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Restoring Proterozoic deformation within the Superior craton

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ABSTRACT

Geometrical patterns of Paleoproterozoic dyke swarms in the Superior craton, North America, and paleomagnetic studies of those dykes, both indicate relative motion across the Kapuskasing Structural Zone (KSZ) that divides the craton into eastern and western sectors. Previous work has optimized the amount of vertical-axis rotation necessary to bring the dyke trends and paleomagnetic remanence declinations into alignment, yet such calculations are not kinematically viable in a plate-tectonic framework. Here we subdivide the Superior craton into two internally rigid subplates and calculate Euler parameters that optimally group the paleomagnetic remanence data from six dyke swarms with ages between 2470 and 2070 Ma. Our dataset includes 59 sites from the Matachewan dykes for which directional results are reported for the first time. Our preferred restoration of the eastern Superior subprovince relative to the western subprovince is around an Euler pole at 51°N, 85°W, with a rotation angle of 14° CCW. Although we do not include data from the KSZ in our rigid-subplate calculations, we can align its dyke strikes by applying a 23° CCW distributed shear that preserves line length of all dykes pinned to the western margin. Our model predicts approximately 90 km of dextral transpressional displacement at *ca.* 1900 Ma, about half of which is accommodated by distributed strain within the KSZ, and the other half by oblique lateral thrusting (with NE-vergence) across the Ivanhoe Lake shear zone. We produce a combined apparent polar wander path for the early Paleoproterozoic Superior craton that incorporates data from both western and eastern subplates, and that can be rotated to either of the subplates' reference frames for the purposes of Archean-Paleoproterozoic supercraton reconstructions.

1. Introduction

Geometrically accurate reconstructions of pre-Pangean paleogeography require definition of ancient cratonic boundaries, between which the lithospheric plates should be assumed as internally rigid. Hypotheses of cratonic rigidity can be tested by intact versus disrupted sedimentary basins, metamorphic zonations, and the geometries of geological/geophysical features such as dyke swarms and structural trends. In the ideal case of excellent paleomagnetic coverage for a single age across an entire craton, one may use the consistency of those results, in the context of an assumed geocentric axial dipole (GAD) magnetic field model, as an additional test. The Superior craton, in eastern Canada with extensions into the northern Great Lakes region of USA, has an extensive paleomagnetic database from precisely dated large igneous provinces and provides just such an opportunity.

The Superior craton consolidated at *ca.* 2700 Ma in a series of southward-younging accretionary events (Card and Poulsen, 1998; Percival, 2007). Tectonic activity within the following 200 million years was limited to isolated granitoid intrusion. The early Paleoproterozoic (2500–2000 Ma) history of Superior craton is marked by numerous dyke swarms and sedimentary basins spanning its southern margin (reviewed by Buchan and Ernst, 2004; Bleeker and Ernst, 2006). Profound tectonic regime changes occurred during the interval 2000–1800 Ma: volcanic and sedimentary basins developed in the Hudson Bay and Ungava regions, followed shortly by convergent tectonism around nearly all of Superior's margins (Hoffman, 1988; St-Onge et al., 2006; Schulz and Cannon, 2007).

The Kapuskasing Structural Zone (KSZ) divides the Superior craton into western and eastern halves. Geological features summarized above, from Archean to Paleoproterozoic age, can be traced from one side of the KSZ to the other, with minor differences (*e.g.*, Card and Poulsen, 1998). Typical rocks of the KSZ are granulite-grade gneisses representing an exhumed lower crustal section of Superior basement (Percival and West, 1994). One of the most spectacular geological features in the KSZ region is the 2473–2446 Ma Matachewan dyke swarm (Fahrig, 1987; Halls and Bates, 1990; Heaman, 1997), consisting of hundreds of near-vertical N- to NW-striking mafic sheets that are typically 5–50 m wide and spaced hectometers to kilometers apart, across a 500-km-wide

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zone. Paleomagnetic studies of Matachewan dykes reveal a pattern of remanence polarities that correspond to structural depths of exposure: dominance of the "N" polarity being restricted to the higher-grade regions of the KSZ (Bates and Halls, 1990; Halls and Zhang, 1998, 2003). Other dykes in the KSZ include the so-called Kapuskasing dykes, which have recently been shown as comagmatic with the 2126–2101 Ma Marathon dyke swarm farther to the west (Halls et al., 2008). Exhumation of the KSZ postdates emplacement of these dyke swarms, which are deflected by vertical-axis rotations both in their emplacement geometries and their paleomagnetic remanence directions (Halls and Davis, 2004; Halls et al., 2008). Also, within the uplifted regions, dykes of both swarms display cloudy feldspar and yield paleomagnetic baked-contact tests impling elevated host-rock temperatures at the time of emplacement (Halls et al., 1994).

Timing of the western/eastern Superior relative motion is constrained by numerous data. Rocks of the Keweenawan large igneous province, and coeval dykes, cut across the KSZ without deflection, implying that most if not all deformation concluded prior to *ca.* 1150 Ma (West and Ernst, 1991). Broadly concordant paleomagnetic overprint poles from the Trans-Hudson orogen (*s.l.*) both west and east of the KSZ indicate that the deformation also preceded *ca.* 1750 Ma (Irving et al., 2004). Concordance of poles from the Haig diabase sills of the Belcher Islands and the Sutton Inlier sill (see Buchan et al., 1998) would also indicate cessation of the west/east Superior rotation by the time of their emplacement, if they were demonstrated to be coeval. Hamilton et al. (2009) show precise U–Pb age equivalence of 1870 Ma between the Sutton Inlier sill and two of the Haig sills. Unfortunately, neither of the dated Haig bodies are the same as those studied paleomagnetically, but an unusual coincidence of factors would be required to generate the pole concordance if the intrusions were of different ages. The youngest dykes known to be affected by the relative rotation are the Fort Frances and Lac Esprit swarms, implying that the deformation is younger than *ca.* 2070 Ma (Buchan et al., 2007). Finally, the paleomagnetically/geometrically documented rotation between the two halves of Superior craton can be constrained by timing of deformation in the KSZ. Available data include: thermobarometry showing 18-20 km of exhumation postdating the so-called Kapuskasing dykes (Percival et al., 1994) one of which, lying within the KSZ, has given a U–Pb baddeleyite age of 2121 ± 8 Ma (Halls et al., 2008); thermochronologic ages of *ca.* 1900 Ma within the KSZ (Percival and Peterman, 1994); only slight dextral offset of the Cargill high-level alkalic intrusion (Percival and West, 1994), dated by U–Pb on baddeleyite at 1896.8 ± 1.4 Ma (Rukhlov and Bell, 2009); paleomagnetic blocking of the Kapuskasing "B" remanence in high-grade basement rocks during exhumation, with a pole (Symons and Vandall, 1990; Symons et al., 1994) similar to that of the Molson dykes at *ca.* 1880 Ma (Halls and Heaman, 2000); and the post-exhumation emplacement of the high-level Borden intrusion in the KSZ at 1872 ± 6 Ma (U–Pb on zircon; Bell et al., 1987).

Previous estimates of the magnitude of western/eastern Superior relative rotation have varied from about 4 to 6° (West and Ernst, 1991), to $12 \pm 9°$ (Bates and Halls, 1991a), to $16 \pm 21°$ (Halls and Davis, 2004), and to $23 \pm 12°$ (Buchan et al., 2007). The first study was based on aeromagnetic synthesis, using dense regions of Matachewan intrusions as delineating three "subswarms" whose boundaries were taken as piercing points for retro-deformation. That kinematic model largely conserved area among all grid elements, and predicted limited orthogonal convergence across the KSZ. The method was particularly suited toward identifying dextral offsets of the subswarm boundaries, which were estimated at 50–60 km. This was coupled to a 4° vertical-axis rotation about a local Euler pole (West and Ernst, 1991). The latter three studies employed paleomagnetic declination offsets between coeval dyke swarms on both sides of the KSZ, to predict rigid-body rotation of one side relative to the other. However, the models only approximated such motion by adjusting remanence declination values of site-mean or swarm-mean data, recomputed to a common reference locality (Bates and Halls, 1991a; Halls and Davis, 2004; Buchan et al., 2007). Such treatment is incompatible with the stated plate-tectonic basis of those models, which would instead require manipulation of all data in paleomagnetic pole space rather than local coordinates. Here we present a rigorous plate-tectonic treatment of the west/east Superior rotation across the KSZ, using paleomagnetic poles adjusted by Euler rotations on the surface of the globe. Our dataset includes 59 newly reported site-mean data from the Matachewan swarm within the KSZ. We also present a simplified model for deformation within the KSZ, which can be used as a basis for further kinematic investigation of that tectonically complex region.

Our rigorous quantitative analysis is important because some proposed supercraton reconstructions involve rotations of cratons to the eastern part of Superior (*e.g.*, Karelia: Heaman, 1997; Bleeker and Ernst, 2006) whereas other proposed reconstructions rotate cratons to western Superior (*e.g.*, Wyoming: Roscoe and Card, 1993). For an integrated kinematic model incorporating all of these cratons simultaneously, we need first to retro-deform the Superior Province itself.

2. Methods

The densest Paleoproterozoic dyke swarm in the southern Superior craton is the Matachewan swarm, represented by more than 300 paleomagnetically studied dykes. Readily seen on aeromagnetic datasets, the swarm displays a prominent Z-kinked pattern in map view, centered on the southern KSZ (Fig. 1). Previous paleomagnetic studies across the KSZ have shown that a substantial portion, if not all, of the kinked pattern is secondary, deflecting remanence declinations by amounts commensurate with the varying dyke trends (Bates and Halls, 1991a). Aeromagnetic expression of this dense swarm includes several sharp discontinuities in dyke trends, thereby distinguishing four subplates of the Superior craton to be considered in the present analysis: (I) an eastern domain including all of Quebec and southern Ontario as far west as the Ivanhoe Lake shear zone that delimits the KSZ; (II) the KSZ itself plus regions to the immediate northwest that contain similarly oriented Matachewan dykes, roughly corresponding to the "Kapuskasing Uplift" defined by Percival et al. (1989); (III) a western Superior boundary domain including the Hornepayne and Hearst regions and delimited by two narrow kink hinges extending northeast from Wawa and Marathon; and (IV) the western Superior domain including all regions north and west of Marathon. The visually apparent difference in strikes between domains (III) and (IV) is rather subtle, and as will be shown below, currently available data from outcrop measurements are insufficient in distinguishing them quantitatively (although larger datasets in the future may reduce the errors and provide a more rigorous test). Note that these domains appear superficially similar to, but are distinct in detail from, the tectonic blocks labeled (I)–(IV) across the southern and western Superior craton by Manson and Halls (1997).

Paleomagnetic directional data from six dyke swarms (distinguishing remanence polarity when age differences are apparent between N and R of the same named swarm) are compared across these four domains: Matachewan R (2473–2446 Ma; Heaman, 1997; Halls et al., 2008), Matachewan N (2446 Ma; Heaman, 1997), Biscotasing (2171–2167 Ma; Buchan et al., 1993; Halls and Davis, 2004; Halls et al., 2008), Marathon N (2126–2121 Ma; Buchan et al., 1996; Halls et al., 2008), Marathon R (2106–2101 Ma; Hamilton et al., 2002; Halls et al., 2008), and Fort Frances–Lac Esprit (2076–2069 Ma; Buchan et al., 1993, 2007). Note that the 'N' and

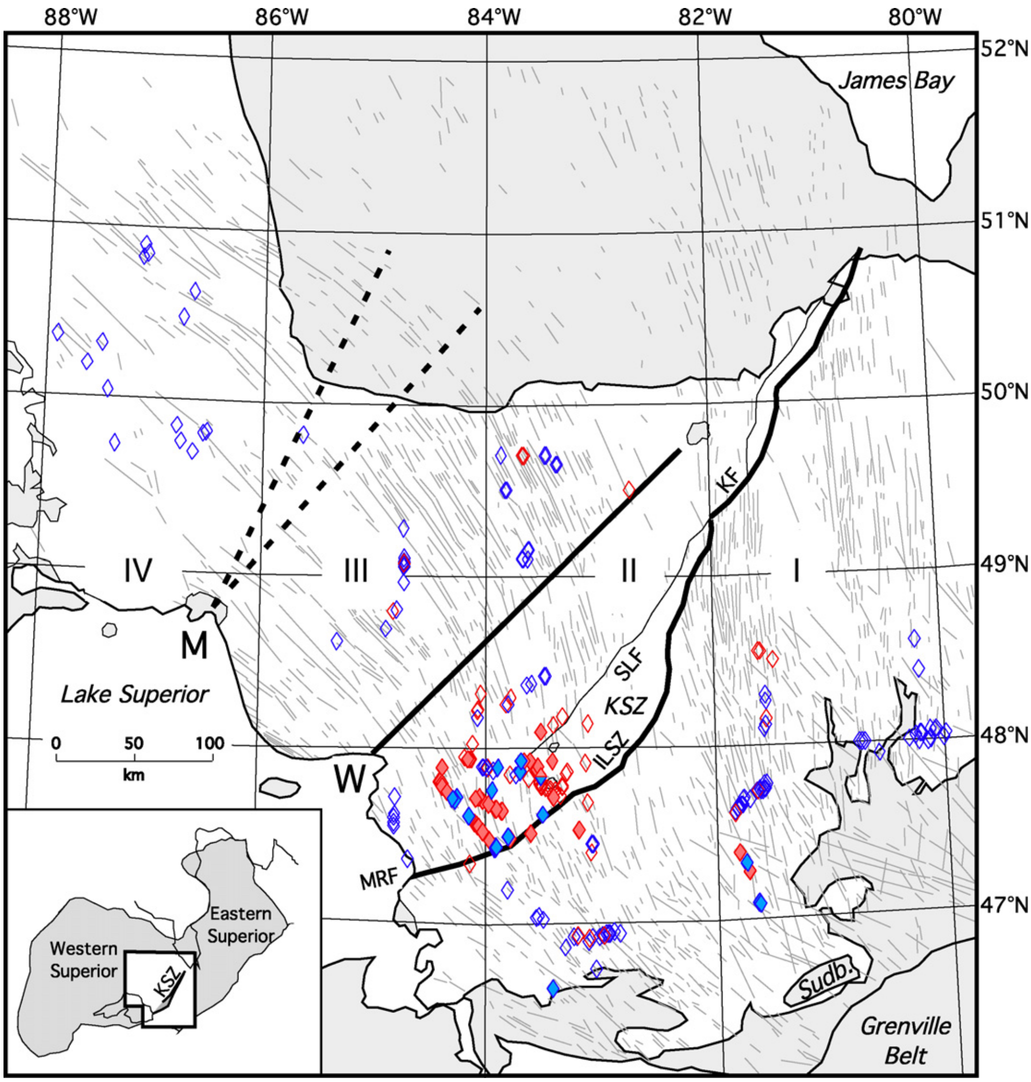

Fig. 1. Regional map of the south-central Superior Province, showing tectonic domains (Roman numerals) as defined in this study, and north- to northwest striking dykes (gray) as inferred from aeromagnetic surveys, Matachewan dyke paleomagnetic sampling sites (blue = R-polarity, red = N-polarity) from this work (solid symbols) and previously published Matachewan data (open symbols). Not all mapped dykes can be ascribed definitively to the Matachewan swarm, as is particularly evident from the WNW-striking Sudbury dykes in the southeastern corner of the map. Gray-shaded areas indicate post-Matachewan sedimentary cover or intrusions. The boundary between domains (III) and (IV) is uncertain and represented by two possible dashed lines. Base map modified from Halls and Palmer (1990). Geological features referred to in the text: CB = Chapleau Block, GB = Groundhog River block, ILSZ = Ivanhoe Lake shear zone, KF = Kineras Fault, KSZ = Kapuskasing structural zone uplift, MRF = Montreal River Fault, and Sudb. = Sudbury structure. Locations referred to in the text: H = Hearst, HP = Hornepayne, M = Marathon, RL = Ranger Lake, T = Timmins, OL = Ogoki Lake, and W = Wawa.

'R' designations of remanence polarities refer to directional similarities with those of the present normal and reverse geomagnetic field at the sampling sites; these designations are meant merely as nomenclature rather than absolute interpretation. In fact, the most parsimonious interpolation of the Superior APW path (Buchan et al., 1994; and subsequent papers) indicates that Superior crossed the paleo-equator between 2445 and 2220 Ma, and hence Matachewan 'N' directions would represent the same geomagnetic polarity as Marathon 'R', and vice versa. These issues with nomenclature have no effect on our conclusions.

For each dyke swarm, all published paleomagnetic data were transcribed to spreadsheets whereby we could calculate (1) mean declinations and inclinations from dykes that were sampled at more than one site, (2) virtual geomagnetic poles (VGPs) from all dyke means, (3) variable Euler rotations of the four tectonic domains to produce suites of rotated VGPs, and (4) recalculated site locations and declination/inclination data according to the Euler rotations. Our analysis assumes a purely geocentric axial dipole (GAD) magnetic field, which is justified to first order by the comparison of paleomagnetic/paleoclimatic latitudes of evaporite deposits through most of the Proterozoic Eon (Evans, 2006).

We have followed Halls et al. (2008) in filtering site-mean data for quality, requiring the total number of data points used to calculate the mean direction to be greater or equal to four. This criterion considers each great-circle analysis (Halls, 1976) as a half-point, as done by McFadden and McElhinny (1988). Likewise, also following Halls et al. (2008), we accept only sites at which the radius of the 95% confidence cone about the mean direction (α_{95}; Fisher, 1953) is less than 15°. We list all the quality-filtered paleomagnetic sites in Table A1 (Appendix). Discussions of data from individual dyke swarms are as follows.

2.1. Matachewan R and N

This paper considers results from all studies that have been carried out after development of adequate demagnetization procedures to remove magnetic overprints. We therefore exclude the generally comparable results from Matachewan dykes within such pioneering studies as Strangway (1964) and Fahrig et al. (1965), the problems in which were discussed by Irving and Naldrett (1977). The published papers for which we summarize paleomagnetic data are: Irving and Naldrett (1977), Halls and Shaw (1988), Halls and Palmer (1990), Bates and Halls (1990), Buchan et al. (1990), Vandall and Symons (1990), Bates and Halls (1991a), Buchan et al. (1996), Smirnov and Tarduno (2004), and Halls et al. (2005). The Matachewan data reported by Schutts and Dunlop (1981) are not presented completely enough to allow inclusion here. Results from single dykes in domain (I) are each taken from unpublished M.Sc. theses by Pesonen (1973) and Aibangbee (1982). Summary data from the rigorously described baked-contact tests of Halls (1991) are tabulated in Halls and Palmer (1990) and Bates and Halls (1991a). Among all studies, if baked-contact tests were conducted we consider only data from the dykes themselves, not their remagnetized wallrocks. Note that the data presented in Ernst and Halls (1984) have been subsumed by the more detailed study of Halls and Palmer (1990). Two Matachewan 'N' sites from the Groundhog River uplifted block, reported by Bates and Halls (1991b), pass our quality selection criteria, but their declinations are anomalous for domain (II) and thus are excluded from the present analysis. In the study of Buchan et al. (2007), two out of four sampled Matachewan dykes yielded usable data, but neither of those two site means satisfied our reliability criteria. We report new data from 59 sites in tectonic domains (I) and (II). The remanence polarities of most of these sites were depicted in Halls et al. (1994) and Halls and Zhang (1998, 2003), but the directional data are reported here for the first time.

There is a distinct possibility that a few of the same sites have been sampled and analyzed by more than one research group, and therefore each VGP from those sites would be counted redundantly in our analysis. For example, both regions of sites in the study by Smirnov and Tarduno (2004) were already sampled extensively by Halls and Palmer (1990) and Bates and Halls (1990). The information on dyke thicknesses and paleomagnetic remanence directions given in these papers suggests that some, but not all, of the sites are duplicated by the different groups. In these instances, we accept high-quality site means from all of the published studies, because each result represents an independent laboratory estimate of the local geomagnetic field at the time of dyke intrusion. We found that including or excluding these potential site redundancies altered the overall Matachewan domain means by no more than 3°, and the final Matachewan R and Matachewan N means by less than 1°.

Two paleomagnetic sites from the aforementioned studies deserve special mention. We omit one site of high quality but only tentative association with the Matachewan N direction (RL31 of Bates and Halls, 1990) because of its anomalously steep inclination (61.3°, as opposed to the more typical Matachewan inclination of *ca.* 20°). We are also uncertain of domain placement for the single site of Matachewan R remanence (29U) reported in Buchan et al. (1996). That site falls directly within the area of uncertain boundary placement between domains (III) and (IV), as shown in Fig. 1, so it is included only in the combined mean from both of those domains, and consequent calculations.

Five Matachewan dykes have been dated by U–Pb methods. In the Matachewan area of domain (I), two dykes contribute to the 2473 + 16/−9 Ma upper-intercept age: one (LH87-15) corresponds to site TM20 of Bates and Halls (1991a) and yielded R-polarity but with statistics that do not pass our current quality criteria, and the other which has not been studied paleomagnetically, to our knowledge. In the Hearst region of domain (II), two dykes contribute to the 2446 ± 3 Ma upper-intercept age: one (LH87-11) corresponds to site 214 of Halls and Palmer (1990) and yielded N-polarity, and the other (208) corresponds to site 208 of Halls and Palmer (1990) and yielded R-polarity with statistics not passing our quality criteria. Finally, in the Okogi Lake area of domain (IV), R-polarity site LL19 yielded an age of 2459 ± 5 Ma (Halls et al., 2005).

2.2. Other swarms

Twelve dykes of the N-polarity Biscotasing swarm are included in our mean calculations: six in domain (I) by Buchan et al. (1993), and six in domain (III) by Halls and Davis (2004). Halls et al. (2005, 2008) reported an age of 2170.7 ± 1.1 Ma for a NE-striking dyke at the boundary between domains (III) and (IV), which had previously been included in the Mesoproterozoic Abitibi swarm (Ernst and Buchan, 1993; their site A1). A paleomagnetic remanence direction with R-polarity (east-up) was reported by both Ernst and Buchan (1993) and Halls et al. (2005) at that locality plus one other that could represent the same dated dyke. About 500 km farther to the west, a U–Pb baddeleyite age of 2174.6 ± 3.2 Ma was obtained from a similarly NE-striking dyke that also yielded a preliminary R-polarity remanence direction (Hamilton and Stott, 2008). Although these unusual R-polarity directions from the westernmost localities of the Biscotasing swarm are intriguing, we exclude them from our calculations, because the available paleomagnetic directions are not precisely antiparallel to the N-polarity directions in domain (III), which could reflect a slight age difference between the polarities (Hamilton and Stott, 2008). Because some of the Biscotasing dykes have been sampled at several localities with significant distances along strike, we calculate a mean of VGPs from all site-mean directions in each of those dykes. From that mean of VGPs, we compute declination and inclination for a reference locality near the center of all sampling localities along that dyke (Table A1). As concluded by Halls and Davis (2004), the mean paleomagnetic remanence declinations between domains (I) and (III) differ by 12° and add further support to west/east Superior relative rotation.

The Marathon dykes are located in domains (III) and (IV), and studied paleomagnetically by Buchan et al. (1996). Halls et al. (2008) showed that the so-called Kapuskasing dykes (see also Halls and Palmer, 1990), which have a steeper remanence inclination than the Marathon swarm, have ages that are precisely coeval with the Marathon "N" dykes (2126–2121 Ma). Most Marathon "R" dykes (2106–2101 Ma) are located within domains (III) and (IV), with a few outlying examples in domain (II). We follow Halls et al. (2008) in excluding dykes from the easternmost parts of the Chapleau block in the KSZ, which appear to have delayed acquisition of remanence due to intrusion at depth, with possible ∼10° tilting during exhumation. As with the Matachewan dataset, site 29 of Buchan et al. (1996) lies within the uncertainty area of domains (III) and (IV), and is thus included only in combined calculations for those two domains. Finally, Halls et al. (2008) identified a possible Marathon "N" dyke located within the Fort Frances swarm (see below). We exclude data from this dyke because of its singular occurrence and possibility that its remanence is secondary (the original interpretation of Halls, 1986; though discussed and discounted by Halls et al., 2008).

The Lac Esprit dykes, located within domain (I) in the James Bay lowlands area of Quebec, are constrained by both paleomagnetic and geochronologic data, the latter indicating an emplacement age of 2069 ± 1 Ma (Buchan et al., 2007). We filter the paleomagnetic data at the site level, according to the criteria described above for Matachewan dykes. Means are then calculated as described above for the Biscotasing swarm. Note that some dyke means are available from only two quality-filtered sites, each given unit weight. In those cases, the calculated α_{95} values can be spuriously larger than the typical cutoff value of 15°, but the dyke means are included in our analysis. The Fort Frances dykes (previously known as the Kenora-Kabetogama swarm), in domain (IV) of Minnesota and southwestern Ontario, are also dated by U–Pb with an age range of 2077–2067 Ma (Buchan et al., 1993; Wirth et al., 1995; Schmitz et al., 2006), the older set of which has been studied paleomagnetically by Halls (1986). We followed the dyke-mean-direction averaging procedure described above, generating a grand mean

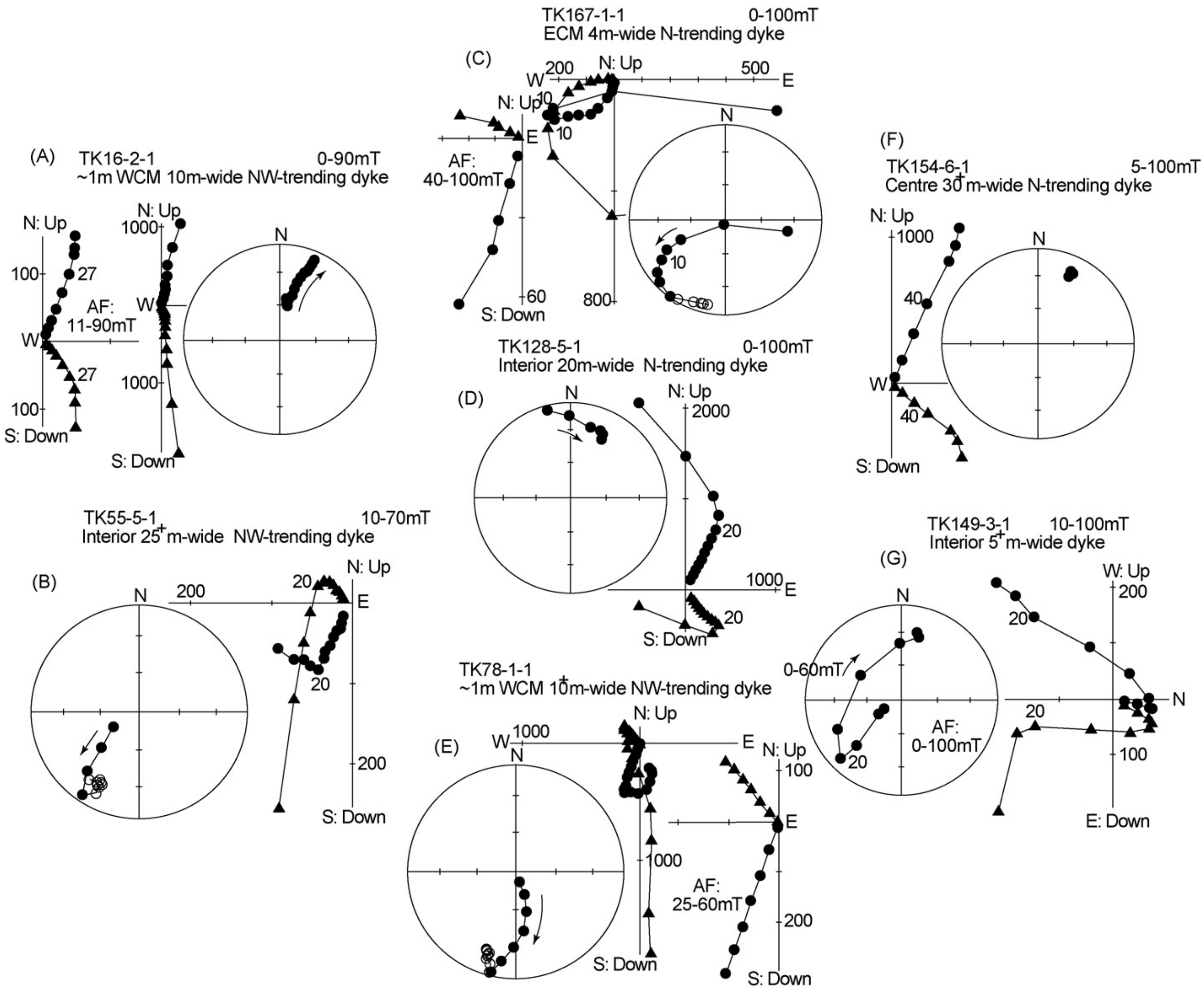

Fig. 2. Representative Matachewan N- and R-polarity data selected from the new paleomagnetic results (Table A1) within the fault-bounded and variably uplifted crustal regions at the southern end of the Kapuskasing zone as depicted in Fig. 2 of Halls and Zhang (2003). Diagrams are arranged schematically in their relative geographic positions. Panels A, D, and F are respectively from the Budd Lake, Pineal Lake and Chapleau uplifts (see Fig. 2 of Halls and Zhang, 2003) where only N-polarity characteristic secondary magnetizations are observed, whereas B, C, and E are from less-exhumed regions which yield primary magnetizations dominantly of R-polarity. Panel G represents the occasional instances, found in both the Chapleau and Pineal Lake blocks, of high-coercivity N magnetization coexisting with lower-coercivity R-polarity, interpreted as incomplete remagnetization of originally R-polarity dykes. On vector diagrams (magnetization intensities in 10^{-3} A/m) circles represent the tip of the magnetization vector projected onto the horizontal plane, and triangles represent the tip projected onto a vertical plane, either E–W or N–S for optimal viewing of directional changes. On stereonets solid/open symbols represent downward/upward pointing magnetizations. Small numbers beside points in vector diagrams give the demagnetization step in mT, and arrows on stereonets indicate the direction of the demagnetization path.

from 12 dykes. Given the nearly precisely coeval age determinations for the Lac Esprit and Fort Frances dyke swarms, Buchan et al. (2007) ascribed a $23 \pm 12^{\circ}$ difference in remanence declinations (all data reduced to a common site for comparison) to the same vertical-axis rotation event as proposed by Halls and Davis (2004).

3. Results: new data from the Matachewan R and N swarms

We report here (Appendix, Table A1) paleomagnetic results from 59 sites of Matachewan dykes exposed in domains (I) and (II). Samples for all sites, oriented using both a sun and magnetic compass, were subject to detailed, stepwise alternating-field demagnetization and measurement on a spinner magnetometer. The full experimental details are given in Halls and Davis (2004). These data were obtained at various times between 1997 and 2006. The majority of them were originally used to map N- and R-polarity domains (Halls and Zhang, 2003), although the paleomagnetic site details have not been published before. Site locations are shown in Fig. 1. These data showed that the Kapuskasing Zone at its southern end is composed of several fault-bounded regions of crustal uplift with surrounding regions of crust with lower-grade, more typical exposure levels of Archean rocks (Halls et al., 1994; Halls and Zhang, 2003). Within the uplifted regions Matachewan dykes carry a high-coercivity magnetization that is exclusively of N-polarity (Fig. 2A, D, and F). This N magnetization is considered to result from secondary mineral growth of micron-sized magnetites in feldspar that contributes to a brown clouding of the host mineral. The growth of the magnetite is in response to slow cooling at crustal depths of perhaps 20 km or more (Halls and Zhang, 2003). Rarely, dykes within the uplifted areas carry vestiges of their primary R signature, indicative of incomplete remagnetization (Fig. 2G). In the surround-

Table 1
Differences in mean dyke paleomagnetic remanence directions from tectonic domains defined in this study.

Domain (IV)	Domain (III)	Domains (IV) + (III)	Domain (II)	Domain (I)	Ref. locality: 48°N, 84°W
16: 190.6, −16.8, 4.2	24: 193.0, −21.0, 4.1	41: 192.3, −19.6, 2.9	33: 220.9, −21.9, 4.3	68: 207.2, −12.7, 3.8	Matachewan-R
–	10: 012.0, 28.6, 5.9	10: 012.0, 28.6, 5.9	67: 027.6, 24.7, 2.3	19: 020.2, 27.2, 3.2	Matachewan-N
–	6: 243.8, 61.4, 7.4	6: 243.8, 61.4, 7.4	–	6: 262.9, 63.6, 7.8	Biscotasing
8: 300.8, 51.8, 10.6	8: 295.4, 62.2, 6.7	16: 298.4, 57.1, 6.2	8: 311.3, 66.4, 7.2	–	Marath./Kap.-N
6: 127.6, −54.9, 10.3	6: 140.5, −53.8, 10.1	13: 135.2, −54.4, 6.2	17: 144.9, −65.7, 7.7	–	Marath./Kap.-R
12: 122.1, −47.9, 6.2	–	12: 122.1, −47.9, 6.2	–	8: 146.7, −53.8, 5.7	F.F.-Lac Esprit
Declination differences relative to domain (IV):	3.2 ± 9.3		**30.3 ± 8.5**	**16.6 ± 8.0**	Matachewan-R
	–		–	–	Matachewan-N
	–	N.A.	–	–	Biscotasing
	−5.4 ± 17.3		10.5 ± 17.8	–	Marath./Kap.-N
	12.9 ± 20.4		17.3 ± 18.0	–	Marath./Kap.-R
	–		–	**24.6 ± 11.9**	F.F.-Lac Esprit
Declination differences relative to domain (III):			**27.9 ± 8.4**	**14.2 ± 7.9**	Matachewan-R
			15.6 ± 8.2	7.8 ± 8.9	Matachewan-N
		N.A.	–	**19.1 ± 15.2**	Biscotasing
			15.9 ± 13.9	–	Marath./Kap.-N
			4.4 ± 17.8	–	Marath./Kap.-R
			–	–	F.F.-Lac Esprit
	Declination differences relative to domains (IV) + (III):		**28.6 ± 7.2**	**14.9 ± 6.7**	Matachewan-R
			15.6 ± 8.2	7.8 ± 8.9	Matachewan-N
			–	**19.1 ± 15.2**	Biscotasing
			12.9 ± 13.4	–	Marath./Kap.-N
			9.7 ± 13.9	–	Marath./Kap.-R
			–	**24.6 ± 11.9**	F.F.-Lac Esprit
			Declination differences relative to domain (II):	**−13.7 ± 8.1**	Matachewan-R
				−7.8 ± 5.3	Matachewan-N
				–	Biscotasing
				–	Marath./Kap.-N
				–	Marath./Kap.-R
				–	F.F.-Lac Esprit

Means are listed as (number of sites): declination, inclination, and α_{95}. Differences in bold are nonzero at 95% confidence.

ing lower-grade crustal regions, where exhumation has been less, dykes with exclusively non-cloudy feldspar carry primary magnetizations of both N- and R-polarity; but R-polarity dykes are about five times more numerous (Fig. 2B, C, and E). In the uplifted blocks, stable N remanence is found in both chilled margins and coarse-grained dyke interiors, because it is carried by the micron-sized magnetite inclusions. In the less-exhumed crustal areas, however, the most stable primary remanence, with the highest coercivities, is found at or within a meter of the dyke margins where chilling has reduced the size of magnetite carriers (see Fig. 2 in Halls, 2008)

4. Results: vertical-axis approximation of regional deformation

Previous discussion on Proterozoic deformation across the KSZ has emphasized the predominance of local vertical-axis rotations between two domains, with the KSZ itself accommodating the rotation by shortening (Halls and Davis, 2004; Buchan et al., 2007) and an element of dextral strike-slip offset (West and Ernst, 1991). If relative motions of internally rigid blocks of lithosphere with narrow boundaries (*i.e.*, microplates) are the cause of the observed differential rotations, then a reconstruction using Euler poles is more appropriate than simple vertical-axis restoration of all blocks. However, as an initial approximation on the magnitude of relative rotations among the four domains identified in this study, we first consider a matrix of paleomagnetic declination data from all dyke swarms spanning the domains. This exercise also facilitates comparison between our analysis, which considers the combined dataset from six dyke swarms, with previous estimates using results from only one or two swarms each (Halls and Davis, 2004; Buchan et al., 2007).

Table 1 tabulates the summary mean paleomagnetic remanence data from the six Paleoproterozoic dyke swarms (treating opposite-polarity subswarms as separate entities) across the four tectonic domains. The quality-filtered dyke data contributing to these means are listed in the Appendix (Table A1). Those site-mean data have all been recalculated (assuming a GAD geomagnetic field model) to a common reference locality near the center of the region (48°N, 84°W) for the sake of the comparisons in Table 1. Differences in remanence declination are significantly nonzero (uncertainties are given as the sum of α_{95} values) for many pairs of swarms across the tectonic domains. Only the (IV) vs. (III) domain comparison shows no significant difference in mean remanence declinations among any of the dyke swarms.

According to the remanence data, we can approximate deformation in the region by the following simple model: relative to domain (I), domain (II) has rotated 9° CW; relative to domain (II), domain (III) has rotated 23° CCW; and domains (III) and (IV) can be treated together as an internally rigid block (III + IV). Twenty-four out of 25 of the declination differences listed in Table 1 are consistent, within error, with this simple model. The lone exception, Marathon/Kapuskasing N between domains (II) and (III) falls just 1° short of consistency, consists of a small number of data points, and has the highest inclination angle (where random errors amplify declination scatter). The uncertainties in the data permit alternative models, but these will all be within a few degrees of our preferred estimate. The 14° relative rotation between domains (I) and (III + IV) is also consistent with our

Table 2
Differences in mean strikes of dykes from tectonic domains defined in this study.

Domain (IV)	Domain (III)	Domains (IV) + (III)	Domain (II)	Domain (I)	
15: 308 ± 16	12: 330 ± 12	28: 318 ± 17	9: 346 ± 14	31: 335 ± 11	Matachewan-R
–	3: 339 ± 4	3: 339 ± 4	30: 348 ± 12	14: 346 ± 16	Matachewan-N
–	6: 033 ± 4	6: 033 ± 4	–	6: 054 ± 4	Biscotasing
2: 025 ± 35	6: 022 ± 7	8: 023 ± 15	8: 063 ± 26	–	Marath./Kap.-N
4: 006 ± 26	5: 026 ± 36	9: 017 ± 32	17: 061 ± 20	–	Marath./Kap.-R
12: 325 ± 17	–	12: 325 ± 17	–	8: 340 ± 15	F.F.-Lac Esprit
Strike differences relative to domain (IV):	22 ± 28		38 ± 30	27 ± 27	Matachewan-R
	–		–	–	Matachewan-N
	–	N.A.	–	–	Biscotasing
	−3 ± 42		38 ± 61	–	Marath./Kap.-N
	20 ± 62		55 ± 46	–	Marath./Kap.-R
	–		–	15 ± 32	F.F.-Lac Esprit
	Strike differences relative to domain (III):		16 ± 26	5 ± 23	Matachewan-R
			9 ± 16	7 ± 20	Matachewan-N
		N.A.	–	21 ± 8	Biscotasing
			41 ± 33	–	Marath./Kap.-N
			35 ± 56	–	Marath./Kap.-R
			–	–	F.F.-Lac Esprit
		Strike differences relative to domains (IV) + (III):	28 ± 31	17 ± 28	Matachewan-R
			9 ± 16	7 ± 20	Matachewan-N
			–	21 ± 8	Biscotasing
			40 ± 41	–	Marath./Kap.-N
			44 ± 52	–	Marath./Kap.-R
			–	15 ± 32	F.F.-Lac Esprit
			Strike differences relative to domain (II):	−11 ± 25	Matachewan-R
				−2 ± 28	Matachewan-N
				–	Biscotasing
				–	Marath./Kap.-N
				–	Marath./Kap.-R
				–	F.F.-Lac Esprit

Errors are quoted at 1σ standard deviation; data limited to dykes with reported dips of 80° or more; references cited in text (Table A1).

more rigorous Euler pole analysis, as will be discussed below. The range in values of relative rotation between eastern and western Superior dykes (Tables 1 and 2) is consistent with all of the earlier-published paleomagnetic estimates of 12 ± 9° (Bates and Halls, 1991a), 16 ± 21° (Halls and Davis, 2004), and 23 ± 12° (Buchan et al., 2007). The remanence data are *not* consistent with the 4–6° of relative rotation proposed by West and Ernst (1991), although the component of strike-slip displacement in their model could be converted to an additional amount of rotation by incorporating concave-NW curvatures to the dextral structures (thus turning them into small-circle segments about a more localized Euler pole).

For a second and independent test of relative rotations, Table 2 tabulates the mean strikes of dykes (in contrast to paleomagnetic remanence declinations) across the four regional domains. In general, strike variance is larger than paleomagnetic declination variance (compare standard deviations in Table 2 versus those of Table 1). This is probably due to anisotropy of the intruded basement gneisses or greenstones, which can deflect the local orientation of a dyke away from its natural geometry according to regional stresses (but not affect the paleomagnetic remanence if the dyke itself is isotropic). The data listed in Table 2 are filtered to exclude those dyke orientations that dip more than 10° from vertical; the excluded subset is almost certainly affected by such anisotropies. Those more shallowly dipping dykes are distributed unevenly throughout the region and are interspersed among near-vertical dykes. Therefore, their presence does not indicate coherent regional tectonic tilting, and their magnetic remanence data are as reliable as any other dykes in the area. All of the mean strike differences between tectonic domains, listed in Table 2, are consistent with the declination-based rotation model as described above. Concordance of the orientation data with paleomagnetic remanence variations is compelling evidence for tectonic rotations across the region (*e.g.*, Bates and Halls, 1991a; Halls and Davis, 2004).

Part of the variance of dyke strikes throughout the KSZ region is due to original fanning geometries of the swams. For example, the fanning geometry of Matachewan dykes within domain (I) is evident as a primary feature of the swarm, because paleomagnetic remanence data do not show a significant difference between the N-striking dykes near Timmins and the NW-striking dykes near Ranger Lake (Bates and Halls, 1991a). Also, the visually apparent (Fig. 1) difference in Matachewan dyke strikes between domains (III) and (IV), which formed the basis of our initially subdividing those domains as a null hypothesis, is in fact not significant at the 95% level in declination data (Table 1), nor is it significant at the 1-sigma level in strike means (Table 2). We suspect that more data from domains (III) and (IV) will eventually reduce the uncertainties to show that there are significant strike differences in the Matachewan R swarm, as is visually apparent on aeromagnetic maps, but that the remanence declinations will show this curvature as mostly, if not entirely, a primary geometrical feature of the swarm. Similar curved geometries of dyke swarms are observed at both small scale (Spanish Peaks) and large scale (Mackenzie large igneous province) according to regional stress-field variations (Muller and Pollard, 1977; Ernst et al., 1995). Strike differences between domains (III) and (IV) in the Marathon swarm are more likely due to a simple radiating pattern about a focus south of Lake Superior (Halls et al., 2008).

5. Results: Euler pole analysis

In order to find the most reasonable location of an Euler pole to describe the relative rotation of western versus eastern Superior, we may use suitable inferences from the geometric boundary conditions and known regional tectonic history to infer likely pole locations, and then optimize the total reconstruction angle to best-align the paleomagnetic and dyke trend data. Initial estimation of the correct Euler pole can be guided by a series of observations. First, vertical-axis rotation appears to be the dominant form of deformation among the domains, thus locating Euler poles in proximity to the region, rather than far away on the globe. Second, age constraints provided by affected versus unaffected dyke swarms (respectively 2070 and 1870 Ma) and deformation in the KSZ (*ca.* 1900 Ma; see above) are compatible, thus permitting tectonic reconstructions of the KSZ to define the Euler pole position more precisely. Third, the most significant KSZ structure is on its southeastern boundary, most notably the Ivanhoe Lake shear zone (ILSZ), thus estimates of tectonic offsets across that structure in particular are most relevant to the analysis. Fourth, seismic constraints on the ~35° dip of that structure, plus the vertical offset of *ca.* 18–20 km as determined by a suite of thermochronologic data for *ca.* 1900 Ma, imply about 27 km of lateral displacement or underthrusting of domain (I) beneath domain (II), as the component of motion normal to the shear zone (Percival and West, 1994). Fifth, for any Euler rotation, the lateral translation distance at any point is proportional to the sine of the great-circle angular distance between that point and the Euler pole. Euler rotation angles in the range of our simple declination model (net 14° across all domains) would be equivalent to the estimated 27 km of lateral underthrusting if the Euler pole were located about 100 km from the ILSZ. This estimate assumes orthogonal convergence across the ILSZ; the distance to the Euler pole can be increased indefinitely if the total sense of motion is made ever-more oblique to the shear zone. As a first approximation, however, the logic presented above implies that the dominant west/east Euler pole of rotation between the two halves of Superior craton should be placed within a few hundred km (*i.e.*, a few degrees of great-circle distance) of the ILSZ—essentially confined within the map area shown in Fig. 1.

Fig. 3 illustrates a range of possibilities for locating Euler poles in the region, according to the data from each of the four dyke swarms that extend across the KSZ. In each panel, the dashed curves represent isopleths of optimal rotation angles for maximizing the cluster of reconstructed VGPs (as measured by Fisher's (1953) concentration parameter '*k*'). Values of optimal *k*-values are given at latitude/longitude nodes across each panel. There are three primary conclusions to be drawn from Fig. 3. First is that the optimal clustering of paleomagnetic data is not sensitive to the precise Euler pole position, as long as it placed somewhere within the region. Second, *k*-values increase toward separate corners of the map area for different dyke swarm datasets, indicating that there is no single, distally located, optimal placement of an Euler pole to account best for all the data. Finally, the optimal rotation angles are distinctly different among the four datasets, ranging from ~8° (Matachewan N) to ~24° (Fort Frances–Lac Esprit). Additional criteria are necessary to pinpoint the Euler pole and its optimal rotation angle.

The amount of rotation is the simpler parameter to choose. As noted above, a simple vertical-axis model among three tectonic domains (I, II, and III + IV) can account for all of the remanence declination data and all but one of the dyke strike comparisons throughout the region. In that model, net rotation between domains (III + IV) and (I) amounts to 14°, partitioned by 23° CW from western Superior to domain (II) and 9° CCW from domain (II) to eastern Superior. A net $14.3 \pm 6.2°$ (95% uncertainty) rotation is also calculated using the four paleomagnetic pole comparisons (Fig. 3), as a mean that is weighted by $1/A_{95}$. Such a weighting appropriately represents the requirement that more precisely determined poles (most notably Matachewan R) should dominate the mean calculation.

The Euler pole placement is best narrowed by the analysis of KSZ and related structures and geometric rules of plate tectonics, as illustrated in Fig. 4. In principle, one of the best constraints on an Euler pole location is a strike-slip boundary, which constitutes a portion of a small circle about the pole. The perpendicular bisector to a strike-slip fault segment thus delineates the locus of possible pole locations. In the north, the Kineras Fault (Fig. 4) offsets two blocks of granulite-facies rocks in the KSZ, and has been interpreted either as a late-stage normal fault (Percival and McGrath, 1986) or a strike-slip fault of sinistral (Goodings and Brookfield, 1992) or dextral sense (Nitescu and Halls, 2002). To the south, Percival and McGrath (1986) inferred that the Ivanhoe Lake thrust zone transforms along its southwestern extremity to a dextral shear zone, a model confirmed by structural studies revealing strong subhorizontal stretching lineations and dextral offsets in the ENE-striking fault segments (Bursnall et al., 1994). This transform should continue to the west-southwest, perhaps segmented by transpressional left-stepping jogs (Halls and Zhang, 1998, 2003). It then follows the course of the Montreal River, defining the boundary between our tectonic domains (I) and (II). No individual dykes have been traced across the Montreal River Fault, which therefore can accommodate any amount of strike-slip motion as required by the regional tectonic data, within the limits of the 100–150-km-wide Matachewan "M3" subswarm, which is continuous across the fault. The Montreal River structural discontinuity, which we consider to be a Kapuskasing-related dextral transform fault system, plunges beneath Mesoproterozoic cover and eastern Lake Superior, probably to connect with compressional structures of the Penokean orogen (Riller et al., 1999), or perhaps in a more southward direction, off the craton and into the paleo-ocean that closed (*ca.* 1850 Ma; Schulz and Cannon, 2007) in association with that orogen.

We are now able to evaluate previous plate-tectonic models of KSZ deformation. West and Ernst (1991) precisely defined a two-part kinematic model of 50–60 km dextral offset along 045°-striking faults, plus a rotation in the range of 4–6° (nominally 5°) clockwise around a pole at (50°N, 81.5°W), to reconstruct the western domain relative to the eastern domain. In order to convert this two-stage model to a single Euler rotation, we first approximate the dextral strike-slip component as purely straight through the map area, thus defining a segment of a great circle, which implies that component's Euler reconstruction of (27.5°N, 150°E, −0.5° CCW). Multiplying the two component Euler matrices then produces a total Euler reconstruction of approximately (54°N, 88°W, −5° CCW) for the western domain relative to the eastern domain (star #1 in Fig. 4). The precise values of this calculation vary slightly according to a prescribed order of the two rotations, which was not specified by West and Ernst (1991), but that effect is minor. As noted above, adding a slight concave-NW curvature to the strike-slip faults will result in a more proximal Euler pole and greater angle of rotation for the dextral component of motion. Our preferred model, to be presented below, is in fact an end-member of this procedure, combining the dextral and rotational components of motion into a single, proximal Euler rotation.

Goodings and Brookfield (1992) depicted the Kineras Fault (KF in Figs. 1 and 4) as the southernmost element of a 300-km-long sinistral transform linking James Bay extension with transpression in the KSZ and the Penokean orogen. The straightness of this transform would imply a distally located Euler pole, perhaps

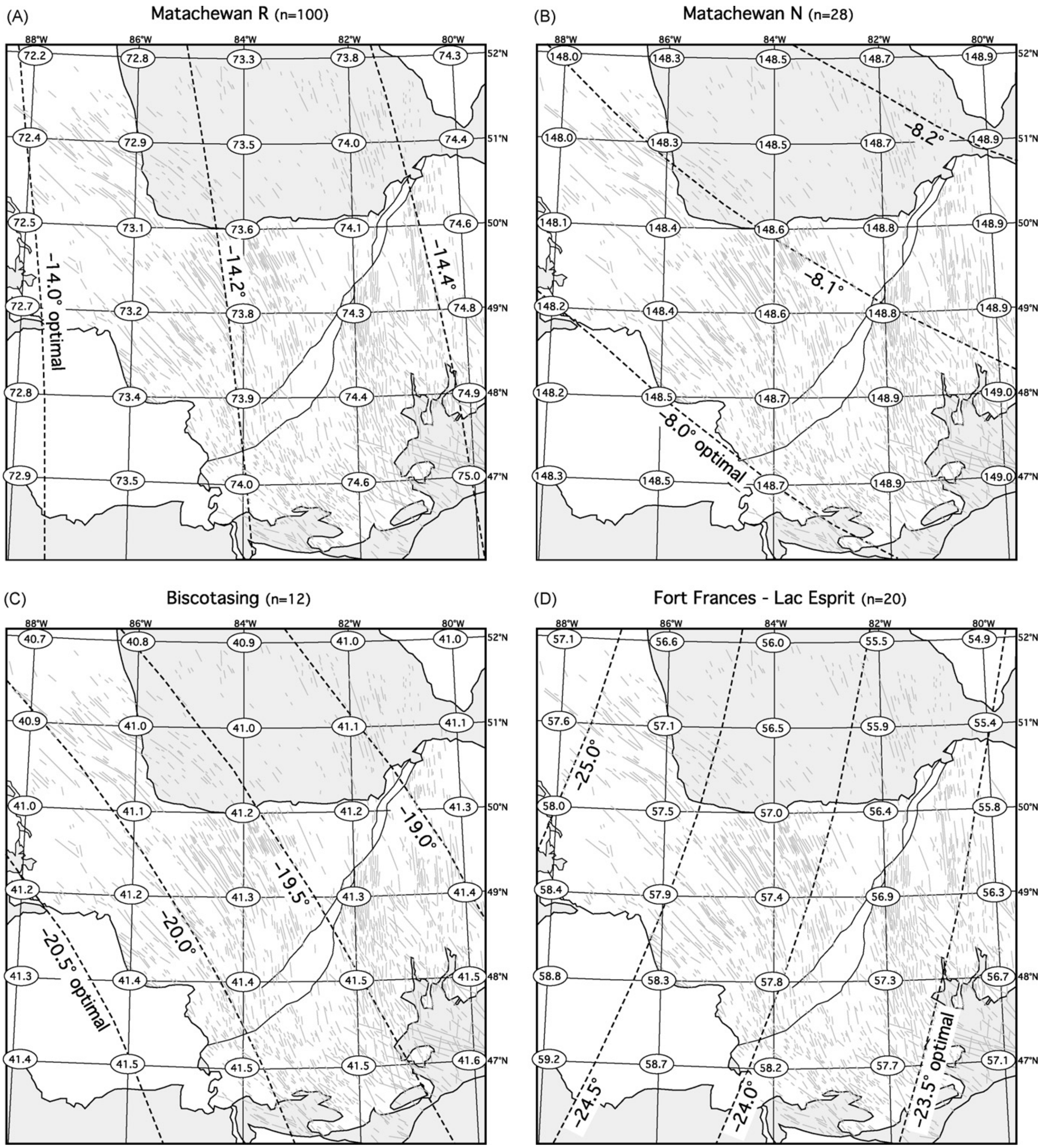

Fig. 3. Map of the region showing, for each of four dyke swarms and as a function of Euler pole location, the Euler angles (contour values) that optimally combine the paleomagnetic remanence data from domains (IV + III) and (I), along with values of Fisher's (1953) precision parameter (k) calculated at the grid nodes. (A) Matachewan R ($n = 100$), (B) Matachewan N ($n = 28$), (C) Biscotasing ($n = 12$), and (D) Fort Frances + Lac Esprit ($n = 20$).

thousands of km away. The model is attractive in that it explains alternating segments of shortening and transcurrent strain along the general orogenic strike of the KSZ. However, the total amount of proposed offset (160 km) plus minor rotation (5°) is incompatible with the observed 14° rotation between western and eastern Superior domains. The sinistral sense of motion in this model is defined largely by the inference of original continuity for the "Sutton" and "Hudson Bay" Arcs, a tenuous proposition due to their contrasting topographic profiles, or by the comparably equivocal matching of specific aeromagnetic anomalies of the Superior craton's Archean basement provinces (Goodings and Brookfield, 1992). A slight adjustment in the azimuth of inferred strike-slip motion relative to KSZ-bounding structures could change the inferred right-stepping transpressional jogs of the Goodings and Brookfield (1992) model, which imply sinistral shear, to left-stepping transpressional jogs as depicted by Nitescu and Halls

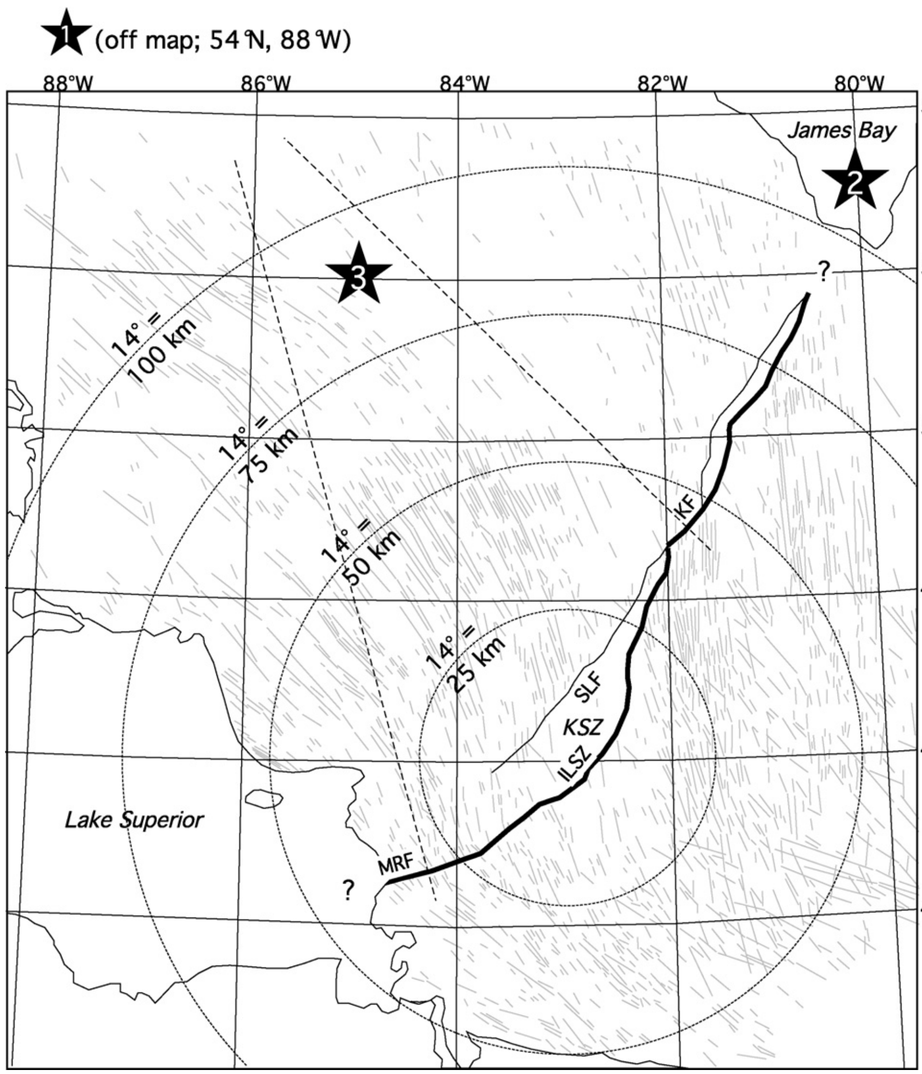

Fig. 4. Tectonic constraints on possible Euler pole locations between western and eastern Superior as accommodated by the KSZ (base map from Fig. 1). Circles concentric around 48°N, 83°W indicate the loci of 14° Euler pole rotations that would correspond to lateral offsets in 25 km increments. Dashed lines are the perpendicular bisectors to presumed strike-slip (transform) faults. Three possible Euler pole locations are indicated by black stars: (1) the total reconstruction pole computed from West and Ernst (1991), (2) an idealized pole location for scissors-like rotation linking KSZ shortening with extension in James Bay (after Halls and Davis, 2004), and (3) our preferred pole location that approximates intersections of the transform-perpendicular bisectors and honors the small distance of Paleoproterozoic lateral transport across the KSZ. KF = Kineras Fault, ILSZ = Ivanhoe Lake Shear Zone, MRF = Montreal River Fault, and SLF = Saganash Lake Fault.

(2002), implying dextral shear. As shown below, our preferred model achieves just such a result, reconciling the dextral sense of motion required by the Matachewan aeromagnetic data (West and Ernst, 1991) in the general context of a segmented transpressional system for the KSZ as envisioned by Goodings and Brookfield (1992).

Halls and Davis (2004) and Buchan et al. (2007) likewise did not specify Euler parameters, but their hypothesized kinematic association of KSZ shortening with coeval extension in James Bay implies a relative pole location near the intersection of those quasi-collinear features, which we approximate for the purposes of discussion at (51.5°N, 80°W) as shown in Fig. 4 (star #2). Such a pole location implies shortening directed normal to the KSZ as far south as 48°N, but allows dextral transpression through the Montreal River area. The model can account for the Z-kinked pattern of Matachewan dykes through the region, if due to non-plate-tectonic buckling about vertical axes, but it has difficulties with the following observations. First, crustal shortening across the ILSZ is predicted to be more than 100 km for this Euler pole with a 14° rotation, significantly greater than the value estimated from seismic profiles (55–70 km; Percival et al., 1989; Geis et al., 1990) or thermobarometry-based estimates for the Paleoproterozoic episode of motion (equivalent to *ca.* 27 km of lateral motion on the dipping structures; Percival and West, 1994). Second, there is lack of evidence for substantial crustal thickening along the length of the Kineras Fault, for which the model predicts *ca.* 60 km of orogen-normal thrusting. Third, and most troublesome, is the predicted increase in shortening south of the ILSZ, for example more than 140 km at the mouth of the Montreal River. Although substantial crustal discontinuities could exist in that region (*e.g.*, Halls and Zhang, 1998, 2003), a predicted displacement substantially larger than at the ILSZ is difficult to accommodate by the patchwork geometric pattern of observed structures.

Fig. 4 illustrates the constraints we use to choose our preferred Euler pole of 14° rotation between western and eastern Superior subprovinces. Perpendicular bisectors of the strike-slip segments of the Kineras Fault and the southwesternmost ILSZ to Montreal River Fault system intersect at about 52°N, 86°W, but an Euler pole at this location would imply about 125 km of lateral displacement on the ILSZ. Such an amount is too large relative to the estimates of shortening across that structure (55–70 km; Percival et al., 1989; Geis et al., 1990), especially when only the Paleoproterozoic episode of total shortening is considered (*ca.* 27 km; Percival and West, 1994). Recognizing the uncertainties of these shortening estimates, as well as their systematic increases permitted by possible oblique transport across the ILSZ, we propose a compromise location at 51°N, 85°W, somewhat more comfortably closer to the KSZ but in the same general area as the intersecting transform constraints (star #3 in Fig. 4). As discussed above, the precise placement of our preferred Euler pole is not crucial for optimizing the paleomagnetic data. Therefore, the model of western Superior rotation with Euler parameters (51°N, 85°W, −14° CCW) relative to eastern Superior fulfills all of our objectives as a tectonically plausible, simple restoration that will enable quantitative reconstructions of the Superia supercraton using paleomagnetic data.

As an additional factor of complexity, but likewise simplified here for the sake of further null-hypothesis testability, we consider data from domain (II) in a non-plate-tectonic sense. There are two principal reasons for abandoning the model of internally rigid plates in this instance. First, continuity of individual dyke anomalies from domain (III) into domain (II), as well as a more subdued metamorphic gradation along that boundary (as contrasted to sharp metamorphic discontinuity across the ILSZ) suggests "pinning" of the two domains with little or no lateral displacement along that boundary. Second, throughout domain (II), numerous small sinistral shear zones or veins have been recognized either within Matachewan dykes or along their margins, suggesting distributed "domino-style" deformation (Bates and Halls, 1991a; West and Ernst, 1991; Halls et al., 1994), and there is also a complex pattern of block faulting within the KSZ *sensu stricto* as depicted in Fig. 1 (Halls and Zhang, 2003). The 23° difference of paleomagnetic remanence declinations and dyke strikes between domains (IV + III) and (II) quantify this amount of simple shear throughout domain II. Table A1 lists not only the *in situ* paleomagnetic data from domain (II), but also columns for site locations and declination adjustments after restoring the distributed shear. In detail, for each site within the domain, a pivot point along the pinned domain (III/II) wall is calculated by extension along the mean Matachewan dyke strike (350° in domain II). Each site is then rotated in a 23° arc about its pivot point, to its adjusted location (Table A1); and 23° is subtracted from that site's remanence declination to its adjusted value (Table A1). The ILSZ and other domain (II) boundaries, as well as the extents of dyke subswarms as depicted in West and Ernst (1991) are illustrated in Fig. 5, in both present and restored geographies. This simple model accounts for the first-order deformation features of Matachewan dykes in the KSZ. More complicated models may subdivide domain (II) further, for example a component of discrete dextral offset along the Saganash Lake Fault (Fig. 4; West and Ernst, 1991), but such details are beyond the scope of this paper. Given the uncertainties involved in our model, and the possibility of horizontal-axis tilting in that region (Percival and McGrath, 1986; Symons et al., 1994) that we have not considered in our analysis, we exclude all directional data from domain (II) in calculating mean paleomagnetic poles for the Superior craton (Table 3).

Our Euler kinematics predict about 90 km of lateral displacement in the central KSZ region (Fig. 4), at a NE-verging azimuth that is highly oblique to the ILSZ and predicts dextral transpressional displacement across that structure. In our model of preserving Matachewan dyke line lengths of about 100–150 km in a dyke-parallel direction across domain (II), the 23° simple shear rotation corresponds to *ca.* 40–60 km of tangential displacement in a similar NE direction. Therefore, about half the total displacement between western and eastern Superior appears to be absorbed by the distributed rotational shear in the KSZ region. The other half is accommodated by oblique dextral transpression across the ILSZ, along the shallowly dipping lateral thrust ramp imaged by Percival et al. (1989) and Geis et al. (1990). Because our predicted sense of motion is highly oblique to the structure, there is no inconsistency between its magnitude (*ca.* 30–50 km) and the lesser estimate provided by thermobarometry at *ca.* 1900 Ma (27 km; Percival and West, 1994).

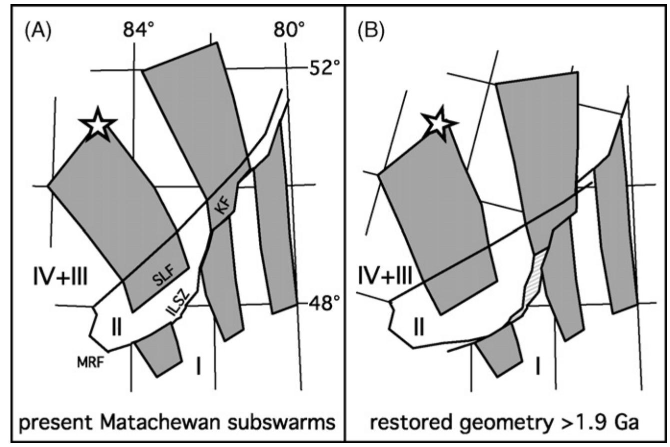

Fig. 5. Simplified representation of Matachewan dyke subswarms (A) in their present outcrop pattern, and (B) undeformed to their original geometry according to our preferred model (Euler pole shown by the star). Note that the KSZ and adjacent northwestern regions, constituting domain (II), are shown to be deformed by distributed shear (resolved by "domino-style" Matachewan-parallel sinistral faults) that results in the presently observed strike changes and paleomagnetic remanence deflections. This deformation is pinned to the eastern margin of domain (III), resulting in partial underthrusting of domain (I) under domain (II) via NE-verging dextral transpression at the Ivanhoe Lake shear zone (ILSZ; hatched region in the reconstruction). Other abbreviations as in Fig. 1.

To the north, our model predicts a substantial component of dextral strike-slip motion with a limited component of crustal thickening north of the Kineras Fault. In that region, our reconstruction realigns the Big Cedar Creek and Mattagami River Faults as part of a semi-contiguous Onaping Fault system (Buchan and Ernst, 1994). Domain (II) likely pinches out altogether near southernmost James Bay, north of which our model predicts dominantly dextral displacement on the order of 100 km. Aeromagnetic data in this region are not of high enough resolution to pinpoint the western/eastern Superior boundary; either transpressional or transtensional offsets are permitted. The latter would be consistent with limited evidence for extension in James Bay, as reviewed by Goodings and Brookfield (1992) and Halls and Davis (2004). Given the uncertain timing of western/eastern Superior relative motion, *i.e.*, between 2070 and 1870 Ma, a tectonic connection with the *ca.* 2000 Ma basaltic volcanism in the eastern Hudson Bay region (Halls and Davis, 2004) cannot yet be assessed.

To the south, the Montreal River Fault is predicted to be dominantly dextral strike-slip in character, and like the ILSZ, accommodating about half (*ca.* 30–50 km, as described above) of the total predicted displacement that is not taken up by distributed deformation in domain (II). Unlike the Penokean indentation model of Riller et al. (1999), which predicts a reduction of deformation to near zero at the apical point of arc-continent collision (near 46°N, 90°W), our Euler pole predicts an increase in total lateral displacement from the Montreal River toward the south and west. The indentation model appears unlikely, however, because internal rigidity of western Superior is demonstrated throughout domains (IV) and (III) since 2100 Ma, as indicated by concordance of the Cauchon Lake and Marathon paleomagnetic poles spanning this geographical breadth from northern Manitoba to Wawa (Table 4). It is possible that the ILSZ and Montreal River Fault connect with the Great Lakes Tectonic Zone in Michigan's Upper Peninsula (Riller et al., 1999), but it is considered here as equally possible that the

Table 3
Euler rotations of paleomagnetic poles from tectonic domains across the Kapuskasing Structural Zone.

Dyke swarm	Domain	*n*	Plat (°N)	Plong (°E)	*K*	A_{95} (°)	Euler rotn to (I)	Plat-I (°N)	Plong-I (°E)
Matachewan R	IV	16	−49.6	259.7	112.8	3.5	51.0, −85.0, −14.0	−45.9	240.0
Matachewan R	III	24	−51.4	255.4	103.4	2.9	51.0, −85.0, −14.0	−47.1	235.6
Matachewan R	IV, III	41	−50.8	256.7	101.8	2.2	51.0, −85.0, −14.0	−46.6	236.9
Matachewan R	II[a]	33	−50.5	247.7	39.7	4.0	51.0, −85.0, −14.0[a]	−45.3	229.0
Matachewan R	I	68	−42.5	239.1	69.8	2.1	None	−42.5	239.1
Matachewan R mean	*IV, III, I*	*109*			*75.6*	*1.6*	*Variable, as above*	*−44.1*	*238.3*
Matachewan N	III	10	−56.1	255.2	98.2	4.9	51.0, −85.0, −14.0	−51.6	233.9
Matachewan N	II[a]	67	−55.0	268.1	83.1	1.9	51.0, −85.0, −14.0[a]	−52.2	245.8
Matachewan N	I	19	−52.6	242.5	173.3	2.6	None	−52.6	242.5
Matachewan N mean	*III, I*	*29*			*125.1*	*2.4*	*Variable, as above*	*−52.3*	*239.5*
Biscotasing	III	6	17.0	232.9	46.3	9.9	51.0, −85.0, −14.0	23.4	224.2
Biscotasing	I	6	28.6	223.5	32.2	12.0	None	28.6	223.5
Biscotasing mean	*III, I*	*12*			*40.0*	*7.0*	*Variable, as above*	*26.0*	*223.9*
Marathon N	IV	8	44.1	190.8	19.5	12.9	51.0, −85.0, −14.0	52.9	179.9
Marathon N	III	8	46.3	205.9	36.7	9.3	51.0, −85.0, −14.0	54.7	198.1
Marathon + Kapusk. N	II[a]	8	44.6	216.8	28.9	10.5	51.0, −85.0, −14.0[a]	52.3	210.7
Marathon N mean	*IV, III*	*16*	*45.4*	*198.3*	*24.2*	*7.7*	*As above*	*54.1*	*188.9*
Marathon R	IV	6	50.6	188.9	33.9	11.7	51.0, −85.0, −14.0	59.4	177.7
Marathon R	III	6	58.2	176.6	29.4	12.6	51.0, −85.0, −14.0	66.6	160.9
Marathon + Kapusk. R	II[a]	17	52.8	213.5	12.0	10.7	51.0, −85.0, −14.0[a]	60.7	208.4
Marathon R mean	*IV, III*	*13*	*55.1*	*182.3*	*31.4*	*7.5*	*As above*	*63.8*	*168.9*
Fort Frances (FF)	IV	12	42.8	184.6	51.3	6.1	51.0, −85.0, −14.0	51.5	172.7
Lac Esprit	I	8	62.0	170.5	75.2	6.4	None	62.0	170.5
FF + Lac E. mean	*IV, I*	*20*			*49.0*	*4.7*	*Variable, as above*	*55.7*	*171.9*

[a] Dextral distributed shear within domain (II) is restored 23°, as described fully in the text, prior to the pole calculations shown here.

boundary between domains (II) and (I) turns southward directly toward the oceanic realms of the Penokean orogen at 85–86°W. If so, the model predicts a KSZ-like zone of convergence (with greater amounts of shortening) deeply buried beneath the Mid-Continent Rift system and eastern Lake Superior. Given the recent advances in understanding the timing of Penokean deformation at *ca.* 1880–1830 Ma (Schulz and Cannon, 2007), only the early phases of that orogen, the 1880 Ma Pembine-Wausau arc collision with southern Superior, can be invoked as related to the pre-1870-Ma deformation in the KSZ. However, that collision has been described as "soft" (Schulz and Cannon, 2007) with only mild deformation and metamorphism. A more likely dynamic scenario

Table 4
Selected 2.68–1.88 Ga poles from the Superior craton in both western and eastern reference frames.

Paleomagnetic pole	Age (Ma)	Western reference frame		Eastern reference frame		A_{95} (°)	1234567 Q	References
		Plat (°N)	Plong (°E)	Plat (°N)	Plong (°E)			
Otto Stock lamproph.	≤2680 ± 1	−62	045	−69	047	5	111c101 6	Pullaiah and Irving (1975) and Buchan et al. (1990)
Ptarm.-Mistassini[a]	2505 ± 2	−52.4	229.9	−45.3	213.0	13.8	1010101 4	Fahrig et al. (1986), Buchan et al. (1998) and recalc. this study (E)
Matachewan R	2473–2446	−48.1	257.4	−44.1	238.3	1.6	111C101 6	See text; this study (W + E)
Matachewan N	2446 ± 3	−55.6	261.5	−52.3	239.5	2.4	111C101 6	See text; this study (W + E)
Nipissing N1 (B)	2217 ± 4	−16	286	−17	272	10.0	111C111 7	Buchan et al. (2000) (E)
Senneterre (B)	2216 + 8/−4	−12.9	297.3	−15.3	284.3	6.0	111C111 7	Buchan et al. (1993) (E)
Biscotasing (N)	2172–2167	19.6	232.3	26.0	223.9	7.0	111C100 5	Buchan et al. (1993) (E), Halls and Davis (2004) (W); this study (W + E)
Marathon N	2126–2121	45.4	198.2	54.1	188.9	7.7	1110100 4	Buchan et al. (1996) and Halls et al. (2008) (W)
Marathon R	2106–2101	55.1	182.2	63.8	168.9	7.5	111C100 5	Buchan et al. (1996) and Halls et al. (2008) (W)
Cauchon Lake (R)[a]	2091 ± 2	53.8	180.9	62.4	167.3	7.7	111C100 5	Halls and Heaman (2000); recalc. this study (W)
Fort Frances (R)	2076 + 5/−4	42.8	184.6	51.5	172.7	6.1	1110100 4	Halls (1986); recalc. this study (W)
Lac Esprit (R)	2069 ± 1	53.3	183.3	62.0	170.5	6.4	1110100 4	Buchan et al. (2007); recalc. this study (E)
Minto (B)[a]	1998 ± 2	30.0	183.2	38.7	171.5	13.1	1110110 5	Buchan et al. (1998); recalc. this study (E)
Molson B + C2 (B)[a]	1877 + 7/−4	28.9	218.0	36.6	209.8	3.8	111C110 6	Zhai et al. (1994) and Halls and Heaman (2000); recalc. this study (W)

Notes: B = both polarities, F.F. = Fort Frances, W = sites in western region, and E = sites in eastern region. Q reliability criteria from Van der Voo (1990); for criterion #4 (field stability tests), C = full baked-contact test with crossover of magnetization into stable host rock at a reasonable distance relative to the depth of dyke emplacement, c = full inverse baked-contact test demonstrating magnetization older than a younger intrusion, but not necessarily primary.

[a] Ptarmigan-Mistassini pole is calculated as the mean of VGPs from three dykes: sites 65–66 of Buchan et al. (1998) are averaged as one dyke mean, plus the U–Pb dated site 64, plus site 7601 of Fahrig et al. (1986); sites 7607R and 7615 of Fahrig et al. (1986) bear a similar remanence direction but are excluded due to large α_{95} values (>15°). Cauchon Lake R pole is computed as the mean of VGPs from six dykes in the Zhai et al. (1994) study, among eight categorized as 'C1' by Halls and Heaman (2000), that passed our site-mean quality citeria. Minto pole is recalculated as the mean of VGPs from six dykes: sites 67–69 are averaged as one dyke mean, and site 80 is excluded (α_{95} > 15°). Molson B + C2 pole recalculated as the mean of VGPs from 34 sites: sites 9, 25, 34, 58, 63, 87, and 92 are excluded (α_{95} > 15°). A rotated position for the Molson B + C2 pole, in the eastern Superior reference frame, is given in parentheses, because timing constraints on the western/eastern Superior rotation are currently too lax to specify whether it occurred before or after emplacement of the Molson dykes.

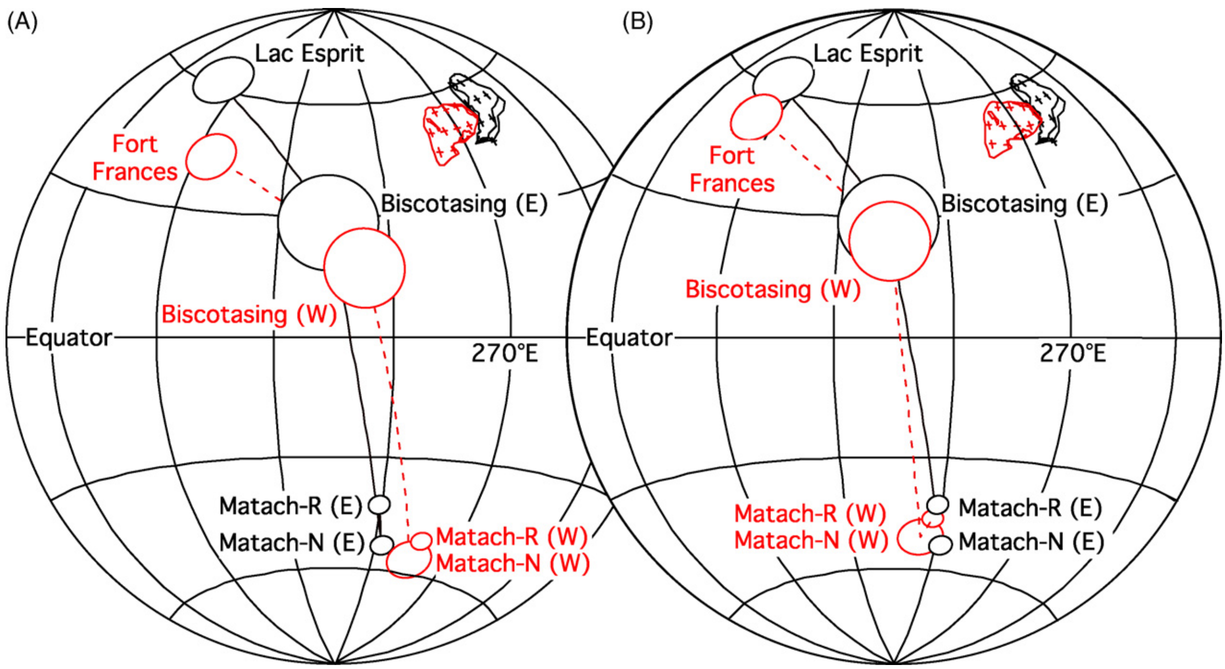

Fig. 6. Paleomagnetic poles from four 2.47–2.07 Ga Superior dyke swarms (A) in the present reference frame, and (B) in the eastern, domain (I) pre-rotational reference frame restored according to our preferred Euler rotation of (51°N, 085.0°W, −14.0° CCW) for domains (IV + III). In both panels, western Superior and its poles are shown in gray color, with poles connected by the dashed curve; eastern Superior and its poles are shown in black, with poles connected by the solid curve.

is that relative rotation between western and eastern Superior was driven by other plate-boundary forces, and that the southerly motion of western Superior "swept up" the Pembine-Wausau terrane in its path. Burial of these terranes beneath Keweenawan strata, and reactivation of KSZ-related structures in Keweenawan time (Manson and Halls, 1997) render these speculations difficult to test.

Paleomagnetic poles combining data from the western (IV + III) and eastern (I) domains are listed in Table 3, of which the rightmost columns present all data in the domain (I) reference frame. As stated above, deformation within domain (II) is too uncertain to allow its paleomagnetic directional data to contribute to the Superior apparent polar wander (APW) path. Paleomagnetic poles from the four dyke swarms that cross the KSZ are shown in Fig. 6, in both the present reference frame and our preferred Euler-reconstructed reference frame of domain (I). Matachewan pole errors are the smallest, so data from those swarms are most useful for constraining the total amount of rotation between the western and eastern Superior blocks. A slight discordance of the Fort Frances and Lac Esprit pole pair (Fig. 6) could be due to the age difference (as large as 10 million years within uncertainty) between those two swarms.

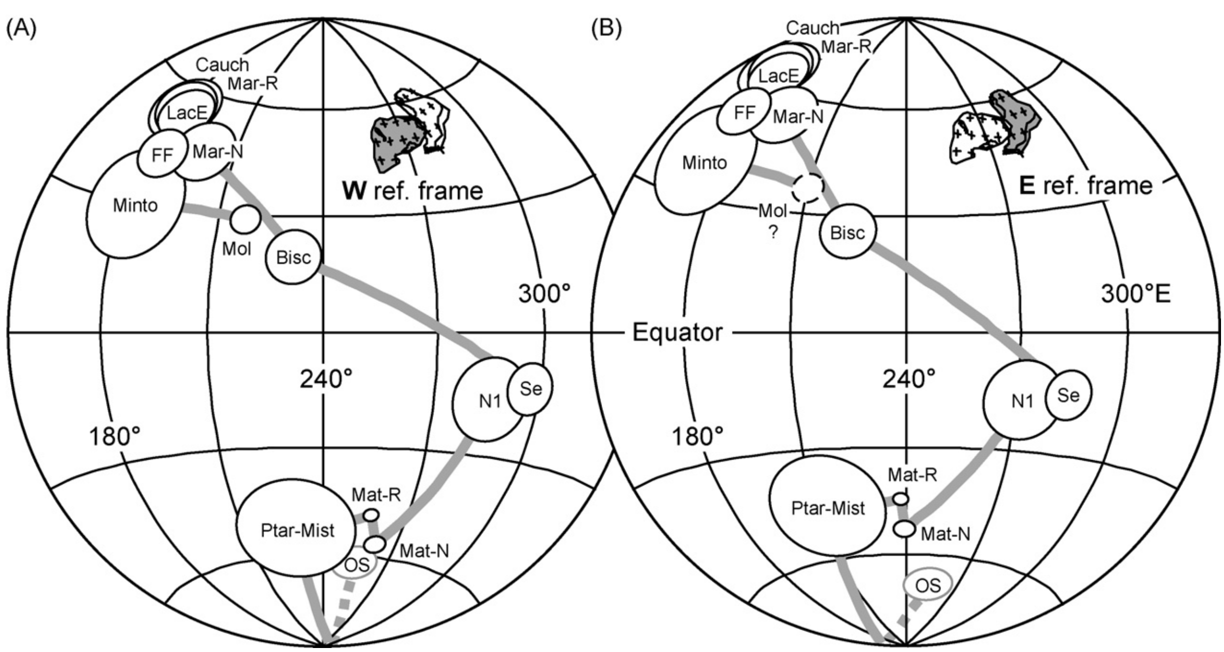

Fig. 7. Apparent polar wander paths in the (A) western and (B) eastern Superior reference frames, combining all reconstructed data from domains (IV), (III), and (I), as well as additional published results. Poles are listed in Table 4. The Otto Stock pole (OS) is shown as projected onto the far hemisphere.

Using our preferred Euler rotation for restoring Paleoproterozoic deformation within the Superior craton, we can generate an aggregate APW path (Table 4) for each of the eastern and western reference frames. The poles are plotted in Fig. 7. These results include our recalculations of the following results according to the uniform site-mean quality criteria outlined above: Ptarmigan-Mistassini (Fahrig et al., 1986; Buchan et al., 1998), Cauchon Lake C1 (Halls and Heaman, 2000), Minto (Buchan et al., 1998), and Molson B + C2 (Halls and Heaman, 2000). Details of the included site means are given in the footnote to Table 4. Poles from the Huronian margin (*e.g.*, Williams and Schmidt, 1997; Schmidt and Williams, 1999; Hilburn et al., 2005; and many earlier studies) are omitted due to the substantial age uncertainties of those results. Many poles from northern Superior are omitted for the same reason (*e.g.*, Schmidt, 1980; Schwarz and Fujiwara, 1981; Buchan and Baragar, 1985). Due to the uncertain timing of the western/eastern Superior rotation within the interval 2070–1870 Ma as defined by the paleomagnetic data, we are not sure whether the same 14° rotation of Molson B + C2 pole into eastern Superior coordinates is a valid exercise; thus it is given in Table 4 in parentheses, and queried in Fig. 7B.

Future paleomagnetic tests of proposed "Superia" craton reconstructions (*e.g.*, Bleeker and Ernst, 2006), should employ the Superior APW reference poles (Table 4) that are of most relevance to the hypothesized juxtapositions. For example, the Roscoe and Card (1993) model of Wyoming rifting away from western Superior, can be tested by paleomagnetic results (*e.g.*, Harlan et al., 2003) rotated directly into the western Superior reference frame. In contrast, proposed reconstructions of Karelia against the southeastern margin of Superior (Heaman, 1997; Bleeker and Ernst, 2006) can be tested directly by rotating European poles into the eastern Superior reference frame (Halls, 1998; Mertanen et al., 1999; Pesonen et al., 2003; Evans and Pisarevsky, 2008). Using the Euler parameters provided in this paper, data from both halves of Superior can be used for these tests. However, because of the uncertainty in timing of western/eastern Superior rotation relative to intrusion of the Molson dykes at *ca.* 1880 Ma, the paleomagnetic pole from those dykes should be considered only *in situ*, in the western reference frame. In Table 4, a restored Molson pole is calculated in the eastern reference frame, but such a calculation would be unnecessary if the rotation were completed by Molson time. Resolution of this detail awaits further study.

6. Conclusions

We combine new paleomagnetic results with those published from previous studies to generate a quantitative plate-tectonic model restoring western/eastern Superior subprovinces across the Kapuskasing Structural Zone (KSZ). The model is parameterized by an Euler rotation of (51°N, 85°W, −14° CCW) to reconstruct western Superior relative to eastern Superior, with such deformation occurring between 2070 and 1870 Ma. The model predicts substantial dextral displacement (total about 90 km) along the concave-NW intra-Superior boundary zone extending from the Montreal River, through the KSZ, and continuing through James Bay. In the KSZ, about half of that amount is absorbed by penetrative simple shear, resolved by "domino-style" rotations of 23° throughout the KSZ and adjacent areas to its immediate NW, and the other half by NE-verging transpression across the Ivanhoe Lake shear zone. Distributed shear throughout the KSZ is likely more complex than the simple model we have constructed for its palinspastic restoration; therefore we discourage the use of paleomagnetic poles from that region in constructing an apparent polar wander path for the Superior craton prior to 1870 Ma. Our quantitative restoration of western and eastern Superior subprovinces permits rigorous treatment of pre-1870 Ma paleomagnetic poles for testing Archean-Paleoproterozoic supercraton reconstructions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.precamres.2010.02.007.

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