Geophys. J. Int. (1993) **113,** 175–185

A palaeomagnetic study of 143 Ma kimberlite dikes in central New York State

Mickey C. Van Fossen and Dennis V. Kent
Lamont–Doherty Earth Observatory, Columbia University, Palisades, New York 10964, *USA*

Accepted 1992 September 14. Received 1992 September 14; in original form 1991 December 1

SUMMARY

A palaeomagnetic study of 143 Ma serpentinized kimberlite dikes near Ithaca, New York, yields a dual-polarity, high unblocking temperature, and high coercivity magnetization which passes the reversal test and two baked contact tests. The mean pole position (58°N, 203°E; A95 = 3.8°, N = 7) differs from published late Jurassic–early Cretaceous North American poles currently used to define the apparent polar wander path. The angular dispersion in mean directions ($\theta_{63} = 3.5°$) is low but the presence of reversals argues that the Ithaca kimberlites magnetization should represent sufficient time for averaging of palaeosecular variation. Similar findings apparently typify palaeomagnetic studies of other serpentinized kimberlite, supporting the suggestion that thermo-chemical remanent magnetization in this lithology prolongs the duration of magnetization acquisition sufficiently to average secular variation per dike. A consistent but weak foliation in anisotropy of ARM parallels the N–S and vertical orientation of the Ithaca dikes, but is apparently unrelated to the northwest-down or southeast-up remanence.

The Ithaca kimberlites pole may therefore record a previously undocumented sharp bend or 'cusp' at ~143 Ma, and the initiation of a Cretaceous and Cenozoic interval of apparent polar wander that generally follows a great circle along the 200°E meridian to geographic north. A coeval (~145 Ma) kimberlite pole from southern Africa transferred to North America agrees with the Ithaca kimberlites pole position whereas reported poles from the Berriasian stratotype (southern France) and 144 Ma Svalbard dolerites provide less diagnostic tests of the Ithaca kimberlites pole due in part to uncertainties in Europe–North America reconstructions.

Key words: Cretaceous, Jurassic, kimberlite, North America, palaeomagnetic poles.

INTRODUCTION

The North American apparent polar wander path is reasonably well established from mid-Cretaceous (~124 Ma) to Recent time (Irving & Irving 1982; Van der Voo 1990). The Jurassic apparent polar wander path has been more controversial (Van Fossen & Kent 1990; Comment: Butler *et al.*, 1992; Reply; Van Fossen & Kent 1992a) and there are hardly any Early Cretaceous pole position data available for North America in compilations (Irving & Irving 1982; Van der Voo 1990). To help fill this gap in the record, we present palaeomagnetic data from ~143 Ma (latest Jurassic–earliest Cretaceous) kimberlite dikes near Ithaca in central New York State. The new results do not resolve the controversy in Jurassic apparent polar wander, but the Ithaca kimberlites pole charts a previously undocumented bend or 'cusp' in the North American apparent polar wander path.

GEOLOGY AND PALAEOMAGNETIC SAMPLING

Dozens of kimberlite dikes ranging in width from <1 cm to 2 m are reported in the Ithaca, New York area (Martens 1924; Meyer 1976; Kay *et al.* 1983); we were able to locate a diatreme and six dikes thick enough for palaeomagnetic sampling (Fig. 1). The generally vertical, north–south trending Ithaca dikes are exposed in stream cuts and intrude

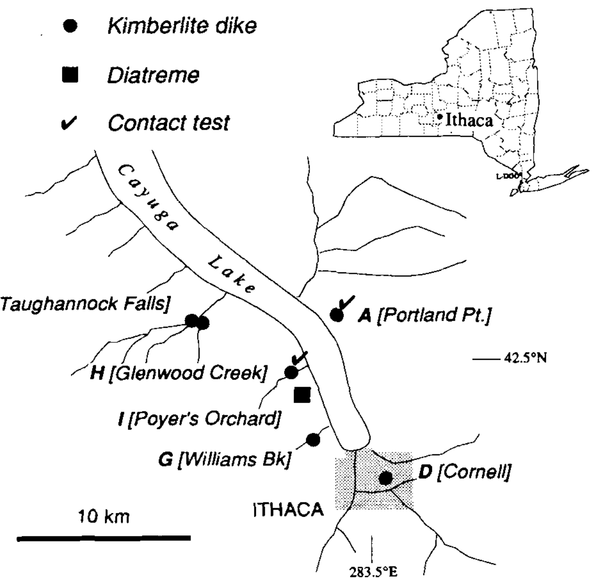


Figure 1. Location map for the 143 Ma kimberlite dikes near Ithaca, New York. Dike and diatreme sampling sites are indicated as well as the two sites at Portland Point and Glenwood Creek where Devonian limestone and shale were sampled for contact tests.

flat-lying middle to upper Devonian limestones and shales of the Allegheny plateau. Basu *et al.* (1984) provide K–Ar age data for five Ithaca dikes including those sampled here for palaeomagnetism. Two of the dikes (Taughannock and Portland Point) give K–Ar dates that are conspicuously younger than the rest and have higher standard errors (121 ± 23 and 113 ± 11 Ma, respectively). The mean K–Ar date of the other three dikes, which Basu *et al.* characterize as the freshest and most xenocryst free, is 142 ± 4 Ma (139 ± 7 Ma, Williams Brook; 140 ± 8 Ma, Frontenac Creek; and 146 ± 8 Ma, Cornell Campus dike), consistent within errors with the Rb–Sr biotite age previously reported for the Portand Point dike (136 ± 8 Ma; Zartman *et al.* 1967). Accordingly, Basu *et al.* (1984) suggested ~143 Ma as a representative K–Ar age for the Ithaca kimberlites. Miller & Duddy (1989) report an apatite fission-track date of 104 ± 22 Ma from one of the Ithaca dikes which can be interpreted as the time of cooling through ~100 °C as the region was eroded and exhumed. Thus the K–Ar, Rb–Sr, and apatite fission-track age data suggest that the Ithaca kimberlite dikes have not experienced any thermal disturbance since crystallization at about 143 Ma, even though, in thin section, the dikes show a generally high degree of serpentinization with pseudo-morphs of olivine visible in a groundmass of serpentine, calcite, chlorite and magnetite.

Standard oriented core samples were collected from six dikes and one 10 m wide diatreme (Fig. 1). Magnetic orientations were checked with back sightings and a sun compass, but no significant local field anomalies were detected. At each site, 5 to 10 oriented samples were taken with a portable coring drill. For the more detailed sampling requisite of baked contact tests, two large oriented block samples were collected from Devonian limestone on opposite sides of the Portland Point dike (15.2 cm wide), yielding a total of 13 specimens at a mean spacing of ~2 cm within one dike width when cored at the laboratory; an additional five core samples were taken evenly spaced beyond one dike width from the country rock. In Devonian shale on the west side of the Glenwood Creek dike (2.4 m wide), seven closely spaced samples were cored within one dike width plus an eighth sample at a distance of ~5 dike widths.

PALAEOMAGNETISM

The majority of natural remanent magnetization (NRM) directions from the dikes are northwest and down with the exception of those from Portland Point samples which are southeast and up (Fig. 2). These magnetizations are similar to the dual polarity directions reported by DeJournett & Schmidt (1975) in an earlier preliminary study of the Ithaca dikes. Intensities range from ~0.01 A/m (sites A and I) to ~1.7 A/m (site D) but are typically between 0.1–0.9 A/m. The kimberlite samples with high magnetization intensity also show high bulk susceptibility: NRM/induced magnetization ratios range from 0.1 to ~1 throughout the collection with no anomalous properties that could be indicative of lightning-related effects (Fig. 2).

Thermal and alternating field demagnetization of the kimberlite is straightforward, revealing only a single component of magnetization nearly parallel to the NRM. Peak unblocking temperatures for the dikes and the diatreme are 570 °C–575 °C and median destructive alternating fields are about 20 mT to 30 mT (Fig. 3). A few samples from each site may show a low coercivity (NRM to 10 mT) and low unblocking temperature (NRM to 200 °C) magnetization that is northerly and steeply down. Together with the efficient acquisition of isothermal remanent magnetization in kimberlite and Devonian host rock (Fig. 4), the demagnetization properties of all samples strongly suggest magnetite as the principal carrier of remanence, although minor haematite may be present in the Portland

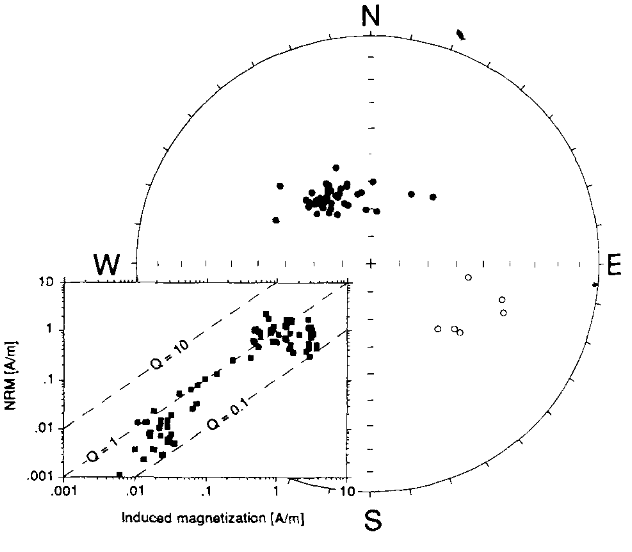


Figure 2. Equal area projection of natural remanent magnetization (NRM) of Ithaca kimberlites. Open (closed) symbols indicate upper (lower) hemisphere. The inset shows NRM intensity versus induction and dashed lines indicate Koningsberger ratios (Q). Most samples yield Q values between 0.1 and ~2.

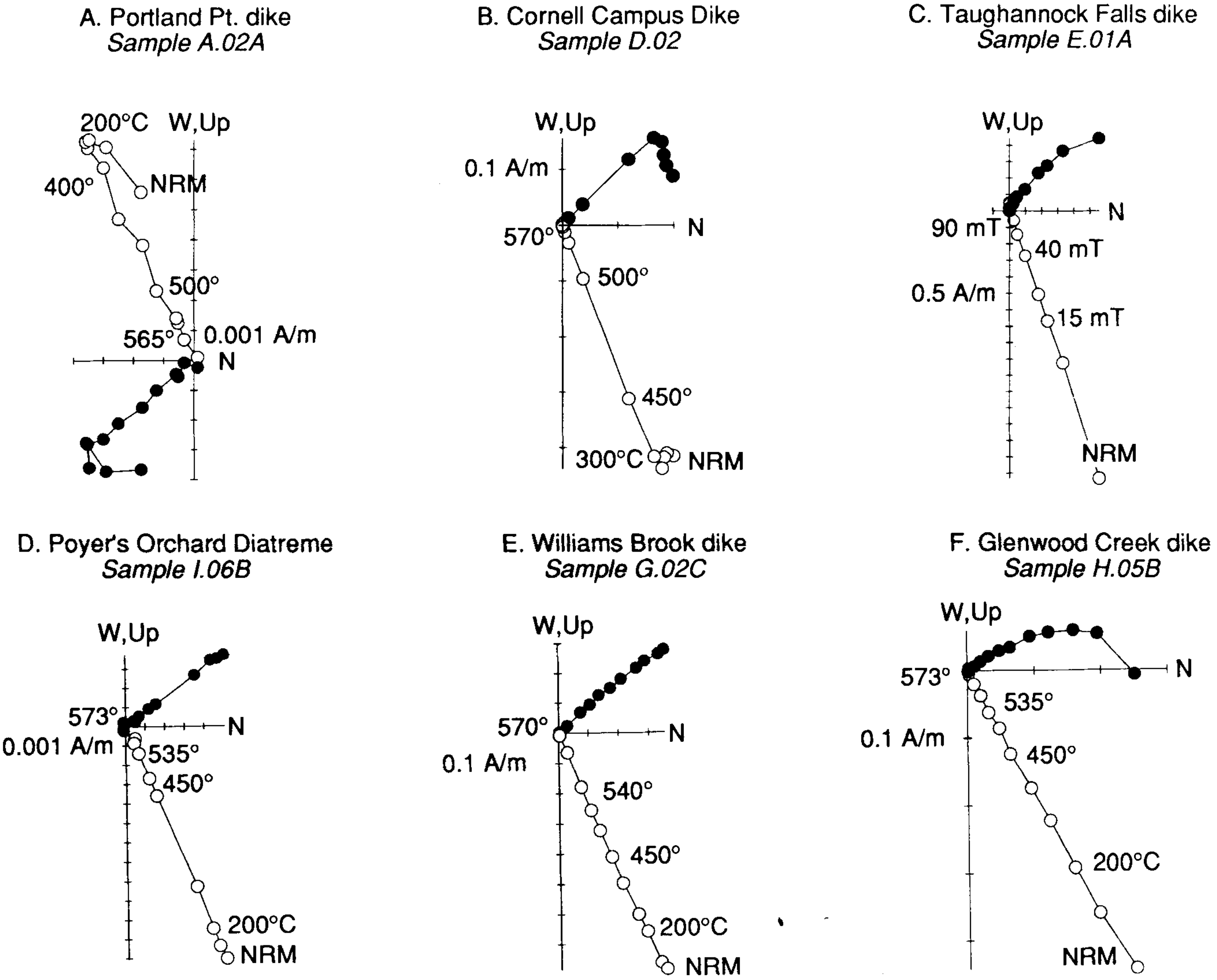


Figure 3. Representative progressive demagnetization of sample NRM from Ithaca kimberlites in orthographic projection. Open (closed) symbols indicate vertical (horizontal) projection of vector endpoints. (A, B) Thermal demagnetization of Portland Point and Cornell Campus dikes, respectively; (C) alternating field demagnetization of Taughannock Falls dike; (D, E, F) thermal demagnetization of Poyer's diatreme, Williams Brook dike, and Glenwood Creek dike, respectively.

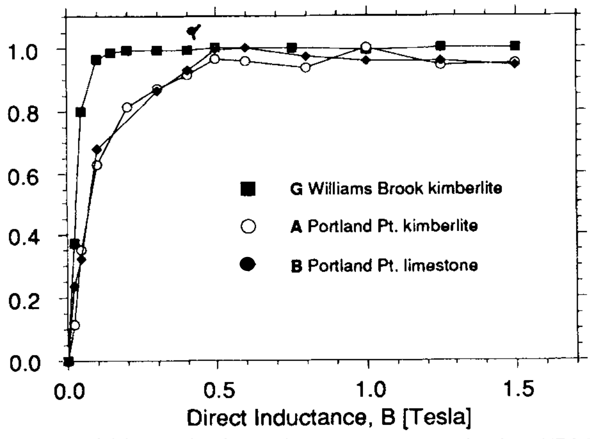


Figure 4. Acquisition of isothermal remanent magnetization (IRM) in reversed and normal polarity kimberlite samples and Devonian limestone at Portland Point. Efficient acquisition of IRM and saturation suggest magnetite as the predominant carrier of remanence.

Point dike which does not quite reach saturation magnetization in fields as high as 1 mT (Fig. 4). Least-squares analysis (Kirschvink 1980) was used to calculate best-fit vectors to the demagnetization data for each sample, usually over eight demagnetization steps (unblocking temperature range 400 °C or 450 °C to 570 °C; coercivity range 20 or 30 mT to 100 mT). The linear trajectory accounted for on average 98 per cent of the demagnetization data variance in each sample. Demagnetization vector data were grouped by site using standard Fisher (1953) statistics.

Like the NRM distribution, the site mean directions are generally well defined and fall into two bipolar groups along a northwest–southeast axis (Table 1 and Fig. 5). Only site F (Taughannock Creek) has a large cone of 95 per cent confidence, and was the only site in which a measured sample was rejected on account of poor demagnetization behaviour. The overall mean for seven sites has declination 317.3°, inclination 58.9° ($\alpha95 = 2.6°$). Sites D to I form a

Table 1. Site mean and pole position data from Ithaca kimberlite dikes, central New York State (42.5°N, 283.5°E).

					Mean		VGP	
Site	N/N_0	R	k	a95	Dec.	Inc.	Lat.	Long.
A	6/6	5.9885	433	3.2	134.0	-57.8	-55.2	022.7
D	7/7	6.9846	388	3.1	321.8	60.1	61.7	203.6
E	6/6	5.9848	330	3.7	308.4	57.8	51.1	205.4
F	4/5	3.9360	47	13.6	311.1	58.1	53.2	204.6
G	7/7	6.9676	185	4.4	322.8	59.2	62.1	201.1
H	10/10	9.9658	264	3.0	325.5	59.0	64.1	199.2
I	8/8	7.9861	504	2.5	318.4	59.5	59.0	203.8
Mean	{7/7}	6.9891	550	2.6	317.3	58.9	58.0	203.1
							A95 = 3.8°	

N/N_O, number of sample [site mean] directions used in mean calculation over number examined; *R*, resultant vector length of total number of vectors in the mean; *k*, Fisher dispersion parameter; a95, radius of 95% confidence about the mean direction; *Dec.*, *Inc.*, the declination and inclination of the mean magnetization; *VGP Lat.*, *Long.*, latitude and longitude of the virtual geomagnetic pole.

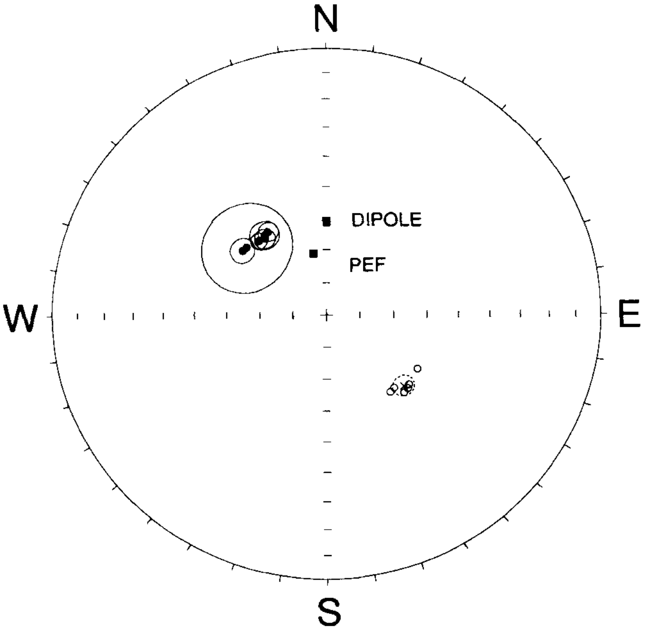


Figure 5. Equal area projection of site mean directions and cones of 95 per cent confidence, Ithaca kimberlites. Open (closed) symbols indicate upper (lower) hemisphere. For the reversed polarity site A (Portland Point dike), sample magnetization vectors are shown in addition to the site mean. This reversed polarity mean and the mean of the normal polarity group (six sites) are 2.4° from antipodality, and the critical angle at the 95 per cent confidence level for these data is 8.0°.

normal polarity group (declination 317.9°, inclination 59.1°; $\alpha95 = 3°$ for $N =$ six sites) with A being the lone reversed polarity site (declination = 134.0°, inclination = −57.8°; $\alpha95 = 3.2°$ for $N =$ six samples). The normal polarity group mean and reversed site mean A are only 2.4° from antipodality and the critical angle at the 95 per cent confidence level for these data is 8.0°. Thus the reversal test is judged positive, 'BI' class (McFadden & McElhinny 1990).

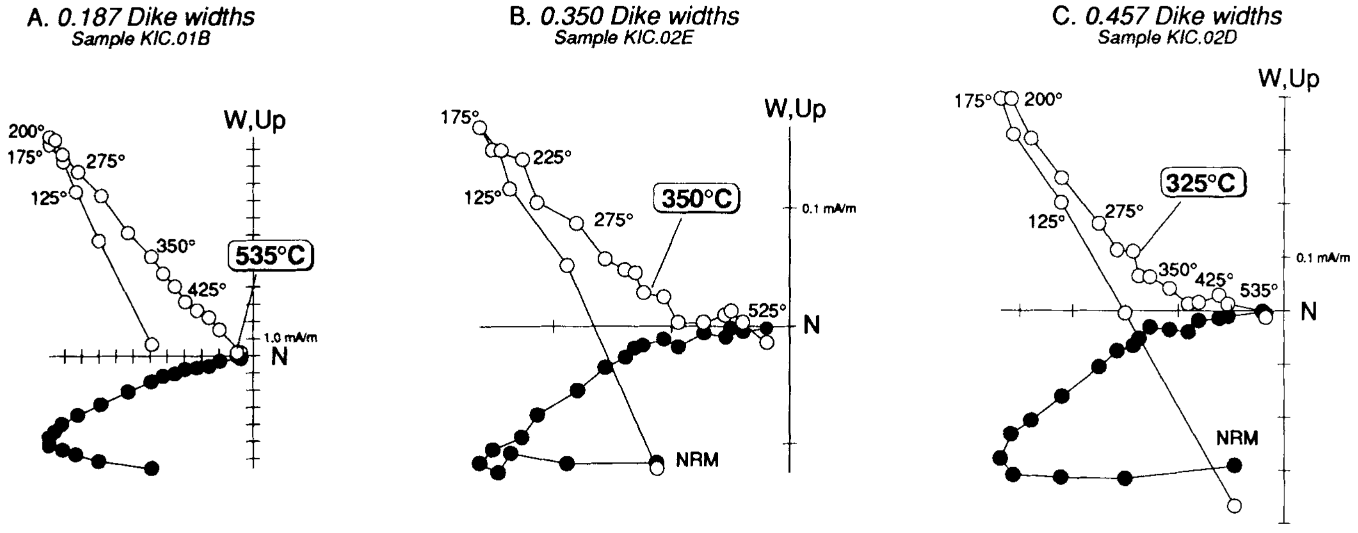
Contact tests

A fold test is obviously not possible given the flat-lying country rock but the Portland Point and Glenwood Creek kimberlite dikes provided the opportunity to apply a baked contact test for palaeomagnetic stability (Everitt & Clegg 1962; Irving 1964). In such a test, one compares thermal demagnetization profiles in samples taken from an igneous intrusion and immediately adjacent country rock, and would obtain a positive result if it is found that with increased distance from the intrusion, a dike-related partial thermal remagnetization declines steadily to reveal a pre-intrusion magnetization in the country rock.

Because of favourable response to thermal demagnetization, limestone samples on both sides of the 15.2 cm wide, reversed polarity Portland Point dike demonstrate well a systematic relationship in magnetization components with distance from the igneous intrusion (Fig. 6a–f). All limestone samples contain a northerly and down magnetization with low unblocking temperatures designated as the A component. The A component is attributed to a viscous remanence of recent origin that is typical of Paleozoic carbonate rocks in the western New York region (Scotese, Van der Voo & McCabe 1982; McCabe *et al.* 1984; Kent 1985). We note, however, that within about one dike width the peak unblocking temperature (200 °C) of this component is appreciably lower than peak viscous remanent magnetization unblocking temperatures (~300 °C) commonly observed in such limestones. At large distances from the dike (4.5 dike widths, Fig. 6g), the A component does indeed extend to ~300 °C, suggesting that near to the kimberlite dike, the intrusion has altered the viscous remanent magnetization character of the limestone.

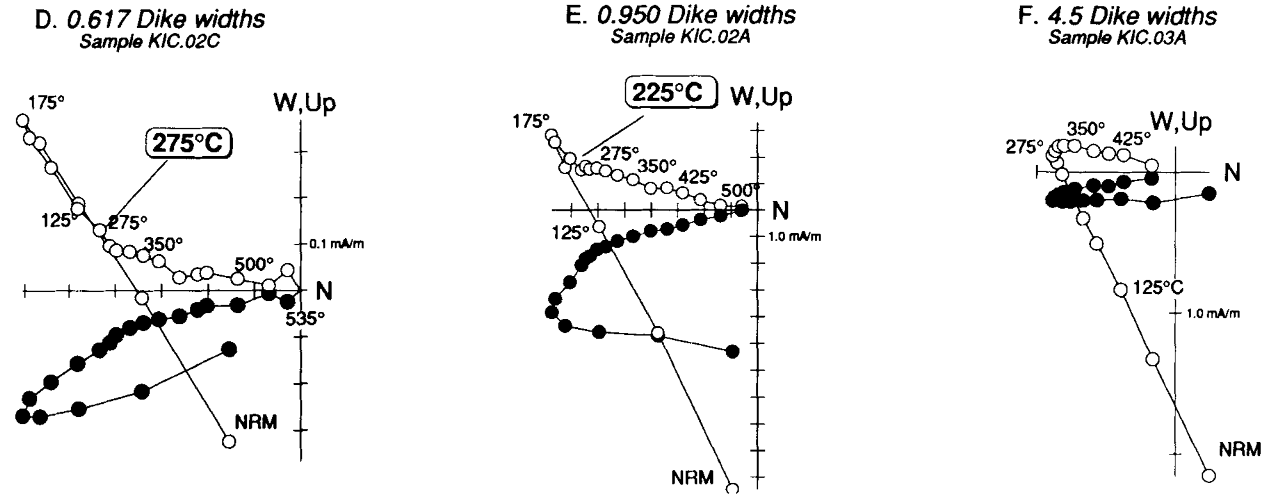
At demagnetization temperatures from 200 °C to the peak unblocking temperature in the limestone (535 °C), the magnetizations decompose further into a B component, a partial thermal remanent magnetization related to kimberlite intrusion, and a pre-existing C component, whose relative contributions vary systematically as a function of distance from the dike (Fig. 6a–f). In very close proximity to the dike (0.19 dike widths = 2.8 cm, Fig. 6a), only the southerly and up B component dominates, which has a direction similar to the high unblocking temperature magnetization of the Portland Point dike. Moving farther from the dike, the B component decreases in relative magnitude and peak unblocking temperature as the C component is revealed over a progressively wider unblocking temperature range (Fig. 6b–f). For example, by about 0.45 dike widths, the B component is isolated between demagnetization temperatures of 200 °C to 325 °C, and the C component, 325 °C to 535 °C (Fig. 6c). By 0.95 dike widths, the C component dominates, occupying the unblocking temperature range 225 °C to >500 °C (Fig. 6e), and far from the dike at 4.5 dike widths (Fig. 6f), the B component is virtually absent and the country rock contains only the pre-existing C and viscous remanent A components.

The B component is identifiable over at least three demagnetization steps in 12 of 13 limestone samples on both sides of the Portland Point dike and has a mean direction Dec. = 144.0°, Inc. = −44.2° ($\alpha95 = 5.5°$) that is about 14° shallower than the mean Portland Point dike direction (Dec. = 134.0°, Inc. = −57.8°; Table 1). The shallowing could be a result of bias by the incomplete removal of the northerly and steep downward A component. The southerly and shallow C component (Dec. = 171.6°, Inc. = −10.0°; $\alpha95 = 4.0°$, $n = 9$) predates dike intrusion and is interpreted as a Late Palaeozoic (Kiaman) secondary magnetization as typically observed in Appalachian limestones and shales (Scotese *et al.* 1982; McCabe *et al.* 1984; Kent 1985).


A. *0.187 Dike widths*
Sample KIC.01B

B. *0.350 Dike widths*
Sample KIC.02E

C. *0.457 Dike widths*
Sample KIC.02D


D. *0.617 Dike widths*
Sample KIC.02C

E. *0.950 Dike widths*
Sample KIC.02A

F. *4.5 Dike widths*
Sample KIC.03A

Figure 6. Positive baked contact test in Devonian limestone country rock adjacent to reverse polarity, 15.2 cm wide Portland Point dike. Progressive thermal demagnetization at 25°C steps above 100°C, where open (closed) symbols indicate vertical (horizontal) projection of vector endpoints. The samples show a systematic relationship in magnetization components with distance from the kimberlite dike (shown in dike widths). The A component (NRM to 200 °C) is present in all samples and attributed to a viscous remanent magnetization in the recent field. Above 200 °C, the B component (dike-related thermal remagnetization) and the C component (pre-existing, upper Paleozoic Kiaman magnetization) vary systematically in their relative contributions as a function of distance from dike. Moving away from the dike (a to f), the B component decreases in relative magnitude and peak unblocking temperature as the C component is revealed over a progressively wider unblocking temperature range.

Peak unblocking temperatures for the B component were selected from each demagnetization diagram of limestone samples on both sides of the Portland Point dike. The relative decrease in peak unblocking temperatures with distance from the dike (Fig. 7a) follows the relative temperature profile predicted from a simple conductive cooling model (Carslaw & Jaeger 1959; Fig. 7b). This correspondence strongly suggests the B component is a partial, thermally induced remagnetization of the country rock. In addition to relative peak temperatures, duration of heating at given positions from the dike can be estimated from the conductive cooling model and is defined as the time spent within ±25 °C of the peak temperature (Fig. 7b). These duration estimates used in conjunction with the magnetite relaxation time–temperature curves of Pulliah *et al.* (1975) or Middleton & Schmidt (1982) can be used to adjust the B component peak unblocking temperatures and estimate profiles of actual peak temperatures experienced by the country rock as a result of dike emplacement (Fig. 7a). Depending on the unblocking temperature and duration of heating estimate, the curve derived from Middleton & Schmidt gives temperatures up to 50 °C lower than that derived using Pulliah *et al.* At around one dike width, the predicted temperatures using Middleton & Schmidt are ~120 °C, approaching the early- to mid-Cretaceous burial temperatures of the Allegheny platform suggested by apatite fission-track data (Miller & Duddy 1989). From conductive cooling, this predicts an emplacement temperature ~700 °C above ambient (i.e. ~820 °C); allowing for latent heat of crystallization, this estimate would be lowered by 13 per cent to ~713 °C (following Harrison & Clarke 1979) which is compatible with the relatively low range of emplacement

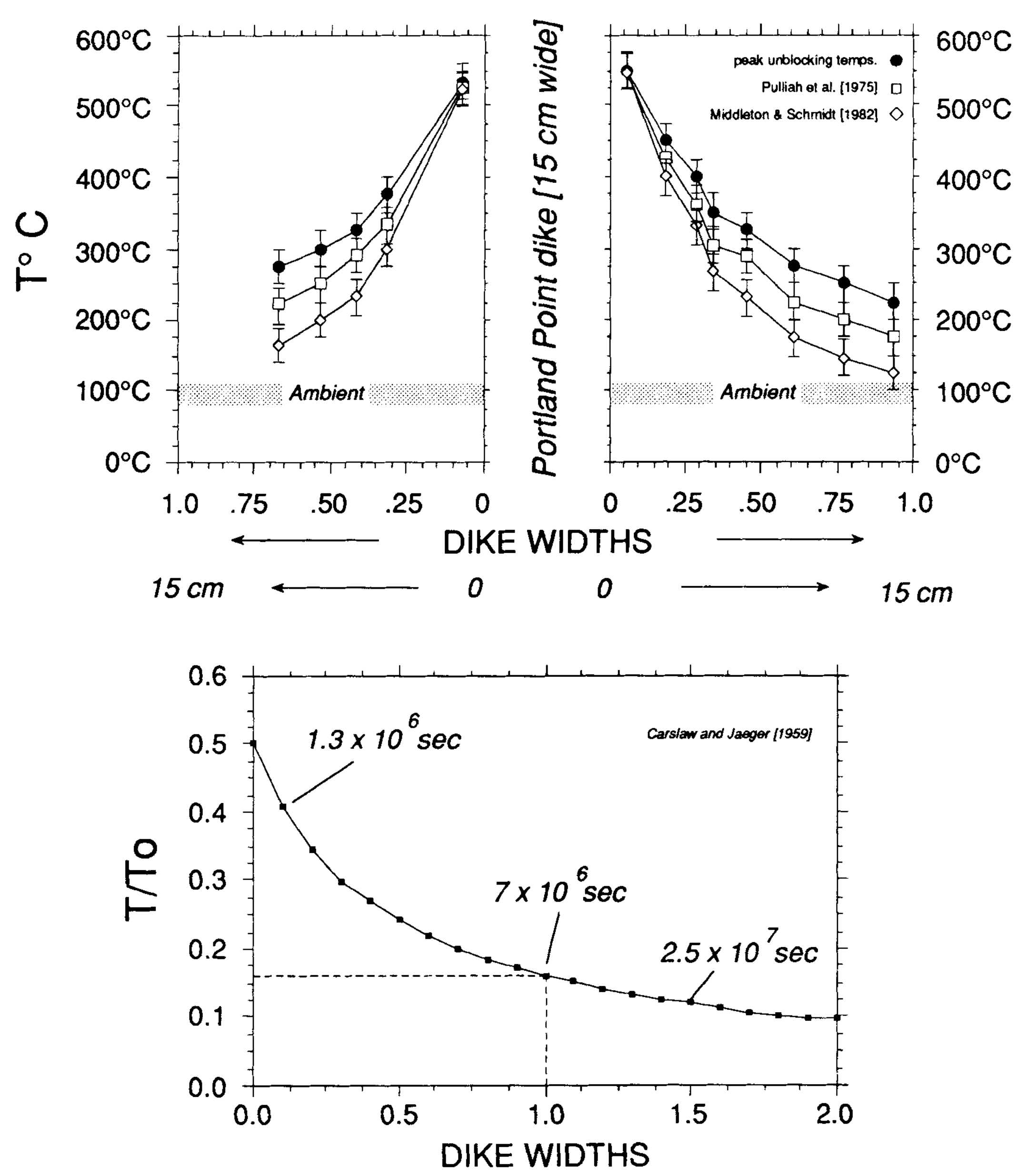


Figure 7. (A) Peak unblocking temperatures for the thermally induced B component from 13 limestone country rock samples on both sides and within one dike width of the Portland Point kimberlite. The decrease in peak unblocking temperatures with distance from the dike follows the profile (B) predicted from a conductive cooling model (Carslaw & Jaeger 1959) with a diffusivity of 7.0×10^{-7} $m^2 s^{-1}$ for typical limestone. Duration of heating at various dike widths (defined as the total time spent within ±25 °C of the peak temperature) can also be estimated from the conductive cooling model, and these durations are used to adjust the peak unblocking temperatures (A) in conjunction with magnetite relaxation time–temperature curves to estimate a profile of actual peak temperatures experienced by the country rock after dike emplacement. At about one dike width, predicted peak temperatures using relaxation time–temperature curves of Middleton & Schmidt (1982) are ~120 °C, approaching the early- to mid-Cretaceous burial temperatures (80–110 °C) estimated with apatite fission-track data for the Allegheny platform (Miller & Duddy 1989). From conductive cooling, this predicts an emplacement temperature ~700 °C above ambient (i.e. ~820 °C) but would be lowered by 13 per cent to ~713 °C allowing for latent heat of crystallization.

temperatures suggested for kimberlite in the petrology literature (see Mitchell 1986).

An additional contact test was attempted in Devonian shale adjacent to the normal polarity Glenwood Creek dike, not only for a test of palaeomagnetic stability, but also to address the possibility of self reversal in the Ithaca kimberlites. Broadly complementary B and C components are present in the country rock at Glenwood Creek, but due to a less favourable response of the shale to thermal demagnetization (scattered directions and possible growth of magnetic phases at high demagnetization temperature), the Glenwood contact test can only be delineated qualitatively as positive. A dike-related, partial remagnetization dominates the high unblocking temperature spectra of the country rock within one dike width of the contact (B component with normal polarity) but at distances greater than 1 dike width, a southerly and shallow high unblocking temperature magnetization (C component) dominates, again attributed to a Late Palaeozoic Kiaman magnetization.

Reliability of Ithaca kimberlites magnetization

The tractable relationship between distance from contact and extent of thermal resetting of country rock indicates positive contact tests for normal polarity (Glenwood Creek) and reverse polarity (Portland Point) dikes. Thus one can argue that not only was the field area spared any remagnetization subsequent to late Jurassic–early Cretaceous dike intrusion, but also that the Ithaca kimberlites have not undergone self reversal.

For a magnetization to be useful in apparent polar wander studies, an adequate sampling of palaeosecular variation is also necessary. Indeed the presence of dual polarity Ithaca kimberlite magnetizations suggests that a sufficient amount of geological time should be represented in the total sampling. A problem emerges, however, because the angular dispersion among the seven Ithaca dike site means ($\theta_{63} = 3.5°$) is appreciably lower than that expected from either modern geomagnetic secular variation at a comparable 40° (palaeo)latitude (~12°, Irving & Pulliah 1976; McFadden & McElhinny 1984), or even for the late Jurassic–early Cretaceous, post-350 Ma low in palaeosecular variation (~9° at palaeolatitude of 40°) determined by Irving & Pulliah (1976). If an individual Ithaca kimberlite dike provides a spot reading of the palaeomagnetic field, then the positive reversal test would require that the dikes recorded two distinct episodes of secular variation where the instantaneous fields were fortuitously very close to antipodal to one another. Moreover, given the presence of a reversed polarity dike with positive contact test, there is no reason to believe that the six normal polarity intrusions necessarily record magnetization acquired simultaneously or even during the same normal polarity interval.

An alternative interpretation for the low angular dispersion is that, in addition to thermal remanent magnetization, some process in kimberlite dike genesis prolongs the magnetization acquisition period to average palaeosecular variation within individual dikes. In this regard, Hargraves (1989) has discussed thermo-chemical remanent magnetization (TCRM) during early serpentinization for the early- to mid-Cretaceous kimberlites in southern Africa. Magnetite is a natural product of serpentinization, the low temperature (<500 °C) hydrothermal alteration of ultramafic rocks (Wenner & Taylor 1971; Brewster & O'Reilly 1988, 1989; Toft, Arkani-Hamed & Haggerty 1990). In thin and polished sections of Ithaca kimberlites, we observed fine-grained magnetite associated with serpentine pseudo-morphs after olivine and also throughout the serpentinized groundmass. Interestingly, Hargraves (1989) also obtained lower-than-expected dispersion in the KP1 and KP2 kimberlites from southern Africa, which otherwise yielded pole positions interpreted as time-averaged palaeomagnetic poles. Thus the TCRM mechanism may extend the duration of the magnetization process in serpentinized kimberlite to greater than 10^2–10^3 yr, as predicted from simple conductive cooling models, but less than about 10^7 yr, that is, long with respect to palaeosecular variation but short with respect to apparent polar wander. General support for this idea comes from not only the kimberlites from southern Africa (Hargraves 1989), but other palaeomagnetic studies of kimberlitic rock in the literature (e.g. Eocene Missouri Breaks, Diehl *et al.* 1983; lower Carboniferous British Columbia, Symons & Lewchuk 1989) in which palaeomagnetic poles were interpreted in terms of apparent polar wander despite low angular dispersion.

The serpentinization process might also impose a fabric in kimberlite dikes (Bina & Henry 1990), which could deflect the magnetization from the direction of the palaeofield. The possibility of an anisotropy in the remanent magnetization of the Ithaca kimberlite dikes was investigated by measuring the anisotropy of anhysteric remanent magnetization (ARM) in oriented specimens available from six of the seven sites. Following the method of Jackson *et al.* (1988), a total of six applied ARMs (positive and negative along three mutually perpendicular axes) over the coercivity range 0–100 mT with 0.05 mT biasing field were measured for each specimen. From these data a mean anisotropy tensor was calculated using the method of Jelinek (1978). No significant lineation was found, but the mean ARM anisotropy data do show a weak (8.6 per cent ± 5 per cent) but consistent foliation in a north–south vertical plane which coincides with the general orientation of the Ithaca dikes, but not with the northwest-down/southeast-up direction of remanence.

POLE POSITION AND DISCUSSION

The positive contact tests, positive reversal test, and lack of secondary magnetization overprints argue for the stability of magnetization in the Ithaca kimberlites. Furthermore, the tectonic and structural stability of the field area and the arguments presented for a sufficient averaging of palaeosecular variation suggest that the Ithaca kimberlites pole (58.0°N, 203.1°E, A95 = 3.8°; Fig. 8 and Table 1) represents a reliable record of the palaeomagnetic field relative to cratonic North America at ~143 Ma. The Ithaca pole, however, does not fall near published late Jurassic–early Cretaceous apparent polar wander paths for cratonic North America (Irving & Irving 1982; Gordon, Cox & O'Hare 1984; May & Butler 1986; Besse & Courtillot 1991). Even allowing for the possibility of grossly inaccurate radiometric dating and considering only the geological constraint on dike age as post-Devonian, the Ithaca kimberlites pole still does not agree with any cratonic North American pole position in the recent compilation by Van der Voo (1990). There is therefore no suspicion of remagnetization. Instead, the Ithaca kimberlites pole may chart a previously undocumented feature of North American apparent polar wander. The Ithaca kimberlites pole does not resolve the controversy in middle to late Jurassic apparent polar wander argued recently in the literature (see Van Fossen & Kent 1990; Comment and Reply: Butler *et al.* 1992; Van Fossen & Kent 1992a). However, if incorporated into North American apparent polar wander paths, the Ithaca kimberlites pole would for instance extend the southeastward trending late Jurassic–early Cretaceous Irving & Irving (1982) path to near 60°N, 200°E (Fig. 8). Alternatively, the Ithaca kimberlites pole would disrupt the so-called 'J2–K' track from May & Butler (1986), once considered a continuous small-circular path of late Jurassic to mid-Cretaceous North American apparent polar wander (Fig. 8).

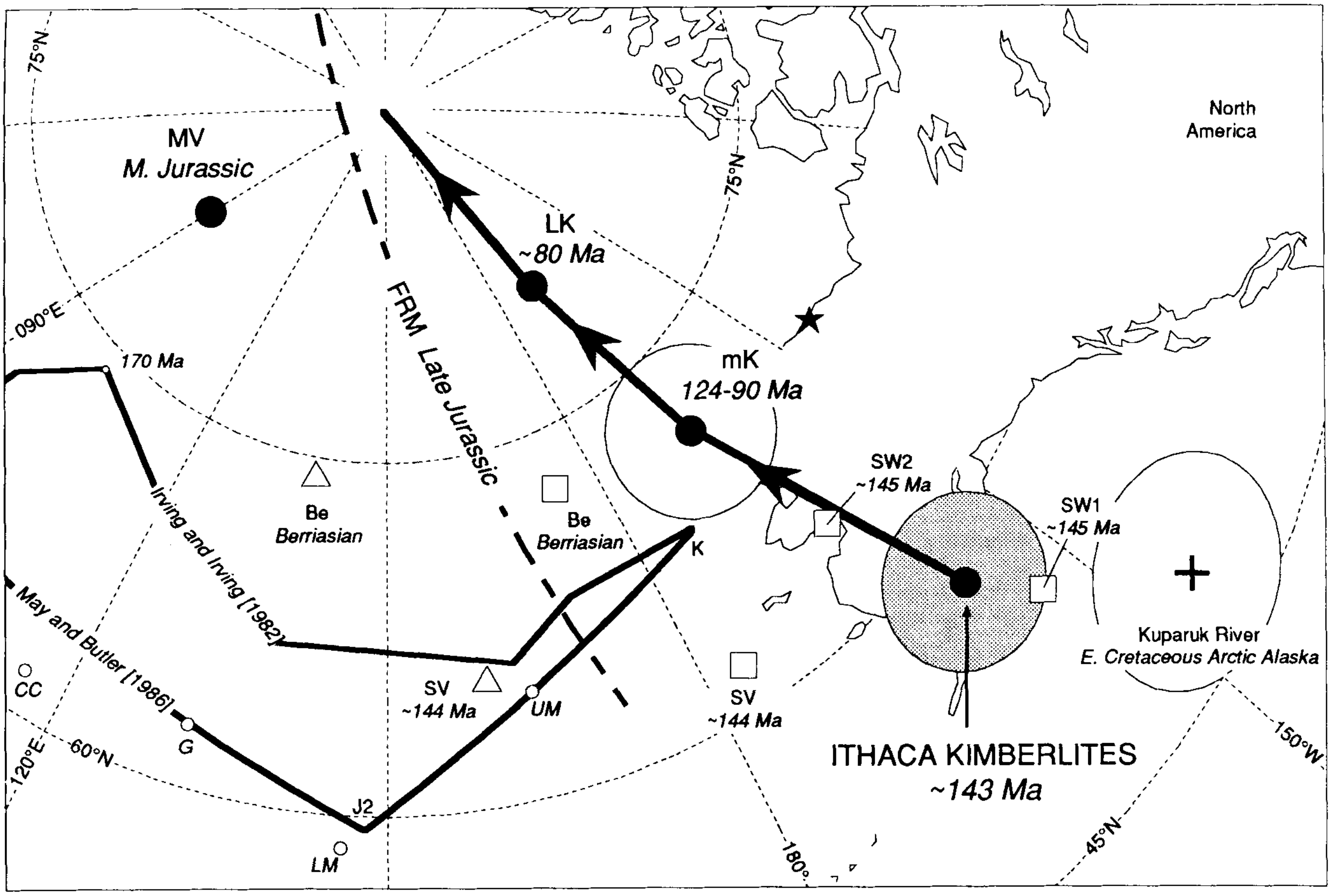


Figure 8. Ithaca kimberlites 143 Ma pole position (grey shading) compared to middle Jurassic to Recent North American apparent polar wander paths and poles. The Ithaca kimberlites pole would further extend the southeastward trending latest Jurassic–earliest Cretaceous path from Irving & Irving (1982), or would disrupt the otherwise continuous 'J2–K' late Jurassic to mid-Cretaceous apparent polar wander track from May & Butler (1986). A broad interval of post-143 Ma apparent polar wander (shown with arrows) along a constant arc from about 58°N, 203°E to the spin axis may be initiated by the Ithaca kimberlites pole. mK: mid-Cretaceous 'standstill' pole (Globerman & Irving 1988; Van Fossen & Kent 1992c); LK: Late Cretaceous pole (Diehl 1991). The Ithaca kimberlites pole is supported by the ~145 Ma Main Swartruggens pole from southern Africa (Hargraves & Onstott 1980; Hargraves 1989) which transfers to 57°N, 218°E (SW1) after simple closure of the central Atlantic (Pindell *et al.* 1988), or 57°N, 218°E (SW2) after rotating southern Africa to North American coordinates (Rabinowitz & LaBrecque 1979; Pindell *et al.* 1988). Coeval poles from Eurasia (BE: Berriasian pole from Galbrun 1985; SV: 144 Ma Svalbard dolerite pole from Halvorsen 1989) yield less diagnostic tests of the Ithaca kimberlites pole due to disagreement between the two Eurasian poles and uncertainties in Europe–North American reconstructions (triangles: Bullard *et al.* 1965 reconstruction; squares: Srivastava & Tapscott 1986 reconstruction). Compared to the Ithaca kimberlites pole, the Early Cretaceous Kuparuk River pole (49.1°N, 213.9°E; Halgedahl & Jarrard 1987) suggests very little azimuthal offset but significant southerly translation of the Arctic Alaska block of 954 km ± 377 km relative to cratonic North America. Kuparuk River sampling site shown by black star. Other published poles shown: ~166 Ma Moat volcanics pole (MV at 82°N, 090°E) from Van Fossen & Kent (1990); Late Jurassic Front Range Morrison pole (FRM, dashed small circle) from Van Fossen & Kent (1992b); 172 Ma Corral Canyon pole (CC at 62°N, 116°E) from May *et al.* (1986); 151 Ma Glance conglomerate pole (G) from Kluth *et al.* (1982); and late Jurassic Colorado Plateau Morrison Formation (LM: lower, UM: upper) from Steiner & Helsley (1975).

The nearest approach to any North American pole position made by the Ithaca kimberlites pole is the mid-Cretaceous 'standstill' (at 71°N, 196°E, Globerman & Irving 1988; Van Fossen & Kent 1992c). This reference pole would predict at the Ithaca sampling site a declination of 334.7° and palaeolatitude of 40.4°, which differs from the mean Ithaca dikes data almost entirely in declination (317.3° with palaeolatitude of 39.6°). A 20° counter-clockwise tectonic rotation is not a viable explanation given the stable Palaeozoic foreland setting of the dikes. If the small anisotropy in the Ithaca kimberlite dikes has somehow affected the northwest/southeast magnetization direction, this still would not explain the distinct pole: possible compensation for a north–south foliation would only drive the pole position even farther away from known North American poles (Fig. 8).

The Ithaca kimberlites pole therefore apparently initiates a Cretaceous to Recent apparent polar wander path along approximately the 200°E meridian from about 58°N to the geographic axis (Fig. 8). The Ithaca pole suggests an average apparent polar wander rate of 0.25°/m.y. from 143 Ma to the present, although the details of the post-143 Ma pole position data indicate that apparent polar wander rates are not at all constant over this interval. For instance, the mid-Cretaceous 'standstill' pole (Globerman & Irving 1988; Van Fossen & Kent 1992c) requires a 34 Ma interval of virtually no motion relative to the pole from ~124 to 90 Ma. Based on our Ithaca kimberlites pole, this standstill was preceded by apparent polar wander at 0.7°/m.y. from ~143 to 124 Ma. The rate of apparent polar wander immediately following the mid-Cretaceous 'standstill' was even faster, at about 2°/m.y. based on the ~80 Ma poles from Montana (Gunderson & Sheriff 1991; Diehl 1991).

Support for the Ithaca kimberlite pole comes from the 145 Ma Main Swartruggens kimberlite dike in southern Africa (Hargraves & Onstott 1980; Hargraves 1989). The Main dike pole position comes from just one site but falls at 34°N, 276°E (A95 = 9°; $n = 6$ samples), distinct from the younger southern Africa mean poles KP1 (81–100 Ma) and KP2 (119–121 Ma) at the 95 per cent confidence level. Rotated to North American coordinates based on the sea-floor spreading models of Pindell *et al.* (1988) and Rabinowitz & LaBrecque (1979), with a linear interpolation to 145 Ma between anomalies M21 and M16 (time-scale of Harland *et al.* 1990), the Main dike pole transfers to 57°N, 218°E in North America coordinates, very close to the Ithaca kimberlites pole at 58.0°N, 203.1°E (Fig. 8).

The available coeval poles available from Europe unfortunately provide less diagnostic tests of the Ithaca kimberlites pole. One problem is that the Berriasian (141–146 Ma; Harland *et al.* 1990) limestones pole from southern France (75.0°N, 179.4°E, A95 = 3.2°; Galbrun 1985) and the 144 Ma dolerites pole from Svalbard (66°N, 200°E, dp = 6°, dm = 7°; Halvorsen 1989) are distinct from one another at the 95 per cent confidence level, suggesting that the magnetizations are not of the same age, there were structural rotations within Svalbard (Hayashida & Suzuki 1988), or that there was some tectonic displacement between the Svalbard archipelago and Europe. For the transfer of these poles to North American coordinates, there is the added uncertainty as to which Europe–North America reconstruction to use (Fig. 8). In his comparison of Palaeozoic to early Jurassic pole positions from Europe and North America, Van der Voo (1990) found best overall agreement among poles using the Bullard, Everett & Smith (1965) Europe–North America reconstruction, and noted that the differences among the reconstructions might reflect the effects of continental extension prior to late Cretaceous sea-floor spreading in the North Atlantic. Post-early Jurassic North American and European poles may be more appropriately transferred using the relatively 'loose' fits, such as Srivastava & Tapscott (1986), but we are unaware of any independent supporting evidence.

New studies are clearly needed to substantiate the Ithaca kimberlites pole, especially because of implications for the analysis and interpretation of suspect terranes. For instance, the Early Cretaceous palaeomagnetic pole from the Kuparuk River formation on the Alaskan North Slope (49.1°N, 213.9°E, dp = 4.9°, dm = 5.2°; Halgedahl & Jarrard 1987) was compared to the available cratonic reference data from Harrison & Lindh (1982), which implied a 66° azimuthal offset of the Arctic Alaska block with respect to the craton, but little latitudinal displacement. Among various Arctic tectonic models, Halgedahl & Jarrard (1987) found that the Kuparuk River palaeomagnetic data were more consistent with a style of tectonic models that evoke anticlockwise rotation of Arctic Alaska off the Sverdrup margin as the Canada Basin opened in a scissor-like fashion (Carey 1955; Tailleur 1969; Grantz, Eittreim & Dinter 1979; Taylor *et al.* 1981). However, if the Ithaca kimberlites pole (58.0°N, 203.1°E) is used for reference, the Kuparuk River pole implies 24° ± 18° azimuthal offset of Arctic Alaska, but a latitudinal displacement of 8.6° ± 3° or 954 km ± 377 km (Fig. 8). Because the reference pole in this case is located south of the Arctic Alaska terrane pole, the implied sense of Arctic Alaska motion is toward the palaeopole or southward relative to the North American craton in present-day coordinates (Fig. 8). The amount and sense of this displacement would be compatible with other Arctic tectonic models which emphasize translation of Arctic Alaska from the Lomonosov Ridge and Barents Shelf (e.g. Dutro 1981; Smith 1987; Hubbard, Edrich & Rattey 1987). It is interesting to note that Hubbard *et al.* (1987) suggest about 1000 km of Late Cretaceous translation of the Arctic Alaska block, indistinguishable from our estimate made by comparison of the Kuparuk River pole with the new Ithaca kimberlites pole.

ACKNOWLEDGMENTS

The authors would like to thank Jack Oliver, Bob Kay and Brandon Foster for providing clues in finding the outcrops. Bill Witte provided excellent field assistance. Access to the Portland Point dike was kindly granted by Mr H. Whetzel of Cayuga Crushed Stone, Inc. This is Lamont–Doherty Earth Observatory contribution #5030.

REFERENCES

Basu, A. R., Rubury, E., Mehnert, H. & Tatsumoto, M., 1984. Sm-Nd, K-Ar and petrologic study of some kimberlites from eastern United States and their implication for mantle evolution, *Contr. Mineral. Petrol.*, **86,** 35–44.

Besse, J. & Courtillot, V., 1991. Revised and synthetic apparent polar wander paths of the African, Eurasian, North American and Indian plates, and true polar wander since 200 Ma, *J. geophys. Res.*, **96,** 4029–4050.

Bina, M. M. & Henry, B., 1990. Magnetic properties, opaque mineralogy and magnetic anisotropies of serpentinized peridotites from ODP Hole 670A near the mid-Atlantic ridge, *Phys. Earth planet. Sci. Lett.*, **65,** 88–103.

Brewster, D. & O' Reilly, W., 1988. Magnetic properties of synthetic analogues of the altered olivines of igneous rocks, *Geophys. J.*, **95,** 421–432.

Brewster, D. & O' Reilly, W., 1989. Thermo-remanent magnetization carried by synthetic analogues of the altered olivines of igneous rocks, *Earth planet Sci. Lett.*, **93,** 123–132.

Bullard, E. C., Everett, J. E. & Smith, A. G., 1965. The fit of the continents around the Atlantic, in: *Symposium on Continental Drift, Phil. Trans. R. Soc. Lond., Ser.* A, **258,** 41–51.

Butler, R. F., May, S. & Bazard, D., 1992. Comment on 'High latitude paleomagnetic poles from Middle Jurassic plutons and Moat Volcanics in New England and the controversy regarding Jurassic apparent polar wander for North America' by Mickey C. Van Fossen and Dennis V. Kent, *J. geophys. Res.*, 1801–1802.

Carey, S. W., 1955. Orocline concept in geotectonics, *R. Soc. Tasmania*, **89,** 255–288.

Carslaw, H. & Jaeger, J. C., 1959. *Conduction of Heat in Solids*, Oxford University Press, Oxford.

DeJournett, J. D. & Schmidt, V. A., 1975. Paleomagnetism of some peridotite dikes near Ithaca, New York (abstract), *Trans. Am. geophys. Un.*, **56**, 354.

Diehl, J. F., 1991. The Elkhorn Mountains revisited: new data for the Late Cretaceous paleomagnetic field of North America, *J. geophys. Res.*, **88**, 9887–9894.

Diehl, J. F., Beck, M. E., Jr, Beske-Diehl, S., Jacobson, D. & Hearn, B. C., Jr, 1983. Paleomagnetism of the late Cretaceous-early Tertiary north-central Montana alkalic province, *J. geophys. Res.*, **88**, 10 593–10 609.

Dutro, J. T., Jr, 1981. Geology of Alaska bordering the Arctic Ocean, in *The Ocean Basins and Margins, Vol. 5, The Arctic Ocean*, pp. 21–36, eds Nairn, A. E. M. *et al.*, Plenum, New York.

Everitt, C. W. F. & Clegg, J. A., 1962. A field test of palaeomagnetic stability, *Geophys. J.*, **6**, 312–319.

Fisher, R. A., 1953. Dispersion on a sphere, *Proc. R. Soc. Lond., Ser.* A, **217**, 295–305.

Galbrun, B. 1985. Magnetostratigraphy of the Berriasian stratotype section (Berrias, France), *Earth planet. Sci. Lett.*, **74**, 130–136.

Geissman, J. W. & Gordon, R. G., 1991. Paleomagnetic reference poles, apparent polar wander paths, paleomagnetic Euler pole analysis, and true polar wander, *Rev. Geophys. US Nat. Rep. IUGG 1987–1990*, 384–394.

Globerman, B. R. & Irving, E., 1988. Mid-Cretaceous paleomagnetic field for North America: restudy of 100 Ma intrusive rocks from Arkansas, *J. geophys. Res.*, **93**, 11 721–11 733.

Gordon, R. G., Cox, A. & O'Hare, S., 1984. Paleomagnetic Euler poles and the apparent polar wander and absolute motion of North America since the Carboniferous, *Tectonics*, **3**, 499–537.

Grantz, A., Eittreim, S. & Dinter, D. A., 1979. Geology and tectonic development of the continental margin north of Alaska, *Tectonophysics*, **89**, 337–357.

Gunderson, J. A. & Sheriff, S. D., 1991. A new Late Cretaceous paleomagnetic pole from the Adel Mountains, west-central Montana, *J. geophys. Res.*, **96**, 317–326.

Halgedahl, S. L. & Jarrard, R. D., 1987. Paleomagnetism of the Kuparuk River formation from oriented drill core: evidence for rotation of the Arctic Alaska plate, in *Alaskan North Slope Geology, Vol. 2*, pp. 581–617, eds Tailleur, I. & Weimer, P., Society of Economic Paleontologists and Mineralogists and Alaska Geological Society, Bakersfield.

Halvorsen, E., 1989. A paleomagnetic pole position of Late Jurassic/Early Cretaceous dolerites from Hinlopenstretet, Svalbard, and its tectonic implications, *Earth planet. Sci. Lett.*, **94**, 398–408.

Hargraves, R. B., 1989. Paleomagnetism of Mesozoic kimberlites in southern Africa and the Cretaceous apparent polar wander curve for Africa, *J. geophys. Res.*, **94**, 1851–1866.

Hargraves, R. B. & Onstott, T. C., 1980. Paleomagnetic results from the southern African kimberlites, and their tectonic significance, *J. geophys. Res.*, **85**, 3587–3596.

Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G. & Smith, D. G., 1979. *A Geologic Timescale 1989*, Cambridge University Press, New York.

Harrison, M. T. & Clarke, G. K. C., 1979. A model of the thermal effect of igneous intrusion and uplift as applied to Quottoon pluton, British Columbia, *Can. J. Earth Sci.*, **16**, 411–420.

Harrison C. G. A. & Lindh, T., 1982. A polar wandering curve for North America during the Mesozoic and Cenozoic, *J. geophys. Res.*, **87**, 1903–1920.

Hayashida, A. & Suzuki, H., 1988. Preliminary paleomagnetic data from the Paleozoic and Mesozoic rocks of the Billefjorden area, southwest Spitsbergen, *Rock. Mag. Paleogeophys.*, **15**, 64.

Hubbard, R. J., Edrich, S. P. & Rattey, R. P., 1987. Geologic evolution and hydrocarbon habitat of the Arctic Alaska microplate, in *Alaskan North Slope Geology, Vol. 2*, pp. 797–830, eds Tailleur, I. & Weimer, P., Society of Economic Paleontologists and Mineralogists and Alaska Geological Society, Bakersfield.

Irving, E., 1964. *Paleomagnetism and Its Application to Geological and Geophysical Problems*, Wiley, New York.

Irving, E. & Irving, G. A., 1982. Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana, *Geophys. Surv.*, **5**, 141–188.

Irving, E. & Pulliah, G., 1976. Reversals of the geomagnetic field, magnetostratigraphy, and relative magnitude of paleosecular variation in the Phanerozoic, *Earth Sci. Rev.*, **12**, 35–64.

Jackson, M., Gruber, W., Marvin, J. & Banerjee, S. K., 1988. Partial anhysteretic remanence and its anisotropy: applications and grainsize-dependence, *Geophys. Res. Lett.*, **15**, 440–443.

Jelinek, V., 1978. Statistical processing of anisotropy of magnetic susceptibility measured on groups of specimens, *Stud. Geophys. Geod.*, **22**, 50–62.

Johnson, R. J. R., Van der Voo, R. & Lowrie, W., 1984. Paleomagnetism and late diagenesis of Jurassic carbonates from the Jura Mountains, Switzerland and France, *Geol. Soc. Am. Bull*, **95**, 478–488.

Kadzialko-Hofmokl, M. & Kruczyk, J., 1987. Paleomagnetism of middle-late Jurassic sediments from Poland and implications for the polarity of the geomagnetic field, *Tectonophysics*, **139**, 53–66.

Kay, S. M., Snedden, W. T., Foster, B. P. & Kay, R. W., 1983. Upper mantle and crustal fragments in the Ithaca kimberlites, *J. Geol.*, **91**, 277–290.

Kent, D. V., 1985. Thermoviscous remagnetization in some Appalachian limestones, *Geophys. Res. Lett.*, **12**, 805–808.

Kirschvink, J. L., 1980. The least-squares line and plane and the analysis of paleomagnetic data, *Geophys. J. R. Astr. Soc.*, **62**, 699–718.

Kluth, C. F., Butler, R. F., Harding, L. E., Shafiqullah, M. & Damon, P. E., 1982. Paleomagnetism of Late Jurassic rocks in the northern Canelo Hills, southeastern Arizona, *J. geophys. Res.*, **87**, 7079–7086.

Martens, J. H. C., 1984. Igneous rocks of Ithaca, New York, *Geol. Soc. Am. Bull.*, **35**, 305–320.

May, S. R. & Butler, R. F., 1986. North American Jurassic apparent polar wander, implications for plate motion, paleogeography and Cordilleran tectonics, *J. geophys. Res.*, **91**, 11 519–11 544.

May, S. R., Butler, R. F., Shafiqullah, M. & Damon, P. E., 1986. Paleomagnetism Jurassic rocks in the Patagonia Mountains, southeastern Arizona: implications for the North American 170 Ma reference pole, *J. geophys. Res.*, **91**, 11 545–11 555.

McCabe, C., Van der Voo, R., Peacor, D. R., Scotese, C. R. & Freeman, R., 1984. Diagenetic magnetite carries ancient yet secondary remanence in some Paleozoic sedimentary carbonates, *Geology*, **11**, 221–223.

McFadden, P. L. & McElhinny, M. W., 1990. Classification of the reversal test in palaeomagnetism, *Geophys. J. Int.*, **103**, 725–729.

McFadden, P. L. & McElhinny, M. W., 1984. A physical model for paleosecular variation, *Geophys. J. R. astr. Soc.*, **78**, 809–830.

Meyer, H. O. A., 1976. Kimberlites of the continental United States: a review, *J. Geol.*, **84**, 377–403.

Middleton, M. F. & Schmidt, P. W., 1982. Paleothermometry of the Sydney Basin, *J. Geophys. Res.*, **87**, 5351–5359.

Miller, D. S. & Duddy, I. R., 1989. Early Cretaceous uplift and erosion of the northern Appalachian Basin, New York, based on apatite fission track analysis, *Earth planet. Sci. Lett.*, **93**, 35–49.

Mitchell, R. H., 1986. *Kimberlites: Mineralogy, Geochemistry and Petrology*, Plenum, New York.

Pindell, J. L., Cande, S. C., Pitman, W. C., III, Rowley, D. B., Dewey, J. F., LaBrecque, J. & Haxby, W., 1988. A plate-kinematic framework for models of Caribbean evolution, *Tectonophysics*, **155**, 121–138.

Pulliah, G. E., Irving, E., Buchan, K. L. & Dunlop, D. J., 1975. Magnetization changes caused by burial and uplift, *Earth planet. Sci. Lett.*, **28,** 122–143.

Rabinowitz, P. D. & LaBrecque, J., 1979. The Mesozoic South Atlantic Ocean and evolution of its continental margin, *J. geophys. Res.*, **84,** 5973–6002.

Scotese, C. R., Van der Voo, R. & McCabe, C., 1982. Paleomagnetism of the upper Silurian and lower Devonian carbonates of New York State: evidence for secondary magnetizations residing in magnetite, *Phys. Earth planet Interiors*, **30,** 385–395.

Smith, D. G., 1987. Late Paleozoic to Cenozoic reconstructions of the Arctic, in *Alaskan North Slope Geology, Vol. 2*, pp. 785–795, eds Tailleur, I. & Weimer, P., Paleontologists and Mineralogists and Alaska Geological Society, Bakersfield.

Srivastava, S. P. & Tapscott, C. R., 1986. Plate kinematics of the North Atlantic, in *The Geology of North America, Vol. M, The Western North Atlantic Region*, eds Vogt, P. R. & Tucholke, B. E., pp. 379–404, Geol. Soc. Am., Boulder, Colorado.

Steiner, M. B. & Helsley, C. E., 1975. Reversal pattern and apparent polar wander for the Late Jurassic, *Geol. Soc. Am. Bull.*, **86,** 1537–1543.

Symons, D. T. A. & Lewchuk, M. T., 1989. Paleomagnetism of the Mississippian HP pipe and the western margin of North American craton, in *Deep Structure and Past Kinematics of Accreted Terranes*, ed. Hillhouse, J., *Geophys. Monoegr., IUGG*, **50.**

Tailleur, I. L., 1969. Rifting speculation on the geology of Alaska's North Slope, *Oil Gas J.*, **67,** 128–130.

Taylor, P. T., Kovacs, L. C., Vogt, P. R. & Johnson, G. L., 1981. Detailed aeromagnetic investigation of the Arctic Basin, 2, *J. geophys. Res.*, **86,** 6323–6333.

Toft, P. B., Arkani-Hamed, J. & Haggerty, S., 1990. The effects of serpentinization on density and magnetic susceptibility: a petrophysical model, *Phys. Earth planet. Interiors*, **65,** 137–157.

Van der Voo, R., 1990. Phanerozoic paleomagnetic poles from Europe and North America and comparisons with continental reconstructions, *Rev. Geophys.*, **28,** 167–206.

Van Fossen, M. C. & Kent, D. V., 1990. High latitude paleomagnetic poles from Middle Jurassic plutons and Moat Volcanics in New England and the controversy regarding Jurassic apparent polar wander for North America, *J. geophys. Res.*, **95,** 17 503–17 516.

Van Fossen, M. C. & Kent, D. V., 1992a. Reply, *J. geophys. Res.*, **97,** 1803–1805.

Van Fossen, M. C. & Kent, D. V., 1992b. Paleomagnetism of the Front Range (Colorado) Morrison Formation and an alternative model of late Jurassic North American apparent polar wander, *Geology*, **20,** 223–226.

Van Fossen, M. C. & Kent, D. V., 1992c. Paleomagnetism of 122 Ma plutons in New England and the mid-Cretaceous paleomagnetic field in North America: true polar wander or large-scale differential mantle motion? *J. geophys. Res.*, **97,** 19 651–19 661.

Wenner, D. B. & Taylor, H. P., 1971. Temperature of serpentinization of ultramafic rocks based on $^{18}O/^{16}O$, *Contr. Mineral. Petrol.*, **32,** 1665–185.

Zartman, R. E., Brock, M. R., Heyl, A. V. & Thomas, H. H., K–Ar and Rb–Sr ages of some alkalic intrusive rocks from central and eastern United States, *Am. J. Sci.*, **265,** 870–884.