Paleomagnetism and U–Pb geochronology of the 2.17 Ga Biscotasing dyke swarm, Ontario, Canada: evidence for vertical-axis crustal rotation across the Kapuskasing Zone

Henry C. Halls and Donald W. Davis

Abstract: U–Pb dates on baddeleyite yield ages of 2167.8 ± 2.2 and 2171.6 ± 1.2 Ma on two northeast-trending dykes west of the Kapuskasing Zone in Ontario, Canada. These ages identify the dykes as belonging to the Biscotasing dyke swarm east of the Kapuskasing Zone, which was previously dated at 2166.7 ± 1.4 Ma by U–Pb on baddeleyite and zircon. The new dates show that the Biscotasing swarm was emplaced over an area of at least 300 000 km^2, much larger than hitherto suspected, and in a geologically short period of time of about 5 million years. A comparison of paleomagnetic data from Biscotasing and 2.45 Ga Matachewan dykes on either side of the Kapuskasing Zone suggests that the western half of the Superior Province has rotated about 10°–20° counterclockwise relative to the eastern half across the Kapuskasing Zone. This movement may have been accompanied by rifting farther north which ultimately led to the Paleoproterozoic embayment, underlying Hudson Bay, that gives the Superior Province its characteristic butterfly-shaped outline.

Résumé : Des datations sur de la baddeleyite ont donné des âges de 2167,8 ± 2,2 Ma et 2171,6 ± 1,2 Ma sur deux dykes de direction NE à l'ouest de la zone de Kapuskasing en Ontario, Canada. Ces âges identifient les dykes comme appartenant à l'essaim de dykes Biscotasing à l'est de la zone de Kapuskasing, laquelle a antérieurement été datée à 2166,7 ± 1,4 Ma par U–Pb sur de la baddeleyite et du zircon. Les nouvelles dates montrent que l'essaim de Biscotasing a été mis en place dans une région d'au moins 300 000 km^2, une région beaucoup plus vaste qu'on ne l'aurait cru auparavant et aussi au cours d'une période géologique relativement courte de 5 Ma. Une comparaison des données paléomagnétiques de Biscotasing et des dykes de Matachewan, 2,45 Ga, de part et d'autre de la zone de Kapuskasing, suggère que la moitié ouest de la Province du Supérieur ait subi une rotation d'environ 10°–20° dans le sens antihoraire par rapport à la moitié est à travers la zone de Kapuskasing. Ce mouvement pourrait avoir été accompagné par de la dérive plus au nord qui, en bout de ligne, aurait conduit à l'enfoncement au Paléoprotérozoïque, sous la baie d'Hudson, donnant ainsi à la Province du Supérieur sa forme caractéristique de papillon.

[Traduit par la Rédaction]

Introduction

The granite–greenstone belts of the Archean southern Superior Province have a well-defined easterly structural grain that extends for more than 1000 km (Fig. 1). The continuity of these belts is disrupted along the Kapuskasing Zone (KZ; Fig. 1), a deep crustal window defined by a NNE- trending fault system, along which several Archean crustal blocks were exhumed at ~2 Ga (Percival and West 1994; Halls and Zhang 2003). Locally more than 30 km of uplift have occurred between reverse faults (Nitescu and Halls 2002; Percival and West 1994) whose movement may also have included a component of dextral displacement with a maximum offset of about 70 km (West and Ernst 1991).

Following the discovery of the KZ by gravity observations (Garland 1950), Operation Kapuskasing (Bennett et al. 1967) was launched in which geological and aeromagnetic surveys showed that extremely magnetic rocks in granulite facies were locally uplifted along major faults. At that time, none of the Archean belts could be traced unequivocally across the KZ, and there appeared to be a 10°–15° counterclockwise change in strike of the Archean structural grain going from east to west across the fault zone (Bennett et al. 1967). Although more recent reconstructions proposed as a result of the Lithoprobe transect (Percival and West 1994) have attempted to match granite–greenstone belts across the KZ, differential rotation across the belt that would explain the change in structural trend remains speculative. The only

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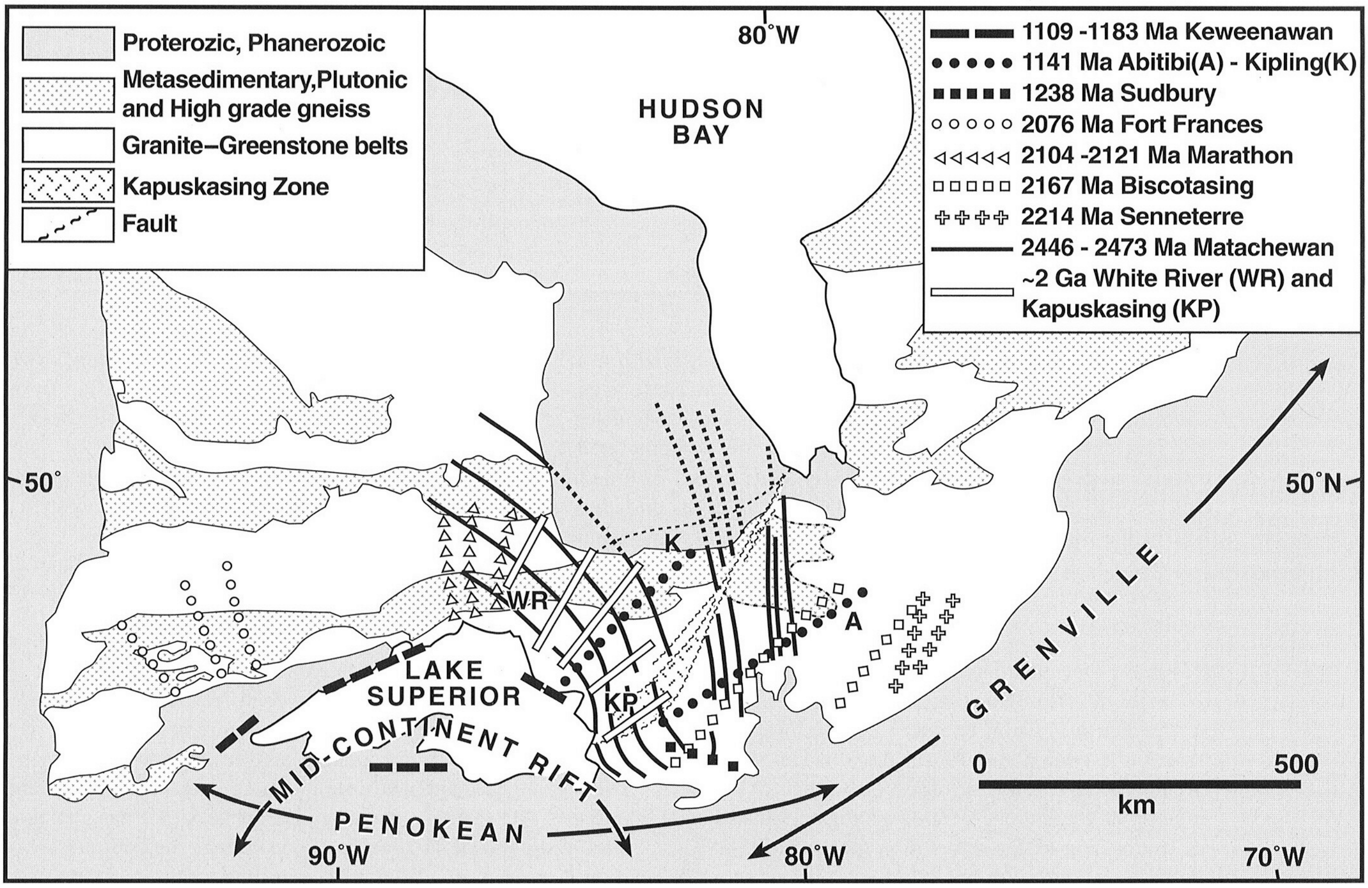
Fig. 1. Simplified geological map of the Superior Province showing the general trend of Archean granite–greenstone and granite–gneiss belts, the Kapuskasing Zone, and the different ages of Proterozoic dykes in its vicinity.



support is from paleomagnetic measurements on ~2.45 Ga Matachewan dykes (Bates and Halls 1991) and from the two-dimensional strain pattern deduced from the dyke swarm configuration (West and Ernst 1991, their fig. 3). In this paper, we present paleomagnetic and U–Pb geochronological results from a younger swarm, the 2.17 Ga Ma Biscotasing dykes, which demonstrate the same relative sense of rotation.

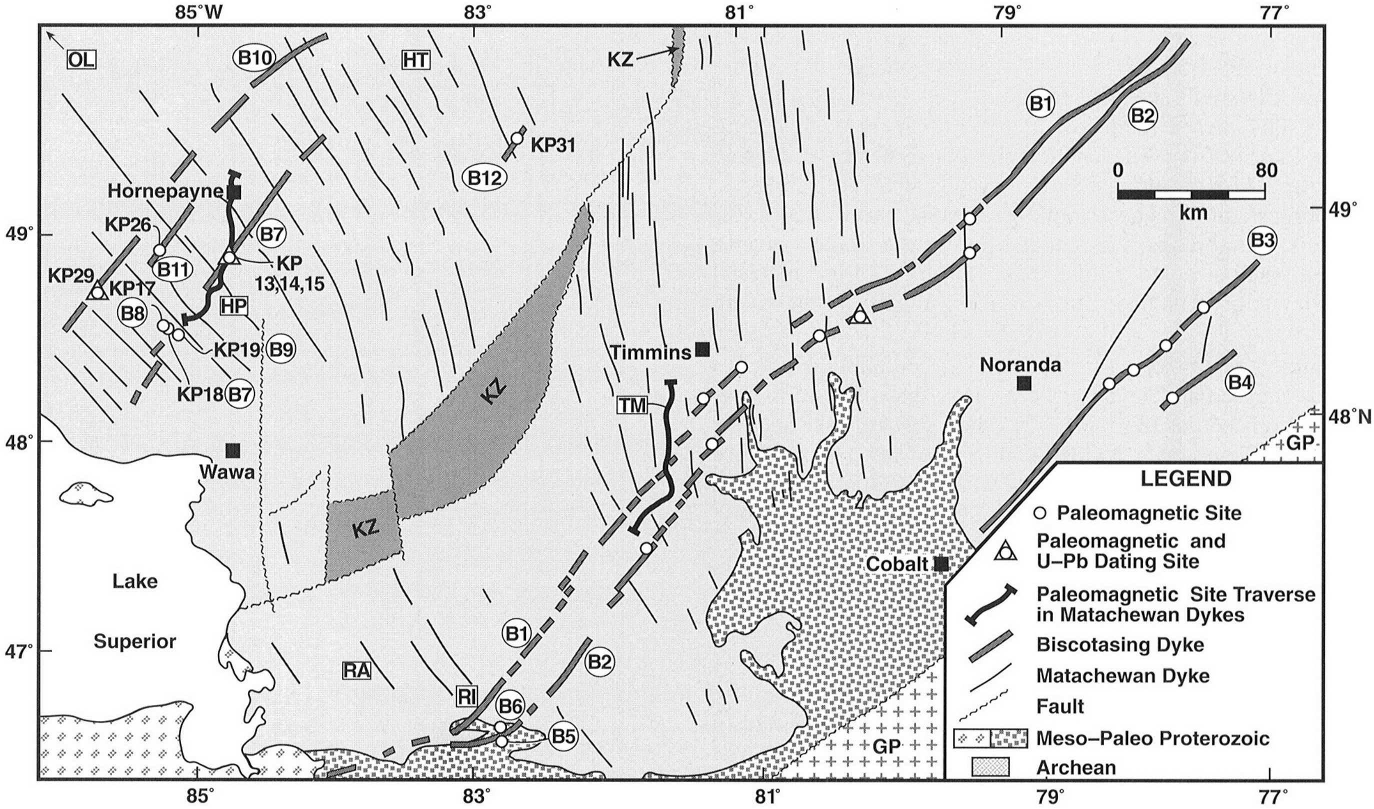
Early Proterozoic dykes of the southern Superior Province

Dykes in the vicinity of the KZ can be grouped into three main time periods (Fig. 1): early Paleoproterozoic (~2.47–2.45 Ga, Matachewan dykes), late Paleoproterozoic, (2.2–2.0 Ga, Senneterre, Biscotasing, Marathon, Fort Frances, and Kapuskasing dykes), and Mesoproterozoic (1.3–1.1 Ga, Sudbury, Abitibi–Kipling, and Keweenawan dykes). In contrast to the Mesoproterozoic dykes, which are olivine-bearing diabase, all the Paleoproterozoic swarms are quartz tholeiites generally devoid of olivine and with modal quartz. They exhibit variable hydrous alteration, in which plagioclase is saussuritized, clinopyroxene is replaced by uralite and chlorite, and magnetite–ilmenite intergrowths are altered to leucoxene– magnetite assemblages. Various kinds of paleomagnetic field tests demonstrate that the remanent magnetization in each swarm is primary (e.g., Halls 1986, 1991; Bates and Halls 1991; Buchan et al. 1993, 1996). This observation indicates that the alteration is deuteric and caused by reaction of groundwater or magmatic fluids with the newly crystallized magma. Chilled margins are generally well preserved, but are susceptible to magnetic and geochemical resetting, often manifest by weak magnetization intensity, greenish colour, and by epidote–chlorite veinlets. All dykes are undeformed at the outcrop scale, apart from minor brecciation, slickenlines along margins, and microfaults. These features are most conspicuous in Matachewan dykes close to the KZ. Within about 50 km of the margin of the Archean craton, dykes can be tilted and (or) metamorphosed (e.g., Halls and Shaw 1988; Halls and Heaman 2000), but farther into the craton interior, beyond ~100 km, they are generally vertical (to within 5°) and relatively fresh.

The various sets of Paleoproterozoic dykes in the vicinity of the KZ (Fig. 1) can be distinguished by U–Pb age, general trend, and paleomagnetic direction. East of the KZ, Matachewan dykes form three subswarms and trend N to NW, whereas younger dykes of the Biscotasing and Senneterre swarms trend ENE to NNE. West of the KZ, Matachewan dykes of the western subswarm trend NNW to WNW, Marathon dykes north to NNE, and a third set, the "White River – Kapuskasing" swarm, trends ENE to NE.

The region extending ~400 km west of the KZ is characterized by large numbers of NE- to ENE-trending dykes of hitherto unknown age and paleomagnetic expression. Their western part has been designated as the "White River" swarm

Fig. 2. Geological map showing the location of paleomagnetic (dots) and U–Pb sites (triangles) in Biscotasing dykes. The location of faults along the Kapuskasing Zone (KZ) is after Halls and Zhang (2003). Sample locations east of the KZ are from Buchan et al. (1993). Biscotasing dykes are labelled B1 to B12. Letters within squares refer to the location of paleomagnetic data sets from Matachewan dykes as defined by Bates and Halls (1991). The heavy lines are the most detailed paleomagnetic traverses of Matachewan dykes, TM and HP, from, respectively, the eastern and western sides of the KZ. Paleomagnetic area OL (50.8°N, 87.2°W) is about 150 km northwest of the map in the direction indicated.



(Ernst and Halls 1984) or, in the vicinity of the KZ, as the "Kapuskasing" swarm (Halls and Palmer 1990). Prior to this study, the only age was an Ar–Ar date of 2040 Ma by Hanes et al. (1994) on a Kapuskasing dyke within the KZ. Preliminary U–Pb dating and paleomagnetism, however, suggest that some of the White River dykes belong to the Marathon swarm (H.C. Halls and D.W. Davis, unpublished U–Pb and paleomagnetic data), while others belong to the Biscotasing swarm as reported in this paper.

Experimental procedure

Sample collection

Seven to eight field-drilled cores or blocks, oriented using both sun and magnetic compasses, were collected for paleomagnetic study from all NNE- to ENE-trending dykes west of the KZ that could be accessed by road or by boat, with emphasis on chilled margins where primary remanence is best preserved. Only the freshest samples were collected, mostly from the base of road cuts to avoid lightning strikes that can remagnetize the rocks. In addition, block samples for U–Pb dating on zircon and (or) baddeleyite were collected from the interiors of the thickest coarse-grained dykes. While most of the dykes gave paleomagnetic directions that were either steeply down (60°–75°) towards the NW or up (40°–80°) to the southeast, and thus not unlike those in Marathon dykes (Buchan et al. 1996), a few gave intermediate down directions (~60°) with a southwest declination, similar to those observed in Biscotasing dykes. After U–Pb dating on two of these dykes confirmed the existence of the Biscotasing swarm, a second field trip was carried out to obtain, for comparative purposes, a similar number of dykes west of the KZ, as that used in the paleomagnetic study by Buchan et al. (1993) for Biscotasing dykes east of the KZ. Field criteria used to distinguish Biscotasing dykes from other White River – Kapuskasing dykes were their greater width and strike length (several 100 km); petrographically they are indistinguishable. Also, the trend of Biscotasing dykes is uniformly northeast, whereas towards the west other "White River" dykes, probably part of the Marathon swarm, have more NNE trends, while to the east in the vicinity of the KZ, the "Kapuskasing" dykes are thinner, shorter, and have more ENE trends. A third and final field trip raised the number of Biscotasing dykes sampled from 4 to 6, the same number used in the study by Buchan et al. (1993). The location of paleomagnetic and U–Pb sites in Biscotasing dykes, together with those of Buchan et al. (1993) is shown in Fig. 2. Although more than 30 NE- to ENE-trending dykes have been sampled, only results from the six dykes considered to be Biscotasing in age are reported here.

U–Pb geochronology

Samples of medium-grained gabbro weighing ~1 kg each for KP14 and KP29 were crushed. Baddeleyite was separated using standard heavy liquid and magnetic separation techniques after removal of the ultra-fine fraction by decanting in water. Rock samples were chosen because their mafic minerals (amphibole and biotite) showed the presence of pleochroic haloes in thin section. However, only nine grains of baddeleyite were recovered from KP14 and 29 grains from KP29, possibly because the small size and high surface- to-volume ratio of the crystals caused them to adhere to other minerals during mineral separation. The baddeleyite consists mostly of tiny (<0.5 μg), brown, elongate, flat crystals with dull surfaces. The largest and freshest looking crystals were chosen for analysis. No abrasion was carried out on the grains because of their small size and tabular shape, but most of the analysed baddeleyite crystals had shiny surfaces, suggesting they were unaltered.

Sample weights were estimated and are probably maximum values. Single baddeleyite crystals were dissolved following standard procedures (Krogh 1973). Mass spectrometer analysis was carried out on a VG354 equipped with a Daly pulse counter. Detector characteristics were monitored for each measurement period using SRM-982 Pb and CBNM 072/6 U standards. Dead time corrections were about 20 ns. Detector mass bias was 0.07% per atomic mass unit (AMU), while thermal mass discrimination was 0.10%/AMU. All common Pb was assumed to have the isotopic composition of blank (see footnotes to Table 1). U blank is taken to be 0.1 pg.

Data regressions and averages were carried out using the program of Davis (1982). Near-concordant data are fitted to a line constrained to have a lower concordia intercept of 0 Ma. The upper intercept of this line gives the weighted average of the $^{207}Pb/^{206}Pb$ ages.

Paleomagnetism

Paleomagnetic core specimens, 2.45 cm in both length and diameter, were prepared either by cutting field-drilled cores or by coring blocks in the laboratory. One specimen per core was subjected to detailed alternating magnetic field (AF) demagnetization using a Schonstedt GSD-1 single axis demagnetizer, with increments of 2.5 to 10 mT up to maximum fields of about 60 mT. Demagnetizing steps above ~30 mT employed an averaging procedure to produce a smoother demagnetization path (Halls 1986).Thermal demagnetization was not done because previous experience on Early Proterozoic mafic dykes shows that unless pyrrhotite is suspected, the thermal data do not provide better component definition, especially as virtually pure magnetite is the remanence carrier with an unblocking temperature spectrum often no more than ~10 °C wide.

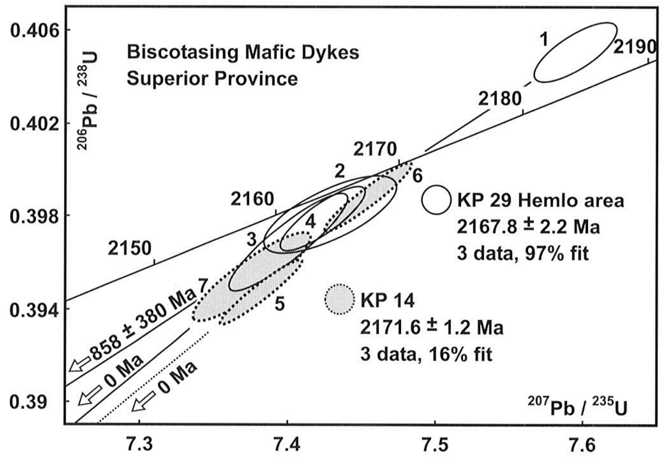
After each demagnetization step, the direction and intensity of magnetization was measured on a modified DIGICO spinner magnetometer with estimated reproducibility of about 10^{-3} A/m. The results were then processed using a modified version of the Principal Component Analysis program of Kirschvink (1980), whereby all possible linear segments satisfying the acceptance criteria (maximum angle of deviation ≤ 10°) were calculated. The linear segment corresponding to the presumed primary component was then selected in conjunction with an

Table 1. U–Pb isotopic data for baddeleyite from mafic dykes in the central Superior Province.

No.	Fraction	Weight (mg)	U (ppm)	Th/U	Pbcom (pg)	$^{207}Pb/^{204}Pb$	$^{206}Pb/^{238}U$	2σ	$^{207}Pb/^{235}U$	2σ	$^{207}Pb/^{206}Pb$ age (Ma)	2σ	Disc. (%)	Error Correlation Coefficient
KP29 mafic dyke, Hemlo area														
1	1 badd, brn, tabular, fresh	0.0005	142	0.07	0.60	436.0	0.4051	0.0012	7.595	0.027	2176.7	3.9	–0.8	0.7895
2	1 badd, brn, lpr, fresh	0.0004	196	0.04	1.90	157.9	0.3981	0.0016	7.429	0.045	2168.5	7.4	0.4	0.7360
3	1 badd, flat, elg, pale brn	0.0005	51	0.03	0.30	309.9	0.3970	0.0023	7.407	0.046	2167.9	4.8	0.7	0.8981
4	1 badd, elg blade, fresh	0.0015	115	0.02	0.39	1548.2	0.3977	0.0012	7.419	0.022	2167.6	3.0	0.5	0.8831
KP14 mafic dyke														
5	1 badd, flat, not fresh	0.0005	235	0.05	0.30	1341.7	0.3947	0.0014	7.382	0.027	2172.4	1.9	1.5	0.9573
6	1 badd, flat, fresh	0.0010	187	0.03	0.65	1017.1	0.3988	0.0015	7.454	0.030	2171.2	2.2	0.4	0.9473
7	1 badd, elg, pale brn, fresh	0.0004	73	0.07	0.35	302.5	0.3954	0.0019	7.376	0.040	2168.0	4.3	1.1	0.8595

Note: Errors are given at 2σ. Sampling locations: KP29: 48.72°N, 85.78°W; KP14: 48.90°N, 84.79°W. badd, baddeleyite; elg, elongate, lpr, long prismatic; brn, brownish. PbCom, Common Pb, assuming all has blank isotopic composition: $^{206}Pb/^{204}Pb$ – 18.221; $^{207}Pb/^{204}Pb$ – 15.612; $^{208}Pb/^{204}Pb$ – 39.36; 2% errors. Th/U calculated from radiogenic $^{208}Pb/^{206}Pb$ ratio and $^{207}Pb/^{206}Pb$ age assuming concordance. Disc., % discordance for the given $^{207}Pb/^{206}Pb$ age.

Fig. 3. Concordia diagram showing U–Pb data from analyses of baddeleyite from site KP14 in mafic dyke B7 and from site KP29 in dyke B10. Zero age lower intercept regressions are shown for near concordant data from both samples. An unconstrained regression to the four data from site KP29 is also shown. Numbers refer to analyses in Table 1.



analysis of the demagnetization path on both vector diagrams and stereo plots.

Results

U–Pb geochronology

Isotopic results are given in Table 1 and plotted in Fig. 3. All errors and error ellipses are given at 2σ. Total common Pb is generally in the range of 0.3–0.65 pg (Table 1). Such low values made it possible to obtain precise age data even on samples that have only a few picograms of radiogenic Pb.

Three baddeleyite crystals from KP29 gave overlapping near-concordant data with an average $^{207}Pb/^{206}Pb$ age of 2167. 8 ± 2.2 Ma. A fourth datum plots above concordia and has a somewhat older $^{207}Pb/^{206}Pb$ age of 2177 ± 4 Ma. Regressing all four data defines a line with an upper concordia intercept age of 2171 ± 3 Ma (93% probability of fit) and a lower intercept age of about 860 Ma. It is unusual for data from baddeleyite or zircon to plot above concordia unless there is a lack of complete equilibration between sample and spike. In this case, the lower concordia intercept would be near zero. The present pattern suggests that the disturbed datum reflects preferential loss of U during the Neoproterozoic. The intercept age defined by all four data is within error of the other three near-concordant data, but it would be biased upward by any recent Pb loss from the near-concordant grains. The three crystals that gave overlapping data apparently experienced no appreciable U or Pb mobility, so their average $^{207}Pb/^{206}Pb$ age of 2167.8 ± 2.2 Ma probably gives the most accurate estimate for the age of dyke emplacement.

Two of the three analyzed baddeleyite crystals from KP14 gave near-concordant data with $^{207}Pb/^{206}Pb$ ages that overlap within error, defining an average age of 2172.0 ± 1.3 Ma (42% probability of fit). A third datum is less precise and gives a slightly younger age. The average $^{207}Pb/^{206}Pb$ age of all three data is 2171.6 ± 1.2 Ma and is largely controlled by the two precise data, but the probability of fit is only 16%. The younger datum agrees well with the near-concordant data from KP-29. An average of these four data gives 2167.8 ± 1.9 Ma with a 100% probability of fit. Both older baddeleyite grains yielded highly radiogenic Pb and produced excellent data. They appear to be slightly older than the age from KP29, as well as the previous Biscotasing age of 2166.7 ± 1.4 Ma (Buchan et al. 1993). The weighted average of the three data from KP14, 2171.6 ± 1.2 Ma, is taken as the best estimate of its age, but possible complications are discussed later.

Paleomagnetism

Paleomagnetic results are summarized in Table 2. Both dykes (B10 and B7) that are of proven Biscotasing age yielded extremely stable, almost single component remanence, from both chilled margin and interior (Fig. 4). At site KP29, corresponding to dyke B10, all samples yielded a single stable component of magnetization, virtually identical in direction to that for dyke B7 (Fig. 4; Table 2). These dykes are part of the Biscotasing swarm because dyke B2 in Fig. 2 gave a previous U–Pb age of 2166.7 ± 1.4 Ma. A positive baked contact test for dyke B2 (Buchan et al. 1993) demonstrates that the remanence in the western dykes, which has a similar direction, is also primary. Two other observations from the data in this paper also support a primary origin:

(1) Site KP15 included chilled margin samples from a relatively narrow dyke that yielded a much stronger characteristic remanence than that preserved in the coarse-grained interiors of the nearby main dyke at sites KP14 and KP16 (Fig. 4). This observation is typical for dykes carrying a proven primary remanence, but untypical for reset dykes where relatively permeable jointed margins, susceptible to chemical alteration, show a much weaker intensity (Halls et al. 2000, their fig. 17).

(2) At site KP29, a 6 cm-wide chilled dyke cuts the main one and gave a stable remanence with a steeper inclination compared with that from the main dyke and a high coercivity as deduced from its resistance to AF demagnetization (Fig. 4). On the basis of paleomagnetic declination, this younger dyke may also be Biscotasing in age, and its small but distinct difference in direction from that in the main dyke suggests the influence of secular variation, rather than a regional overprint, that would impart the same magnetization direction to both dykes. A common observation is that dykes a few centimetres wide invariably occur close to a much wider master dyke that forms the main feeder. At site KP29, the only major dyke is the earlier one, so that the dykelet probably represents a late-stage injection along the main conduit.

Criteria for recognizing undated Biscotasing dykes are that they should have a similar trend to the dated dykes B7 and B10 and a characteristic magnetization with a moderate to steep positive inclination in the southwest quadrant. Four other dykes were thus identified as belonging to the Biscotasing swarm (Figs. 5, 6). Figure 5 summarizes data from three sites KP17–KP19 in close proximity to one another (Fig. 1). Chilled margins at sites KP18 and KP15 had identical major and minor element geochemistry so that site KP18 was considered part of dyke B7 (Table 2). The chilled margins of dykes at sites 17 and 19 were geochemically unlike one another and dissimilar to dyke B7 and were, therefore, considered as

Table 2. Paleomagnetic site data for Biscotasing dykes west of the Kapuskasing Zone.

Site	Dyke	*D* (°)	*I* (°)	*N*	*k*	α_{95} (°)	Plat	Plong
KP14	B7	233.1	60.6	4	343	5.0	11.8	122.5
KP15	B7	246.1	61.6	7	309	3.4	18.4	129.8
KP16	B7	236.6	62.0	7	268	3.7	14.6	123.7
KP18	B7	229.0	64.8	7	95	6.2	14.4	117.5
KP17	B8	230.7	61.8	7	48	8.2	11.8	120.9
KP19	B9	249.3	74.3	9	37	8.6	32.6	118.1
KP29	B10	238.4	54.2	17	442	1.7	8.3	130.8
KP26	B11	239.1	61.0	4	199	6.5	14.8	126.4
KP31	B12	259.1	53.6	10	86	5.2	19.1	148.8

Note: *N*, number of independently oriented samples per site. Site locations are given in Table 3. Plat and Plong are, respectively, the latitude (°N) and longitude (°W) of the virtual paleomagnetic pole. *D* and *I* are, respectively, mean declination and inclination at the site. *k* and α_{95} are, respectively, Fisherian precision parameter and half angle of the 95% cone of confidence about the mean.

Fig. 4. Orthogonal vector diagrams and equal area nets showing paleomagnetic results after AF demagnetization from the U–Pb dated dykes B7(sites KP14 to KP16) and B10 (site KP 29). In vector diagrams dots and triangles, respectively, refer to projections of the tip of the magnetization vector onto the horizontal and vertical east–west plane. Numbers on axes are magnetization intensity in units of 10^{-3} A/m. The range of demagnetization is shown at the top of each diagram on the right. The value in mT of one demagnetization step is also shown for reference. In stereo plots, closed and open circles, respectively, refer to downward and upward pointing magnetizations. Note the extreme directional stability of the dominant magnetization component. ECM, eastern chilled margin of the dyke; WCM, western chilled margin of the dyke.

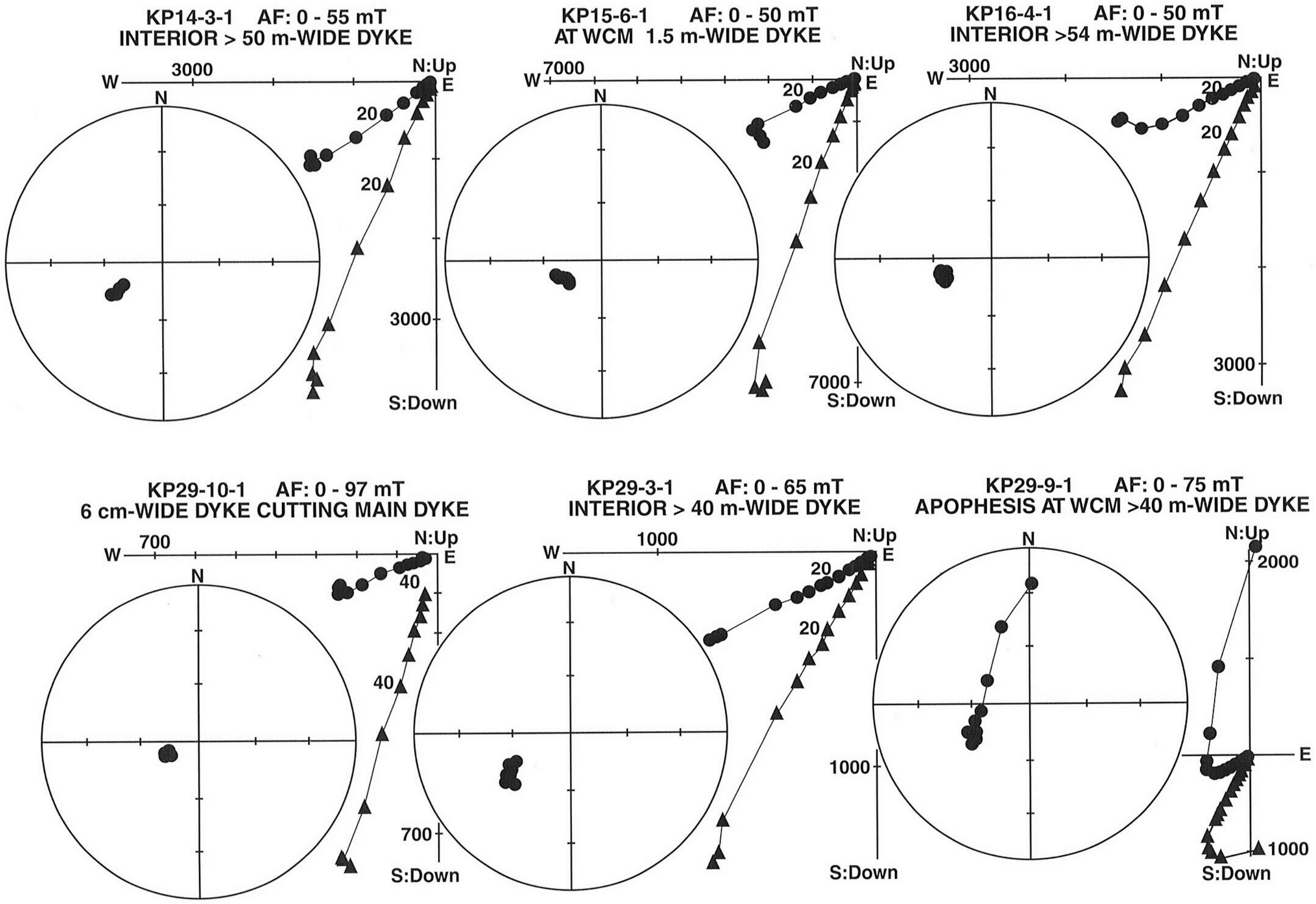
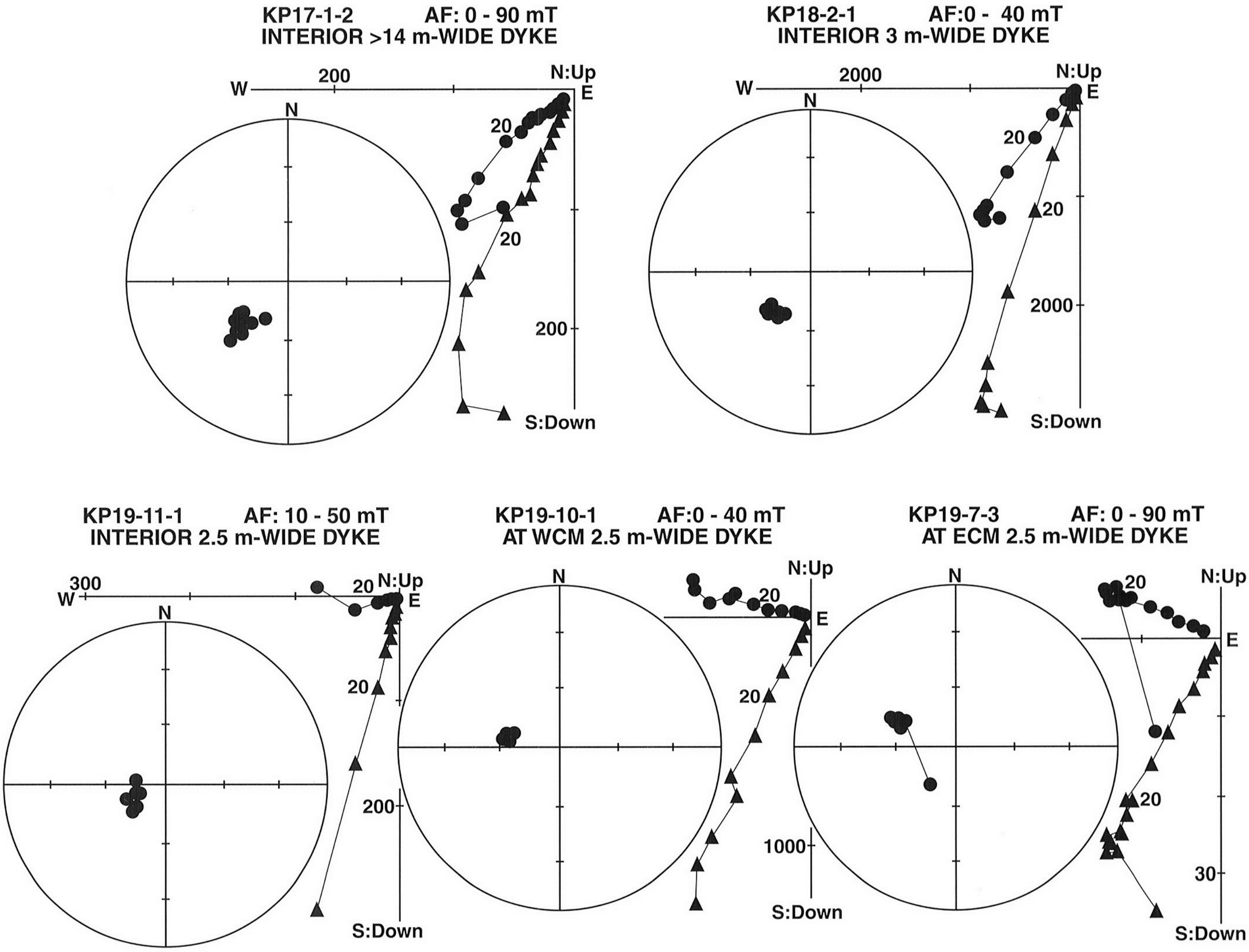


Fig. 5. Paleomagnetic results after AF demagnetization of sites KP17–KP19. Symbols and abbreviations same as in Fig. 4.



separate dykes B8 and B9. At site 19, the results were relatively scattered, and magnetically weak margins (e.g., sample KP19-7-3 in Fig. 5) may have been overprinted during intrusion of the ~2.1 Ga Normal polarity Marathon dykes (cf. Buchan et al. 1996). Overprinting, probably during intrusion of Reversed polarity Marathon dykes, is also seen as a high coercivity component in sample KP31-2-2 (Fig. 6). In general, most overprints were of low coercivity and did not survive beyond AF demagnetization of 10 mT. At one site (KP26), despite high intensity isothermal remanent magnetization due to lightning, the characteristic component could still be recovered in some samples (e.g., KP26-6-1 in Fig. 6).

Interpretation of results

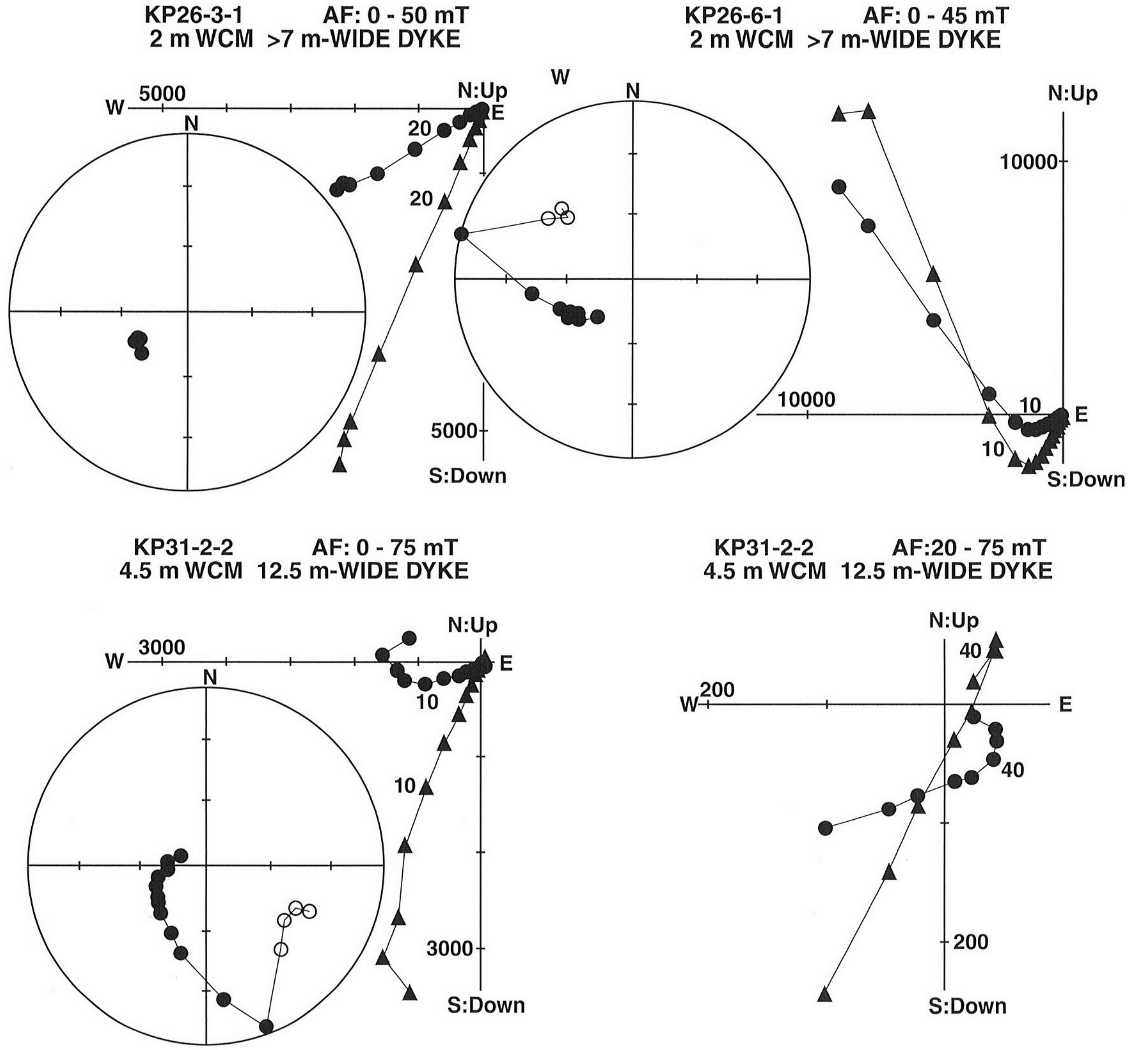
U–Pb geochronology

The 2167.8 ± 2.2 Ma age from site KP29 (dyke B10) agrees well with the previous age of 2166.7 ± 1.4 Ma, reported by Buchan et al. (1993) for somewhat discordant but collinear zircon and baddeleyite data from dyke B2 (Fig. 2). The slightly older age for the two baddeleyite crystals from KP14 suggests a number of possibilities.

(1) KP14 was emplaced several million years earlier than other Biscotasing dykes.
(2) Mafic dykes can contain xenocrystic baddeleyite that crystallized during a stage of plume ascent predating dyke emplacement by a few million years.
(3) Baddeleyite ages can be biased by some mechanism that is not clearly understood.

Regarding the first possibility, detailed dating of the Mackenzie dykes suggests that large dyke swarms can be emplaced over a time span of less than a million years (Heaman and LeCheminant 1993). However, magmatism associated with plume impact can also last for tens of millions of years in one region, as is well documented in the 1.1 Ga Midcontinent Rift (Davis and Green 1997). The fact that KP14 contains one baddeleyite crystal which appears to agree with other ages from the Biscotasing dykes supports the second and third possibilities, the third one being supported also by the one anomalously old age from KP29. A similar case of baddeleyite that appears to slightly predate emplacement of its host rock was found from the Logan sills, which are associated with Midcontinent Rift magmatism around Lake Nipigon.

Fig. 6. Continuation of Fig. 5, showing paleomagnetic results from sites KP26 and KP31. Symbols and abbreviations same as in Fig. 4.



Substantial work on the timing of the Midcontinent Rift has shown that magmatism began abruptly at 1108 ±1 Ma (Davis and Green 1997). This agrees with U–Pb ages of zircons from the Logan sills. However, baddeleyite from the same sample gave near-concordant data with ages that are 2–3 million years older than the zircon age (Davis and Sutcliffe 1985). An excess of ^{231}Pa could produce such an effect. This has never been documented in baddeleyite, but substantial excesses of ^{207}Pb, presumably from decay of ^{231}Pa, have been reported in zircon from an alkali-granite dyke (Anczkiewicz et al. 2001) and from a pegmatite (Mortensen et al. 1997). Another effect that could produce upward ^{207}Pb/^{206}Pb age biases is slight ^{222}Rn loss, which would result in a ^{206}Pb deficiency. This was discussed for the Logan sills by Davis and Sutcliffe (1985). Analyses that show distinctly higher ^{207}Pb/^{206}Pb ages here and from the Logan sills also show distinct discordance. These are likely to have been from slightly altered grains. Small baddeleyite crystals with surface alteration might be susceptible to partial diffusive ^{222}Rn loss (and possibly also loss due to alpha-recoil) because of a high surface to volume ratio. The crystals generally take the form of thin laths, and irregular alteration fronts could increase the surface area available for diffusive loss. Alteration may also be accompanied by direct Pb and (or) U loss. General surface lustre is the only available criterion in evaluating the degree of alteration for such tiny grains. The few grains available from KP14 generally seemed less shiny than those from KP29. The oldest and most discordant grain, in particular, had a dull surface. These few observations suggest that only fresh baddeleyite crystals are useful for precise dating, although slightly biased data can still be effective for distinguishing different dyke swarms. The few remaining crystals from KP14 appear to be quite altered and are likely to be of little use in determining a precise age. In any case, it is clear that both dykes are sufficiently close in age that their primary paleomagnetic poles should agree within error with that defined by the rest of the Biscotasing swarm.

Paleomagnetism

A comparison of paleomagnetic data between Biscotasing dykes east and west of the KZ (Table 3) shows that the western ones have similar inclination but a mean declination that is about 16° less than the eastern dykes. A test was made to see at what probability level the hypothesis could be accepted that the two means are not drawn from the same Fisherian population. The result, using the method of McFadden and Lowes

Table 3. Comparison of paleomagnetic data between Biscotasing dykes east and west of the Kapuskasing Zone.

Dyke	Slat	Slong	Strike (°)	Dip (°)	*N*	*D* (°)	*I* (°)	*k*	α_{95} (°)
Biscotasing East (Buchan et al. 1993)									
B1	48.36	81.07	051±1		3*	287.1	62.4	67	15.2
B2	48.47	80.55	053±11		5*	260.2	59.7	97	7.8
B3	48.27	78.21	051±1		4*	263.7	58.9	146	7.6
B4	48.12	77.94	50		5	266.0	58.0	164	6.0
B5	46.62	82.80	60		5	246.4	54.8	125	6.9
B6	46.62	82.80	60		5	291.3	73.7	612	3.1
Mean					6**	266.4	62.0	64	8.4
Biscotasing West (This Paper)									
B7	48.9	84.79	45,25 (35)	85NW	4*	244.7	59.8	479	4.2
B8	48.57	85.28	35	90	7	238.2	59.0	49	8.7
B9	48.52	85.17	25	90	9	256.7	71.9	37	8.6
B10	48.72	85.78	45 (35)	80NW	17	245.2	50.4	442	1.7
B11	49	85.18	55 (35)	–	4	246.1	58.2	199	6.5
B12	49.67	83.51	35	90	10	268.4	46.1	86	5.2
Mean					6**	250.3	58.0	56	9.0

N, Number of independently oriented samples; *N** = number of sites; *N*** = number of dykes; Slat and Slong are site latitude (°N) and longitude (°W). For dyke B7, the location given is for sites KP14–KP16; the location of site KP18 is 48.57°N, 85.26°W. The Biscotasing data of Buchan et al (1993) have been modified to exclude host rock data. *D* and *I* have been computed for a common location at 48°N, 79°W. The strike of the dyke is either measured at the site for the western data or taken from the geological map (Fig. 2 of Buchan et al. 1993) for the eastern data. Mean values (±1σ) are averages for several paleomagnetic sites in the same dyke, or measured from the trend of aeromagnetic anomalies (values in parentheses).

(1981) on the data in Table 3 is that the hypothesis can only be accepted with a probability of about 85% (p = 0.15). The probability is thus less than the 95% normally required to be confident that the two populations are paleomagnetically distinct. Given that the two means are only 10° apart, more data are required to demonstrate a difference at the 95% confidence level, particularly considering that secular variation of 10°–20° is likely to be present. However a second observation strengthens the case that the declination difference is real. A comparison of paleomagnetic data from two traverses across reversely magnetized Matachewan dykes from the same areas where the Biscotasing dykes are found (Fig. 2; data sets HP and TM of Bates and Halls 1991) shows a virtually identical difference in mean declinations (Table 4), which is significant at the 95% confidence level (Bates and Halls 1991). However, the TM data set comes from the central subswarm, which has a slightly older U–Pb age (2473 Ma) compared with the western subswarm (2446 Ma, Heaman 1997) from which the HP data set is derived, and therefore the directions may not be strictly comparable. Two other data sets (RL and RA, Fig. 2) from the younger western subswarm occur east of the KZ and have directions that are virtually identical to the TM data set (Table 4). Since there is no obvious correlation between age and remanence direction, we have compared the mean of the three eastern data sets (TM, RL, and RA in Fig. 2) with that from three data sets from west of the KZ (OL, HP, and HT in Fig. 2). These means are only significantly different at the 82% confidence level, a probability which rises to 99% if the normally magnetized data sets from these areas (Table 4) are also included by taking the antipodes of their directions (Fig. 7).

In addition to the change in trend of the Archean belts across the KZ, changes of trend in the dykes may also be expected. The mean trend of Biscotasing dykes east of the KZ is 054° ± 4°, whereas the mean trend west of the KZ is about 033° ± 4°, which would support the rotation if the Biscotasing swarm was once composed of parallel dykes. However on the eastern side of the KZ the trend of the dykes changes northwards from northeast to ENE without any change in paleomagnetic direction (Buchan et al. 1993), so that regional differences in trend may not necessarily indicate deformation. A comparison in trend of the Matachewan dykes cannot be made across the KZ because in those regions where Biscotasing dykes occur, they are not part of the same subswarm.

Since all measured Matachewan and Biscotasing dykes lie within 5° of the vertical and are assumed on this basis not to have been tilted, the only way to explain the apparent paleomagnetic difference in declination (and relatively small difference in inclination) seen in both Matachewan and Biscotasing dykes *from the same areas* is that the crust to the west of the KZ has been rotated counterclockwise around an approximately vertical axis with respect to that in the east (Fig. 7). Using the error analysis of Beck (1983), rotations with 95% confidence limits for the Matachewan and Biscotasing data are 12° ± 9° and 16° ± 21° respectively. These results suggest that the western Superior Province has rotated counterclockwise about 10°–20° relative to the eastern Superior Province across the Kapuskasing Zone.

Discussion

Quality of paleomagnetic data

The Biscotasing paleomagnetic data are not as secure as

Table 4. Comparison of Biscotasing and Matachewan paleomagnetic data across the Kapuskasing Zone.

Dyke Swarm	Location	Dykes	D (°)	Inc (°)	k	α_{95} (°)	Reference
Biscotasing (U–Pb 2167 ± 1.4 Ma)	E (N)	6	266.4	62	64	8.4	[1]
Biscotasing (U–Pb 2170 ± 3 Ma)	W (N)	6	250.3	58	56	9.0	This paper
Matachewan (TM)*	E (R)	15	211.1	−16.3	87	4.0	[2]
(U–Pb 2473 +16/–9 Ma)	E (N)	5	22.8	29.2	430	4.0	
Matachewan (RI)*	E (R)	19	212.0	−10.4	42	5.0	
(U–Pb 2446 ± 3 Ma)	E (N)	3	21.7	24.0	45	19.0	
Matachewan (RA)	E (R)	17	207.5	−16.1	52	5.0	
(U–Pb 2446 ± 3 Ma)	E (N)	3	25.8	21.6	49	18.0	
Mean N (East)	N	3	23.5	24.9	348	6.6	
Mean R (East)	R	3	210.2	−14.3	397	6.2	
Mean (East)	N+R	6	206.9	−19.6	109	6.4	
Matachewan (HP)*	W (R)	11	194.8	−26.0	100	5.0	[2]
(U–Pb 2446 ± 3 Ma)	W (N)	3	13.9	24.3	220	8.0	
Matachewan (HT)	W (R)	10	201.0	−16.8	66	6.0	
	W (N)	6	16.4	30.4	89	7.0	
Matachewan (OL)	W (R)	4	190.4	−19.4	110	9.0	
Mean N (West)	N	2	15.1	27.4	312	14.2	
Mean R (West)	R	3	195.4	−20.8	138	10.5	
Mean (West)	N+R	5	195.3	−23.4	156	6.1	
Mean (East and West)		11	201.7	−21.5	80	5.1	

Note: All D and I values have been recomputed for a common location at 48°N, 79°W. * indicates data sets are derived from Matachewan dykes, where Biscotasing dykes also occur. N, normal polarity; R, reversed polarity. References: [1] Buchan et al. (1993); [2] Bates and Halls (1991).

those from the Matachewan swarm because there are fewer dykes and because the remanence inclination is much steeper, thereby reducing the sensitivity of the paleomagnetic method to a vertical axis rotation. A more subtle problem concerns the identification of dykes whose remanence declination lies in the northwest quadrant. Normally these dykes would be identified as Marathon dykes, but if some Biscotasing dykes have the same direction, the mean Biscotasing west direction moves towards that for the eastern dykes. Conversely, the same result occurs if data from the younger dykes have been inadvertently included into the Biscotasing east data. For example, one site (B6) in the data of Buchan et al. (1993) gives a direction that is not unlike that found for Marathon dykes. If this dyke is discarded from the Biscotasing east data set, the probability of acceptance that the two dyke groups are not drawn from the same Fisherian population drops to about 75%.

However, despite the foregoing uncertainties, we believe the rotation to be real based on the fact that it is supported by several observations: (1) the difference in trend across the KZ of both the Archean structural grain and the Biscotasing dykes; (2) a strain pattern in the Matachewan swarm, which is consistent with dextral displacement along the KZ (Bates and Halls 1991; West and Ernst 1991); and (3) similar paleomagnetic differences in declination across the KZ for two crosscutting dyke swarms of different age.

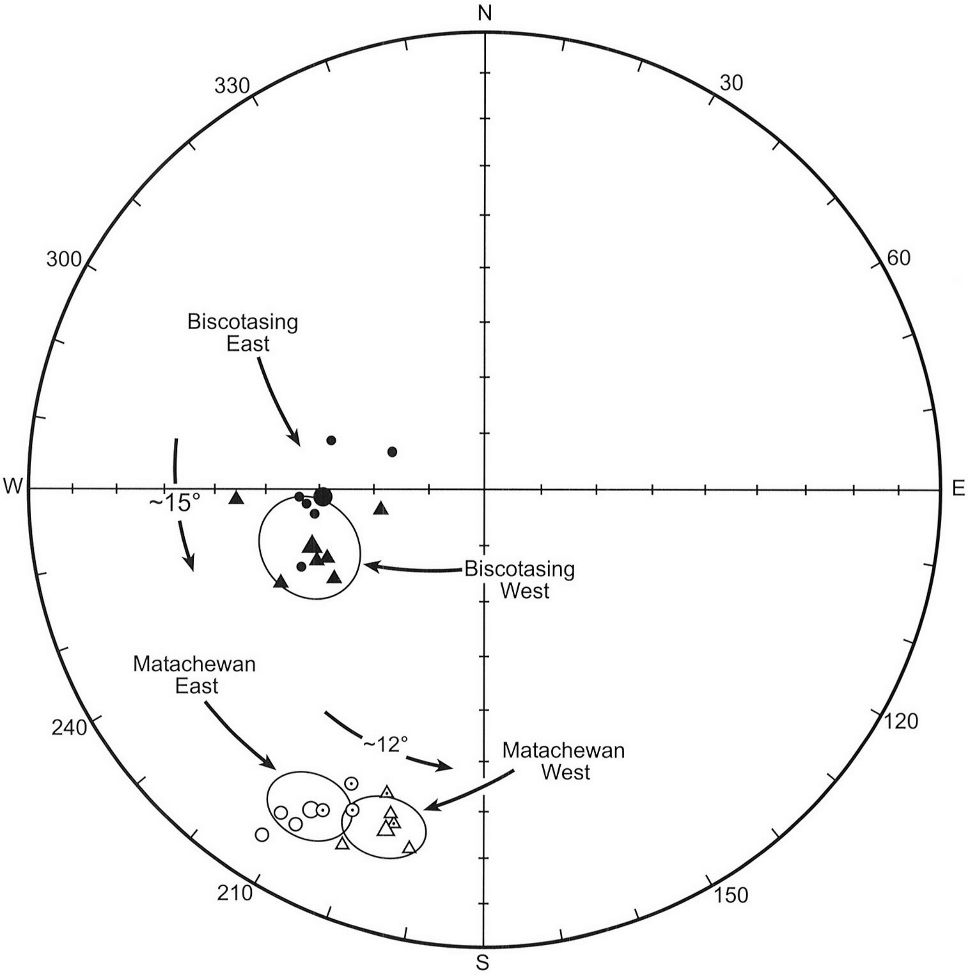
Age of relative rotation of Superior Province across the Kapuskasing Zone

Aeromagnetic interpretation of Matachewan dykes suggests a pattern of deformation that involved dextral displacement along the KZ, together with a regional bending of the Superior Province both within and west of the KZ (West and Ernst 1991). This deformation is younger than 2167 Ma, the age of Biscotasing dykes east of the KZ, because they are offset along Onaping faults, which in turn are offset along the KZ (Buchan and Ernst 1994). However, the deformation is older than the assumed 1140 Ma age of the Kipling dyke (K, Fig. 2), which crosses the KZ at its northern end without deflection (West and Ernst 1991). Recent gravity evidence suggests that uplifted blocks along the KZ are positive flower structures that can form by dextral movement along a series of older left-stepping en echelon faults (Nitescu and Halls 2002), rather than by upthrusting due to horizontal compression normal to the surface trace of the thrust, followed by gravitational collapse (see Percival and West 1994 for summary). Therefore, the relative rotation of terranes across the KZ and associated dextral faulting may have accompanied uplift within the KZ.

Tectonic implications of dextral displacement along and west of the Kapuskasing Zone

If dextral faulting accompanied the relative rotation of the Superior Province across the KZ, the ~70 km of displacement across northern KZ (where it is only 20 km wide) must be composed of smaller offsets along several faults towards the south where the fault zone broadens to about 100 km, as suggested by West and Ernst (1991). Northeast-trending faults cut the Michipicoten greenstone belt (MG in Fig. 8) and are potential loci for Paleoproterozoic vertical and dextral motion. Proterozoic deformation in this area is consistent with the occurrence, in northwest-trending Matachewan dykes, of sinistral faulting (Halls et al. 1994, their fig. 2) and brecciated margins with slickenlines showing subhorizontal sinistral displacement. Conjugate sets of small-scale faulting in Matachewan dykes around the southern KZ suggest a maximum compression

Fig. 7. Equal area stereonet summarizing site directions of magnetization (all reduced to a common location at 48°N, 79°W) for Biscotasing and Matachewan dykes east and west of the KZ. Ovals of confidence about each mean are at the 95% confidence level. Closed and open points, respectively, are downward and upward pointing magnetizations plotted on the lower and upper hemispheres. For the Biscotasing data, small and large symbols, respectively, refer to values for dyke and mean directions. For the Matachewan data, small open symbols are means of reversely magnetized dyke populations from different regions (TM, RL, RA, HT, HP, and OL in Fig. 2), and small open symbols with central dots are mean antipodes of normally magnetized dyke populations (see Table 2). The large symbols represent the combined means of the reversed and normally magnetized populations.



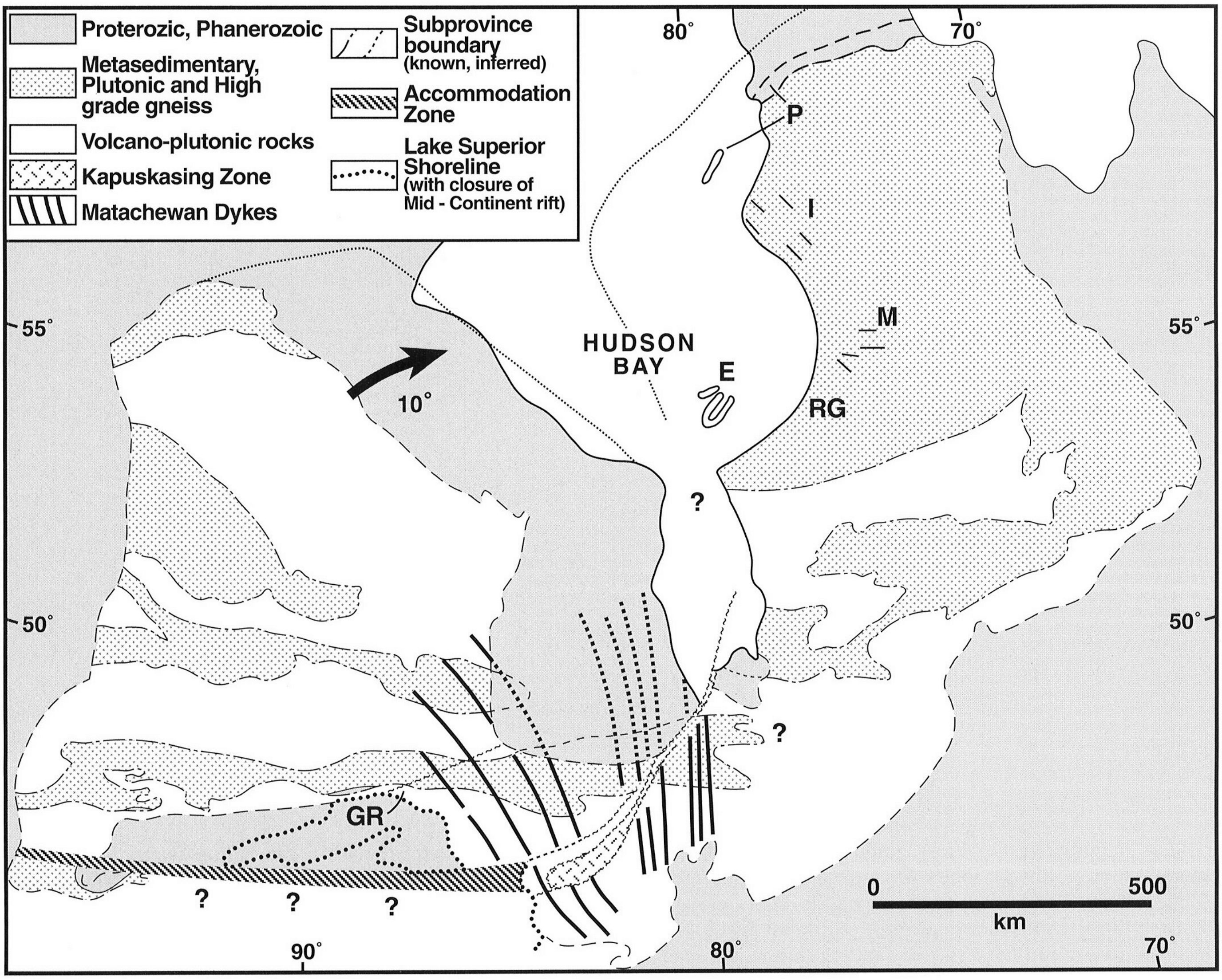
oriented roughly west, which would be conducive to the generation of northeast faults having dextral displacement (Zhang 1999). The change in trend of the faults along the KZ from NNE in the north to more northeast in the south yields a curvature in the strike of faulting that would lead to the observed counterclockwise rotation, rather like a listric fault but in a horizontal plane (Fig. 8).

Paleomagnetic data from Matachewan dykes within the western half of the Superior Province suggest that the counter-clockwise rotation increases westwards from the KZ, reaching a maximum of about 20° north of Lake Superior (OL data from Ogoki Lake, Bates and Halls 1991). The width of that part of the Superior Province, across which this more distributed rotation takes place appears to extend on the basis of disturbed K–Ar ages (Manson and Halls 1997, their fig. 9) from the eastern margin of the KZ to the Gravel River fault (GR in Fig. 8), a distance of about 400 km.

Age of crustal uplift within the Kapuskasing Zone

The timing of uplift within the KZ is poorly defined. The distribution of Rb–Sr biotite ages across the KZ suggest to Pericival and Peterman (1994) that the crust had already cooled prior to uplift and that the maximum age of uplift is given by the youngest Rb–Sr biotite age, namely 1.93 Ga. However, Ar–Ar data from the same area give ages closer to 2.3 Ga (Hanes et al. 1994), a discrepancy ascribed to excess argon by Percival and Peterman (1994). Whole-rock Ar–Ar dating of a Kapuskasing dyke within KZ granulites together with biotite from adjacent baked host rock gives an age of 2043 ± 14 Ma (Hanes et al. 1988), which is generally taken as the age of the dyke. Other Kapuskasing dykes in the same region exhibit cloudy feldspar (see Halls et al. 1994 for its significance in relation to Matachewan dykes) and negative paleomagnetic baked contact tests (Symons et al. 1994), suggesting that they have been deeply exhumed. The amount of

Fig. 8. A schematic map restoring, through a 10° clockwise rotation, the western Superior Province to its pre-2.17 Ga configuration with respect to the eastern Superior Province. Note that Archean belts now have a common trend across the KZ and that the arms of the radiating Matachewan swarm are straighter. The displacement at the southern end of the KZ is not obvious in the vicinity of the Michipicoten Greenstone Belt (MG) and may be incremental across the full 100-km width of the fault zone. The westerly continuation of the KZ along the accommodation zone is conjectural and, after closure of the 1.1 Ga Midcontinent Rift through Lake Superior, approximately coincides with the 1.8 Ga Penokean orogen (Fig. 1). The boundary of the Superior Province beneath Hudson Bay is mainly based on the interpretation of regional magnetic and gravity maps of the Geological Survey of Canada (e.g., Hoffman 1989). Paleoproterozoic rocks, which may be related to ~2 Ga continental rifting, are labelled as follows: E, Eskimo volcanics on the Belcher Islands; RG, Persillon volcanics of the Richmond Gulf Group; P, Povungnituk volcanics on mainland and Ottawa Islands; M, 1998 Ma Minto dykes; I, Inukjuak dykes. Note that a further 10° of clockwise rotation of that part of the Superior Province west of the Gravel River fault (GR) could substantially close the rift beneath Hudson Bay.



exhumation within the Kapuskasing Zone that occurred after the intrusion of Kapuskasing dykes is estimated to be between 10 and 17 km, based on amphibole geobarometry (Percival et al. 1994). Temperatures close to the biotite Rb–Sr resetting temperature (~280 °C) could lie at depths of about 10 km (Percival and Peterman 1994), so that any uplift greater than 10 km would presumably reset the biotite clock. Within the Kapuskasing uplift, which lies between two reversed faults (Nitescu and Halls 2002), the Saganash Lake on the west, and the Ivanhoe Lake on the east, six Rb–Sr biotite ages average 1.97 ± 0.4 Ga, with no age progression across the block (fig. 5 of Percival and Peterman 1994). It is unclear if the uniformity in Rb–Sr ages between the two faults represents uplift–exhumation of a previously cooled terrane (and hence the ages give the maximum age of uplift as preferred by Percival and Peterman (1994)) or whether they represent an uplift, > ~10km, that has reset the Rb–Sr system, in which case the ages will reflect a later stage of the uplift. If we take the amount of uplift in excess of 10 km as between 5 and 10 km, as allowed by the geobarometric data, and a typical exhumation rate of 0.5–1 km/Ma, then uplift, relative to surrounding terranes outside the KZ, could have started about 5–20 Ma before the times given by the Rb–Sr biotite dates and perhaps even earlier if actual uplift rates were slower and the amount of uplift greater. We, therefore, conclude that dextral faulting, uplift, and relative rotation of the Superior Province across the KZ may be all part of a single episode of deformation that may have begun at about 2 Ga.

Possible connection of Kapuskasing crustal uplift to rifting beneath Hudson Bay

If the western Superior Province has rotated 10°–15° counterclockwise with respect to the eastern half, and possibly up to 20° as distance increases westwards from the KZ, the question arises as to whether there are connections with rifting events that occurred both to the north and south of the KZ between ~2 and 2.1 Ga. Although all Paleoproterozoic dyke swarms in the vicinity of the KZ (Fig. 1) appear to be older than the deformation (and therefore should be affected by it), the youngest rifting events may have been contemporaneous with at least the earliest stages of the deformation. The youngest of these magmatic events is represented by the W to NW-trending Minto dykes (M in Fig. 8), which have been dated by U–Pb at 1998.4 ± 1.3 Ma (Buchan et al. 1998). These dykes have been correlated paleomagnetically (Schwarz and Fujiwara 1981; Buchan et al. 1998) with the sub-aerial Eskimo volcanics on the Belcher Islands and with the sub-aerial Persillon volcanics in the Richmond Gulf area of eastern Hudson Bay (Fig. 8). These volcanics are also geochemically similar (Legault et al. 1994) and can in turn be geochemically correlated with NW-trending Inukjuak dykes on the eastern side of Hudson Bay, and with the western part of the Povungnituk volcanics in the Cape Smith fold belt (Fig. 8). The age of the latter is probably close to 2038^{+4}_{-2} Ma (Machado et al. 1993), the U–Pb age from a sill at the base of the western Povungnituk volcanics. Therefore, a ~2 Ga old continental rift zone active from at least 2038–1998 Ma may underlie Hudson Bay. The direction of extension based on dyke orientation is about northeast–southwest, although near Richmond Gulf some Minto dykes, perhaps associated with the Richmond Gulf aulacogen (Ricketts and Donaldson 1980), indicate local rifting in a north–south direction. A Bouguer gravity traverse across the Belcher Islands suggests that the Paleoproterozoic rocks there rest on Archean basement (Mukhopadhyay and Gibb 1981), so that any northwest-trending oceanic crust produced by the rift lies west of the islands.

Most models for the crustal structure beneath Hudson Bay show a pronounced embayment formed by linking the Circum-Ungava and Trans-Hudson orogens. Interpreted arc volcanics on the Belcher islands and the evidence of the earlier widespread ~2 Ga continental rifting suggest closure of a rift beneath Hudson Bay. The rift might have formed in response to dextral movement along the KZ and the relative rotation of the Superior Province across it (Fig. 8). The rapid transition from a zone of compression or transpression along the KZ to a rifting environment no more than ~1000 km north of the KZ would require an intervening pole of rotation, and, assuming a rigid crust, an increase in crustal shortening southwards along the KZ, opposite to that observed. However, paleomagnetic data from Matachewan dykes suggest that the western side of the Superior Province may not have behaved as a rigid block (Bates and Halls 1991) so that the model, linking crustal uplift along the Kapuskasing Zone to rifting beneath Hudson Bay, is still tenable.

Conclusions

New U–Pb data on baddeleyite from two dykes demonstrate that the 2.17 Ga Biscotasing dyke swarm occurs on both sides of the Kapuskasing Zone and now occupies an area of about 300 000 km^2. Paleomagnetic data from both the Biscotasing and Matachewan swarms suggest that the two halves of the Superior Province have rotated relative to one another about 10°–20° across the KZ. Two manifestations of this motion, initial rifting beneath Hudson Bay, and early stages of crustal uplift along the Kapuskasing Zone may both date to about 2 Ga. The rift was subsequently closed to form the Paleoproterozoic embayment in the Superior Province that underlies Hudson Bay.

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References

Anczkiewicz, R., Oberli, F., Burg, J.P., Villa, I.M., Günther, D., and Meier, M. 2001. Timing of normal faulting along the Indus Suture in Pakistan Himalaya and a case of major $^{231}Pa/^{235}U$ initial disequilibrium in zircon. Earth and Planetary Science Letters, **191**: 101–114.

Bates, M.P., and H.C. Halls, H.C. 1991. Broad-scale deformation of the central Superior Province revealed by paleomagnetism of the 2.45 Ga Matachewan dyke swarm. Canadian Journal of Earth Sciences, **28**: 1780–1796.

Beck, M.E. 1983. Paleomagnetic record of plate margin tectonic processes along the western edge of North America. Journal of Geophysical Research, **85**: 7115–7131.

Bennett, G., Brown, D.D., George, P.T., and Leahy, E.J. 1967. Operation Kapuskasing. Ontario Department of Mines, Miscellaneous paper 10.

Buchan, K.L., and Ernst R.E. 1994. Onaping fault system: age constraints on deformation of the Kapuskasing structural zone and units underlying the Sudbury Structure. Canadian Journal of Earth Sciences, **31**: 1197–1205.

Buchan, K.L., Mortensen, J.K., and Card, K.D. 1993. Northeast-trending Early Proterozoic dykes of southern Superior Province: multiple episodes of emplacement recognized from integrated paleomagnetism and U–Pb geochronology. Canadian Journal of Earth Sciences, **30**: 1286–1296.

Buchan, K.L., Halls, H.C., and Mortensen, J.K. 1996. Paleomagnetism, U–Pb geochronology and geochemistry of Marathon dykes, Superior Province, and comparison with the Fort Frances swarm. Canadian Journal of Earth Sciences, **33**: 1583–1595.

Buchan, K.L., Mortensen, J.K., Card, K.D., and Percival, J.A. 1998. Paleomagnetism and U–Pb geochronology of diabase dyke swarms on Minto Block, Superior Province, Quebec, Canada. Canadian Journal of Earth Sciences, **35**:1054–1069.

Davis, D.W. 1982. Optimum linear regression and error estimation applied to U–Pb data. Canadian Journal of Earth Sciences, **19**: 2141–2149.

Davis, D.W., and Green, J.C. 1997. Geochronology of the North American Midcontinent Rift in western Lake Superior and implications for its geodynamic evolution. Canadian Journal of Earth Sciences, **34**: 476–488.

Davis, D.W., and Sutcliffe, R.H. 1985. U–Pb ages from the Nipigon plate and northern Lake Superior. Bulletin of the Geological Society of America, **96**: 1572–1579.

Ernst, R.E., and Halls, H.C. 1984. Paleomagnetism of the Hearst dike swarm and implications for the tectonic history of the Kapuskasing zone, northern Ontario. Canadian Journal of Earth Sciences, **21**:1499–1506.

Garland, G.D. 1950. Interpretation of gravimetric and magnetic anomalies on traverses in the Canadian Shield of northern Ontario. Publications of the Dominion Observatory (Ottawa) 16 (1).

Halls, H.C. 1986. Paleomagnetism, structure and longitudinal correlation of Middle Precambrian dykes from northwest Ontario and Minnesota. Canadian Journal of Earth Sciences, **23**: 142–157.

Halls, H.C. 1991. The Matachewan dyke swarm, Canada: an early Proterozoic magnetic field reversal. Earth and Planetary Science Letters, **105**: 279–292.

Halls, H.C., and Heaman, L.M. 2000. The paleomagnetic significance of new U–Pb age data from the Molson dyke swarm, Cauchon Lake area, Manitoba. Canadian Journal of Earth Sciences, **37**: 957–966.

Halls, H.C., and Palmer, H.C. 1990. The tectonic relationship of two early Proterozoic dyke swarms to the Kapuskasing Structural Zone: a paleomagnetic and petrographic study. Canadian Journal of Earth Sciences, **27**: 87–103.

Halls, H.C., and Shaw, E.G. 1988. Paleomagnetism and orientation of Precambrian dykes, eastern Lake Superior region, and their use in estimates of crustal tilting. Canadian Journal of Earth Sciences, **25**: 732–743.

Halls, H.C., and Zhang, B. 2003. Crustal uplift in the southern Superior Province, Canada, revealed by paleomagnetism. Tectonophysics, **362**: 123–136.

Halls, H.C., Palmer, H.C., Bates, M.P., and Phinney, W.C. 1994. Constraints on the nature of the Kapuskasing Structural zone from the study of Proterozoic dyke swarms. Canadian Journal of Earth Sciences, **31**: 1182–1196.

Halls, H.C., Davis, D., Hou, G., Zhang, B., and Qian, X. 2000. A precisely dated Proterozoic paleomagnetic pole from the North China craton, and its relevance to paleocontinental reconstruction. Geophysical Journal International, **143**: 185–203.

Hanes, J.A., Archibald, D.A., Queen, M., and Farrar, E. 1994. Constraints from $^{40}Ar/^{39}Ar$ geochronology on the tectonothermal history of the Kapuskasing uplift in the Canadian Superior Province. Canadian Journal of Earth Sciences, **31**: 1146–1171.

Hanes, J.A., Queen, M., and Archibald, D.A. 1988. $^{40}Ar/^{39}Ar$ Geochronology of dykes and their contact aureoles in the Kapuskasing uplift. *In* Project Lithoprobe, Kapuskasing Structural Zone Workshop II, University of Toronto, Toronto, Ont., pp. 165–172.

Heaman, L.M. 1997. Global mafic magmatism at 2.45 Ga: Remnants of an ancient large igneous province? Geology, **25**: 299–302.

Heaman, L.M., and LeCheminant, A.N. 1993. Paragenesis and U–Pb systematics of baddeleyite (ZrO_2). Chemical Geology, **110**: 95–126.

Hoffman, P.F. 1989. Precambrian geology and tectonic history of North America. *In* The geology of North America—an overview. *Edited by* A.W. Bally and A.R. Palmer. Geological Society of America, Boulder, Colo., Vol. A, pp. 447–512.

Kirschvink, J.L. 1980. The least squares line and plane and the analysis of paleomagnetic data. Geophysical Journal of the Royal astronomical Society, **62**: 699–718.

Krogh, T.E. 1973. A low contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations. Geochimica et Cosmochimica Acta, **37**: 485–494.

Legault, F., Francis, D., Hynes, A., and Budkewitsch, P. 1994. Proterozoic continental volcanism in the Belcher Islands: implications for the evolution of the Circum Ungava Fold Belt. Canadian Journal of Earth Sciences, **31**: 1536–1549.

Machado, N., David, J., Scott, D.J., Lamothe, D., Phillipe, S., and Gariepy, C. 1993. U–Pb geochronology of the western Cape Smith Belt, Canada: new insights on the age of initial rifting and arc magmatism. Precambrian Research, **63**: 211–223.

Manson, M.L., and Halls, H.C. 1997. Proterozoic reactivation of the southern Superior Province and its role in the evolution of the Midcontinent rift. Canadian Journal of Earth Sciences, **34**: 562–575.

McFadden, P.L., and Lowes, F.J. 1981. The discrimination of mean directions drawn from Fisher distributions. Geophysical Journal of the Royal astronomical Society, **67**: 19–33.

Mortensen, J.K., Williams, I.S., and Compston,W. 1997. Ion microprobe and cathodoluminescence investigations of unsupported ^{207}Pb in zircon. Geological Association of Canada Annual Meeting Abstract Vol., Ottawa, Ont., 105 p.

Mukhopadhyay, M., and Gibb, R.A. 1981. Gravity anomalies and deep structure of eastern Hudson Bay. Tectonophysics, **72**: 43–60.

Nitescu, B., and Halls, H.C. 2002. A gravity profile across the southern Saganash Lake fault: implications for the origin of the Kapuskasing structural zone. Canadian Journal of Earth Sciences, **39**: 469–480.

Percival, J.A., and Peterman, Z.E. 1994. Rb–Sr biotite and whole-rock data from the Kapuskasing uplift and their bearing on the cooling and exhumation history. Canadian Journal of Earth Sciences, **31**: 1172–1181.

Percival, J.A., and West, G.F. 1994. The Kapuskasing uplift: a geological and geophysical synthesis, Canadian Journal of Earth Sciences, **31**: 1256–1286.

Percival, J.A., Palmer, H.C., and Barnett, R.L. 1994. Quantitative estimates of emplacement level of post-metamorphic mafic dykes and subsequent erosion magnitude in the southern Kapuskasing uplift. Canadian Journal of Earth Sciences, **31**:1218–1226.

Ricketts, B.D., and Donaldson, J.A. 1980. Sedimentary history of the Belcher Group of Hudson Bay. *In* Proterozoic basins in Canada. *Edited by* F.H.A. Campbell. Geological Survey of Canada, Paper 81-10, pp. 235–254.

Schwarz, E.J., and Fujiwara,Y. 1981. Paleomagnetism of the Circum-Ungava Fold Belt II: Proterozoic rocks of Richmond Gulf and Manitounik Islands. *In* Proterozoic basins in Canada. *Edited by* F.H.A. Campbell. Geological Survey of Canada, Paper 81-10, pp. 255–267.

Symons, D.T.A., Lewchuk, M.T., Dunlop, D.J., Costanzo-Alvarez, V., Halls, H.C., Bates, M.P., Palmer, H.C., and Vandall, T.A. 1994. Synopsis of paleomagnetic studies in the Kapuskasing

Structural Zone. Canadian Journal of Earth Sciences, **31**: 1206–1217.

West, G.F., and Ernst, R.E. 1991. Evidence from aeromagnetics on the configuration of Matachewan dykes and the tectonic evolution of the Kapuskasing structural zone, Ontario, Canada. Canadian Journal of Earth Sciences, **28**: 1797–1811.

Zhang, B. 1999. A study of crustal uplift along the Kapuskasing zone using 2.45 Ga Matachewan dykes. Ph.D. Dissertation, Department of Geology, University of Toronto, Toronto, Ont.