Et-Then	Murky (post-fold)	Et	ca. 1780?	**4**	**310**	–	–	–	–	8	14	3
Great Slave	Christie Bay	Pearson (A)	Pear	1870 ± 4	–19	283	–	–	**–22**	**269**	9	12	4
Great Slave	Christie Bay	Tochatwi	Toch	ca. 1885–1870	–18	217	–	–	**–14**	**204**	12	8	5
Great Slave	Christie Bay	Stark	St	ca. 1885–1870	–15	212	–	–	**–11**	**199**	8	39	1, 6
Great Slave	Pethei	Douglas Peninsular	Doug	ca. 1885–1870	–17	258	–	–	**–17**	**245**	16	6	2
Great Slave	Kahochella	(K)	Kah	1882 ± 4	–7	298	–	–	**–11**	**286**	9	18	7
Great Slave	Kahochella	Seton (C)	Se	1885 ± 5	2	267	–	–	**1**	**256**	6	19	2
Great Slave	Sosan	Akaitcho River	Ak	1885 ± 5	–4	268	–	–	**–5**	**256**	7	35	8
Nonacho		Martin	Mart	1818 ± 4	**–9**	**287**	–	–	–	–	9	15	9
		Lac de Gras dikes	LdG	2029–2023	**12**	**268**	–	–	–	–	7	4	10

Notes: Bold values are those preferred herein as cratonic poles part of the resurrected Coronation loop. Plat, pole latitude; Plong, pole longitude; Fixed-MFS, structural model where McDonald fault system (MFS) is fixed and the Bathurst Fault system (BFS) rotated 24° CW; Equal rotation, structural model where MFS and BFS have rotated equally and oppositely 12° CCW and CW, respectively; Only poles in the MFS and BFS that also pre-date transcurrent faulting have been structurally corrected. N, number of paleomagnetic sites; Ref; reference: (1) Evans and Hoye (1981), (2) Irving and McGlynn (1979), (3) Irving et al. (1972), (4) McGlynn and Irving (1978), (5) Evans and Bingham (1976), (6) Bingham and Evans (1976), (7) Reid et al. (1981), (8) Evans et al. (1980), (9) Evans and Bingham (1973), and (10) Buchan et al. (2009).

The principal axis (274°) is closer to that in Wopmay orogen (266°).

(3) *Wopmay axis*: The McDonald Fault system rotated clockwise, but 24° less than the Bathurst Fault system. The Tochatwi paleopole rotated westward relative to the coeval, quasi-cratonic, Takiyuak pole from the Coronation basin, as is observed (Fig. 1). The principal axis was close to that in Wopmay orogen.

As detailed in Section 4.2, antithetically left-stepping, right-lateral, transcurrent faults within the McDonald system are connected by steeply dipping, oblique-slip, reverse faults. Kinematic models (2) and especially (3) are each inconsistent with these observations. Model (2), no rotation or fixed-McDonald, cannot readily account for the high normal stresses implied by antithetically stepping faults. Model (3), wherein the McDonald fault system would have rotated clockwise, would oppositely predict extensional rhombochasms instead of compressional oblique-slip, reverse faults as observed. Since model (3) conflicts directly with field observations we do not consider it further in preference of models (1) and (2). Aside from their abilities to restore paleomagnetic correlations discussed next, the equal rotation model (1) may be preferred over model (2) because it entails rotation toward σ_1 and consequently toward conditions of increased normal stress.

5. Paleomagnetic restoration of Coronation loop

Using stratigraphic correlations between the Great Slave, Kilohigok, and Epworth basins (Table 1; Section 2), we can test to see which of the proposed structural corrections detailed just above in fact restore correlative paleomagnetic poles to overlapping coincidence or not (Fig. 6). In Table 3 we rotate the Coronation loop poles according to structural models (1) versus (2), i.e., equal rotation versus fixed-McDonald (Section 4.4). For model (1), equal rotation, Bathurst poles are rotated 12° anticlockwise and McDonald poles (except Et-Then) are rotated 12° clockwise. For model (2), fixed-McDonald, only Bathurst poles are rotated 24° anticlockwise.

The Mara and Peacock Hills paleomagnetic poles (Evans and Hoye, 1981) from the Kilohigok basin (Table 1) are contemporaneous with the Akaitcho River and Kahochella poles (Evans et al., 1980; Reid et al., 1981), respectively, of the Great Slave basin. In each case, the Great Slave pole lies significantly to the east of the correlative Kilohigok pole, the younger pair having greater separation (Fig. 6a and b). According to structural model (1), equal rotation, the Mara pole from the Kilohigok basin and the Seton and Akaitcho River poles from the Great Slave basin (which themselves are consistent) rotate toward each other and overlap (Fig. 6a). According to structural model (2), fixed-McDonald, the Mara pole rotates toward but just past the Seton and Akaitcho River poles from the Great Slave basin (Fig. 6a). Both structural models successfully restore the Peacocks Hills pole from Kilohigok and the Kahochella pole from Great Slave to match each other (Fig. 6b).

The Stark/Tochatwi poles may be expected to correlate with the Takiyuak pole from the Coronation basin. In actuality, the proposed retrodeformation increases their misfit (Fig. 6c). On the other hand, considering that rapid motion may characterize this part of the APW path, it may be incorrect to expect a precise APW match provided a broad stratigraphic match. What can be asserted at present is that the consistent paleocurrent data from the Tochatwi Formation provide no evidence for the ~80° CW rotation invoked by Irving et al. (2004), or other any significant rotation (Fig. 4; Table 2).

The Pearson paleomagnetic pole (McGlynn and Irving, 1978) from Great Slave and the Kilohigok sill virtual geomagnetic pole (VGP) from that basin (Evans and Hoye, 1981) are contemporaneous with the Peninsular sill VGP from the eastern autochthonous Coronation prism (Irving and McGlynn, 1979). According to structural model (1), equal rotation, the two sill VGPs and Pearson pole agree closely, especially considering that VGPs are not time-averaged directions (for the past well-studied 5 myr VGP dispersion at low latitudes is ~12° (Johnson and Constable, 1995)). According to structural model (2), fixed-McDonald, the two sill VGPs rotate away from each other and the unrotated Pearson pole remains removed from either sill VGP (Fig. 6d).

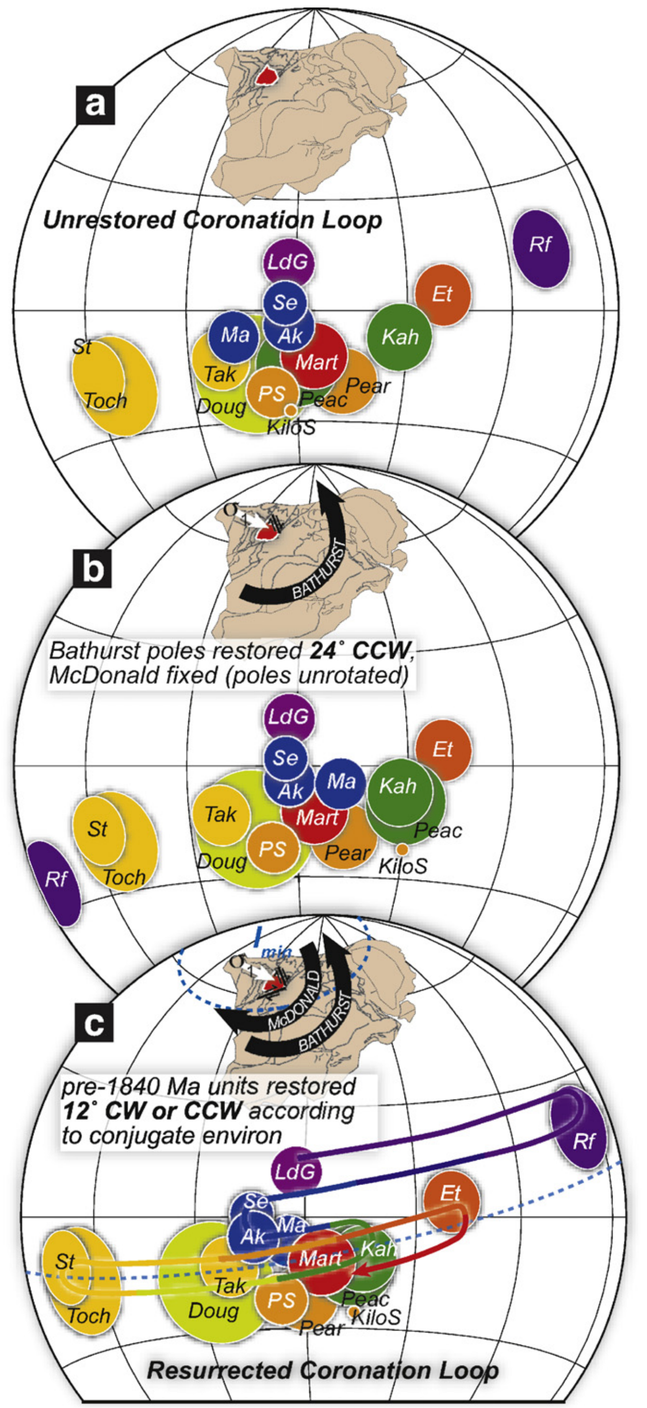

Fig. 7. Restoration of the Coronation loop. (a) Unrotated poles plotted in present-day coordinates. As before, color associates with superposition and relative age (correlates are colored similarly). The Slave craton (red) is shown on the Laurentia continent. (b) Resultant pole positions according to fixed-McDonald model. (c) Resultant pole positions according to equal rotation model. This is the proposed structurally corrected, resurrected, and cratonic Coronation loop. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 4
Structurally corrected Orosirian mean paleomagnetic poles for Slave craton.

Name	Age (Ma)	Plat (°)	Plong (°)	A95 (°)	*N*	1234567 Q
Pearson	1870 ± 4	−22	269	6	22	1101111 6
Kahochella	1882 ± 4	−12	285	7	33	1100111 5
Seton	1885 ± 5	−6	260	4	82	1111111 7

Notes: Plat, pole latitude; Plong, pole longitude; A95, semi-angle of cone of confidence ($P = 0.05$); N. number of sites; Q, quality value according to Van der Voo (1990).

Although no correlative units have paleopoles for comparison, the discordant pole from the Rifle Formation (formerly Western River Formation; Evans and Hoye, 1981), into which the Kilohigok sill intrudes, cannot easily be explained by deformation or rotation since deposition, for the sill VGP is broadly concordant with its correlative in the Coronation basin, and the gentle Kilohigok basin folds in the paleomagnetically sampled region do not appear capable of accommodating many 10 s of degrees of local rotation. The equal-rotation structural correction slightly increases the discordance of the Rifle result (Fig. 7).

With the exception of the Stark/Tochatwi correlation with Takiyuak (which neither model (1) nor (2) restores), kinematic model (1), equal rotation, is generally more effective than model (2) at restoring paleomagnetic correlations (Fig. 6). Mean poles for those correlations as restored by model (1), equal rotation, are provided in Table 4 including an estimate of their reliability according to standard paleomagnetic criteria (Van der Voo, 1990). Recall from Section 4.4 that model (1) is preferable on structural grounds as well. While we prefer the equal rotation model, we emphasize that none of the three plausible kinematic models are as dramatic as the vertical-axis rotations implied by Irving et al. (2004). None of the models diminish the broad swath-like structure of the empirical Coronation loop. We regard those solutions in bold in Table 3 and Fig. 7c as reliable for paleogeographic use (also see Table 3 for mean pole calculations for correlative poles shown in Fig. 6).

6. Discussion

According to the preferred equal rotation kinematic model, the paired CW and CCW 12° rotations for the McDonald and Bathurst environs, respectively, actually increase the angular sweep of the Coronation loop (Fig. 7c). At first consideration the proposed structural corrections make matters worse. Nonetheless, three out of four correlations—Seton and Akaitcho with Mara (Fig. 6a); Kahochella with Peacock Hills (Fig. 6b); and Peninsular sill with Pearson (Fig. 6d)—rotate from originally different directions into overlapping agreement once they are structurally corrected. Paleomagnetic correlation across circum-cratonic basins demonstrates that these restored poles can be considered cratonic and have not suffered from dramatic tectonic rotation or overprinting (contra Irving et al. (2004)). Further paleomagnetic investigation of cratonic units in Slave, in particular its dike swarms, will test the general conclusion and particular details of our resurrected Coronation loop.

There is little doubt why and how the Coronation loop was rejected before now: the data seem incompatible with typical rates and styles of plate tectonic motions, and they were rejected by the measure to which they did not conform to that pattern (Irving et al., 2004). Plate tectonics cannot easily accommodate translational velocities in excess of ~20 cm/yr based (among other considerations) on how quickly bending stress may be imposed upon a down-going slab (Conrad and Hager, 2001). Meaningful discussion of the *maximum* rates implied by the Coronation loop awaits further combined geochronologic–paleomagnetic work. Nonetheless, most APW swings do have dated endpoints, allowing estimation of minimum rates: ~90° swing between 2025-Ma Lac de Gras dikes (Buchan et al., 2009) and 1963-Ma Rifle Formation implies ~15 cm/yr; ~100° return swing from Rifle to 1885-Ma Seton mean pole also implies ~15 cm/yr; ~30° swing from Seton to 1882-Ma Kahochella mean pole implies ~110 cm/yr; ~160° roundtrip swing from Kahochella, out to Stark/Tochatwi, and back to 1870-Ma Pearson mean pole implies ~150 cm/yr; and ~100° roundtrip swing from Pearson to Et-Then and back to 1818-Ma Martin Formation (Morelli et al., 2009) implies ~20 cm/yr. Again, provided the paucity of geochronologic and paleomagnetic sampling, these rate estimates represent minima and great weight should not be put on them, except to rule out plate motions as an explanation. Broadly speaking then, rates do successively speed up and slow down, with commensurate starting and ending rates (10–20 cm/yr) and consistently fast rates (110–150 cm/yr) during the central duration of the Coronation loop. We also note with curiosity that the two modes of TPW rate (fast and slow) are an order of magnitude separated. True polar wander, unlike plate tectonics, can theoretically achieve rates of motion as fast as centimeters to meters per year, particularly when one acknowledges uncertainties about the mantle's viscosity structure in deep time (Tsai and Stevenson, 2007).

TPW is the wholesale rotation of solid Earth (mantle and crust) about the liquid outer core in order to realign the principal moment of inertia (I_{max}) with the spin axis (Gold, 1955). The long-wavelength mantle upwelling induced underneath mature and vanished supercontinents (Anderson, 1994; Gurnis, 1988; Holmes, 1931; Phillips et al., 2009; Zhong et al., 2007) is thought to stabilize Earth's minimum moment of inertia (I_{min}) not only on the equator but also at a particularly long-lived, constant longitude (Evans, 1998, 2003) such as for Africa during the last 200 million years (Torsvik et al., 2008). Any slight change in relative magnitude between the subequal I_{max} and I_{int} would displace the geographic location of Earth's spin axis along the same great circle. The pole to that great circle would approximate the center of the mature or vanished supercontinent. Coplanar oscillations of solid Earth relative to the spin axis have now been observed following assembly and breakup of both the Rodinia and Pangea supercontinents (Kirschvink et al., 1997; Raub et al., 2007; Steinberger and Torsvik, 2008).

If TPW is the correct interpretation for the rapid and oscillatory Coronation loop, then the observed declination changes would appear to restore the Slave craton close to the I_{min} axis defined by that Coronation oscillation (Fig. 7). It is intriguing to thereby suggest that the Coronation loop was a consequence of, and centered on, the relict Sclavia supercraton (with Slave as its equatorial center at the time of breakup). As of now, Sclavia's hypothesized paleogeographic cohorts are limited to two or three other paleomagnetically poorly studied cratons: Wyoming, Zimbabwe, and Dharwar (Bleeker, 2003). Another possibility is that the Coronation loop was centered about the vanished supercraton Superia, which probably included at least 4 other cratons (Ernst and Bleeker, submitted for publication). An alternative, "Kenorland" supercontinent might have included Sclavia, Superia, and other cratons such as Vaalbara (De Kock et al., 2009). Whether a legacy of Sclavia, Superia, or Kenorland, the Coronation loop would imply that expansive Archean-Paleoproterozoic landmasses modulated large-scale mantle convection in much the same manner as increasingly larger and later supercontinents.

Any proposed TPW signal should find support from the paleomagnetic records of all of Earth's cratons at that time. Superior's path is noteworthy in its 30–40° angular distance between poles from the Molson dyke swarm at ca. 1877 Ma (Halls and Heaman, 2000) and the Haig sills plus Flaherty volcanics at ca. 1870 Ma (Hamilton et al., 2009; Schmidt, 1980). Similarly, Kalahari craton's poles include a reliable result from 1872–1879 Ma (Hanson et al., 2004), but this differs by 30–40° from the Mashonaland sills, recently dated at ca. 1875 Ma (Söderlund et al., in press). Joe Kirschvink, Nick Swanson-Hysell, one anonymous reviewer, and the editor provided several insightful suggestions to help complete the analysis. RNM was funded by a NSFGRF. PFH was supported by the Canada Pension Plan and U.S. Social Security.

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