Earth and Planetary Science Letters 406 (2014) 134–141

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Assessing the GAD hypothesis with paleomagnetic data from large Proterozoic dike swarms

J.E. Panzik *, D.A.D. Evans

Department of Geology and Geophysics, Yale University, 210 Whitney Avenue, New Haven, CT 06511, United States

ARTICLE INFO

Article history:
Received 24 March 2014
Received in revised form 18 August 2014
Accepted 2 September 2014
Available online 29 September 2014
Editor: J. Brodholt

Keywords:
geomagnetic field geometry
Proterozoic
GAD

ABSTRACT

Previous compilations of paleomagnetic studies have suggested that the Proterozoic geomagnetic field may have had as large as 12% quadrupole and 29% octupole components, relative to the dipole intensity. These values would have significant implications for geodynamo secular cooling and outer core dynamics, and for paleogeographic reconstructions. Herein we test the validity of one method, using paleomagnetic remanence of three Proterozoic large igneous provinces (LIPs), as well as younger paleomagnetic datasets, to determine zonal geomagnetic field models. Our results show that individual LIPs are not laterally widespread enough to support claims of significant global non-dipole field components in Proterozoic time. The geocentric axial dipole hypothesis remains viable for Proterozoic paleogeographic and geodynamic models.

1. Introduction

Most paleomagnetic studies are performed using the assumption that Earth's time-averaged magnetic field can be treated as a geocentric axial dipole (GAD; Hospers, 1955). M.E. Evans (1976) created a test of this assumption, comparing paleomagnetic inclinations of the entire global database to theoretical curves of simple, zonal field models (dipole, quadrupole, octupole, etc.) generated by random sampling across the Earth's surface. That work, as well as a subsequent study using the same test on a larger database Piper and Grant (1989) suggested validity of the GAD assumption to as old as 3000 Ma.

A third iteration of the test, however, considered combinations of zonal field components and found a significant bias toward shallow inclinations among Paleozoic and Precambrian datasets (Kent and Smethurst, 1998). A stationary $\pm10\%$ axial quadrupole and $+25\%$ axial octupole field relative to dipole strength was used to explain the data. Inspired by this result, Bloxham (2000) generated a geodynamo simulation, with specified heat-flow patterns at the core–mantle boundary, containing stationary octupole terms of similar magnitude. Nonetheless, the test itself has been called into question on the basis of whether there is sufficient geologic time to permit continents to representatively sample Earth's entire surface area, which is the underlying assumption inherent to the test (Meert et al., 2003; McFadden, 2004; Evans and Hoye, 2007; Grower, 2005). Although such debate is worthwhile, a simple reinvestigation of the inclination test using a much larger and quality-filtered database Veikkolainen et al. (2014) found starkly diminished departures from GAD for Precambrian time.

Independent tests of GAD include a compilation of Precambrian evaporite deposits, which have yielded slightly lower inclinations than their Mesozoic–Cenozoic counterparts, and could indicate as much as a 10–15% octupole component of the Precambrian geomagnetic field (Evans, 2006). Regional polarity reversal asymmetries in some Precambrian rocks were explained by the presence of non-dipole magnetic field components (Pesonen and Nevanlinna, 1981), perhaps documenting the existence of an axial, eccentric, subsidiary dipole field relative to the main dipole field; but a revisited study showed that the asymmetries could alternatively be explained by significant continental motion during the emplacement of those rocks (Swanson-Hysell et al., 2009).

Williams and Schmidt (2004) devised an additional test, using dike swarms with distributions spanning sufficient paleolatitudinal range across rigid tectonic blocks, for comparison to various geomagnetic field models, calculated from the modified relation between magnetic inclination, I, and the paleocolatitude, θ':

$$\tan(I)=\frac{2\cos\theta'+1.5G_2(3\cos^2\theta'-1)+2G_3(5\cos^3\theta'-3\cos\theta')}{\sin\theta'+G_2(3\sin\theta'\cos\theta')+1.5G_3(5\sin\theta'\cos^2\theta'-\sin\theta')} \tag{1}$$

where $G_2=g_2^0/g_0^0$ and $G_3=g_3^0/g_0^0$ are the intensities of the axial quadrupole and octupole terms relative to GAD respectively (Schneider and Kent, 1990). When G_2 and G_3 are precisely zero, Eq. (1) reduces to the well-known GAD-paleolatitude formula.

* Corresponding author.

http://dx.doi.org/10.1016/j.epsl.2014.09.007

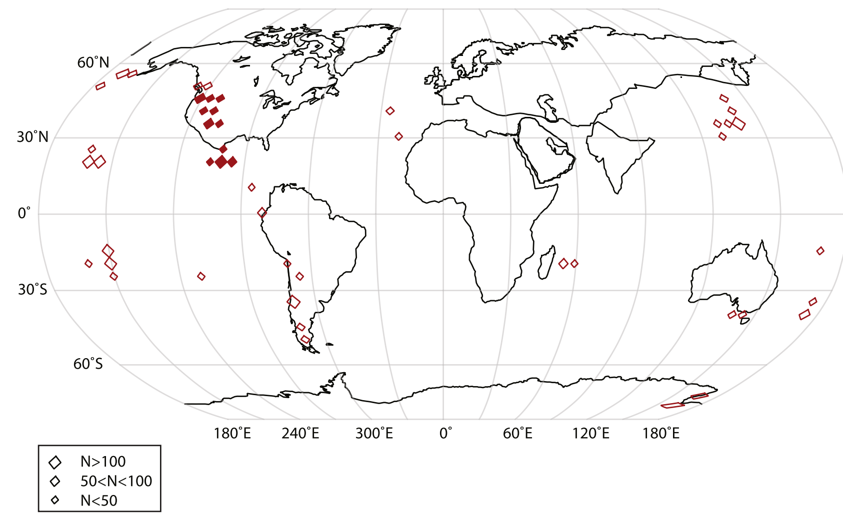

Fig. 1. Locations of paleomagnetic results from 0 to 5 Ma volcanic rocks (C.L. Johnson, pers. comm.). For the purposes of this illustration, the sites were binned and plotted in $5° \times 5°$ grids. Symbol sizes denote the number of sites within the specific grid; $3° = N < 50$, $4° = 50 < N < 100$, $5° = N > 100$. The combined western USA and Central American data subset, selected for comparison to the regional distribution of more ancient datasets, is denoted by the filled symbols.

A combined treatment of the mid-Proterozoic Mackenzie and Sudbury dike swarms, extending across the Canadian Shield, yielded results of $G_2 = 12\%$ and $G_3 = 29\%$ (Williams and Schmidt, 2004). However, those swarms are distinct in age by ca. 30 million years, thus the observed paleomagnetic variations between them could well be attributed to plate tectonic motion. Here we revisit the dike swarm remanence-variation test, modifying it to include both declination and inclination data from site-mean remanence directions among well-sampled large igneous provinces (LIPs), each emplaced within a span of a few million years or less, and together spanning the latter half of Earth history. Rather than only determining paleolatitudes, we compute virtual geomagnetic pole positions from the site-mean data.

2. Methods

Using Eq. (1) and paleomagnetic data compiled from each dataset in the published literature, paleolatitudes and virtual geomagnetic pole (VGP) positions were calculated at each sample site in 5% increments of G_2 and G_3, from -15% to 15% and from -30% to 30%, respectively. The data were quality-filtered using the requirements that the sites have 3 or more samples and the angular cone of confidence radius on the site-mean remanence direction (α_{95}) is less than 15°. The VGP positions were plotted for various magnetic field geometries as a visual check each dataset and as a means to identify spurious outliers (>40° from the primary cluster mean). Angular confidence at 95% (A_{95}) and precision parameter estimate (K) were determined by applying Fisher statistics (Fisher, 1953) to the VGP positions for each G_2 and G_3 contribution. The calculated K values are displayed on a contour plot for the computed magnetic field geometries. For each contour plot of K values, we determined an upper and lower 95% statistical significance from F variance tests using the K value determined from the GAD field geometry as such:

$$\frac{K_2}{K_1} = F(\nu_1, \nu_2) = F(\nu, \nu) = F\big(2(N-1), 2(N-1)\big) \tag{2}$$

where K_2 is the precision before altering the field (GAD), K_1 is the precision after altering the field (non-dipole field), F is the variance ratio, ν_2 and ν_1 are the degrees of freedom before and after altering the field respectively, and N is the number of data points. We perform the F variance test to determine which VGP distributions are statistically distinguishable from the distribution generated under the GAD assumption. We recognize that Fisher (1953) statistics are only strictly valid for datasets that are circularly symmetric about the mean direction, and that some of our (G_2, G_3)-adjusted datasets are likely non-Fisherian, especially those with large octupolar components, and therefore use Fisher parameters throughout our analysis as a matter of convenience in computations; strongly elongated datasets will always generate relatively low precision parameters (k) and large radii of confidence (α_{95}), qualitatively consistent with the essence of our analysis.

We examined datasets from global and regional 0–5 Ma igneous rocks (Johnson, pers. comm.; Fig. 1), the 180 Ma Karoo–Ferrar LIP, and the 200 Ma central Atlantic magmatic province LIP (CAMP; Fig. 2) as a test of the method's robustness for ages that are well understood in the sense of paleogeographic reconstructions. The 0–5 were further constrained with the additional criteria that the VGP location (using the GAD assumption) is within 30° from the respective geographic pole for normal and reverse polarities. The Karoo–Ferrar and CAMP datasets were compiled from published literature (Ex. Kent, 2005; Kosterov and Perrin, 1996), and filtered using the aforementioned criteria. Such exclusions were minor in number, and only limited to data clearly lying outside their respective modes. To determine the sensitivity of the method, both temporally and spatially, tests were run on the 0–5 Ma dataset comparing results with and without plate motion correction, and for smaller geographic regions. The method is not affected by plate motion on a 5 million-year timescale, as demonstrated by nearly identical results either with or without plate motion correction (Figs. 3, 4). Such an initial test demonstrates that ancient LIP events, spanning as long as a few million years' duration, should be temporally suitable for the method's application. As will be shown below, however, the spatial extent of each LIP is unlikely to provide an accurate representation of the global geomagnetic field geometry at the time of emplacement.

3. Results

The results gathered from the 0–5 Ma dataset show an agreement with previous results for the time-averaged geomagnetic field, with a small G_2 and G_3 contribution of approximately 5% and 3%, respectively (Schneider and Kent, 1990; McElhinny et al., 1996; Carlut and Courtillot, 2002). Because the sign of G_2 is computed relative to the dominant dipole polarity, a symmetrical pattern about the $G_2 = 0$ axis between N and R polarities can be

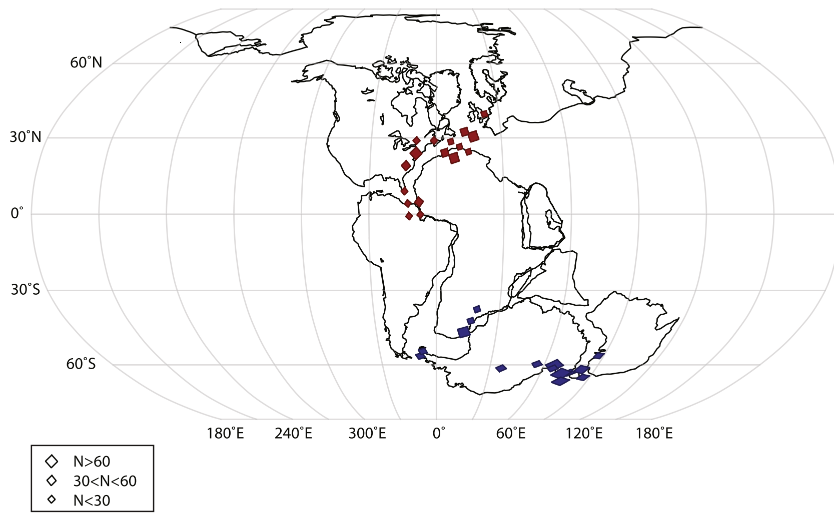

Fig. 2. Global reconstruction at 180 Ma (Torsvik and Van der Voo, 2002) with paleogeographic site locations of Karoo–Ferrar large igneous province (LIP) [blue], spanning Australia through Antarctica, and the central Atlantic magmatic province (CAMP) [red], spanning from northern South America to Europe, sampling localities that are binned in a 5° × 5° grid. Symbol sizes denote the number of sites within the specific grid; 3° = $N < 30$, 4° = $30 < N < 60$, 5° = $N > 60$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

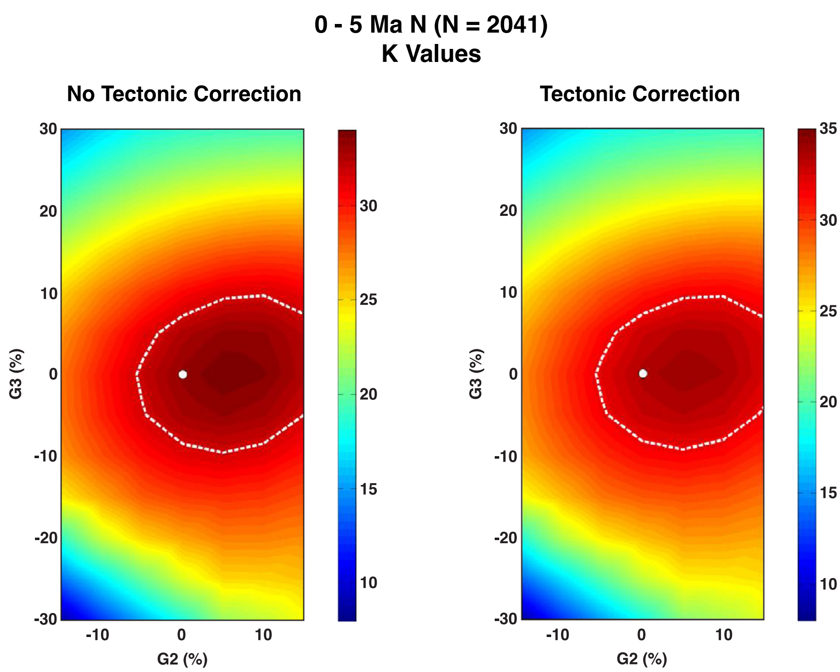

Fig. 3. Comparison of Fisher's precision parameters on the mean paleomagnetic poles (K) according to a variety of axial dipolar, quadrupolar, and octupolar combinations for 0–5 Ma normal polarity data, treated *in situ* (left) or with a correction for Neogene plate-tectonic motions (right). The small, central white circle represents pure GAD geometry, and the dashed line denotes 95% significance of the precision parameter estimate from that of GAD.

interpreted as a non-reversing quadrupolar component. Such a pattern is indeed observed in the global 0–5 Ma data (Figs. 3, 4). The spatial robustness of the method deteriorates as the analysis is run on a smaller subset of the 0–5 Ma dataset that includes western USA and Central America, which shows, for both polarities of data, highest and lowest levels of VGP clustering at the corners of the studied parameter space with 30% axial octupole components. The western North American data subset was chosen because of its similar areal coverage and sample density to the Mesozoic Karoo–Ferrar and CAMP large igneous provinces (Figs. 1, 2, and 5). The paleomagnetic results from Karoo–Ferrar and CAMP also show a deviation from the global results of the 0–5 Ma dataset, but similar to the 0–5 Ma North American data subset, they show a tendency for highest VGP clustering toward one of the positive-G_3 corners of the studied parameter space. Intriguingly, all regions of smaller areal coverage, both Neogene and Mesozoic, continue to display the asymmetry between the normal and reverse polarity suggestive of a non-reversing quadrupole. Based on optimization of paleomagnetic poles in a globally consistent plate-circuit kinematic framework, Torsvik and Van der Voo (2002) suggested that the mid-Mesozoic surface geomagnetic field may have contained as much as 5% axial octupole. Our analysis of mid-Mesozoic LIPs (Fig. 5) shows marginally improved VGP clustering toward positive G_3 components, but not at statistically significant levels.

We apply the same method to three Proterozoic dike swarms that are exceptionally well sampled for paleomagnetism (Fig. 6);

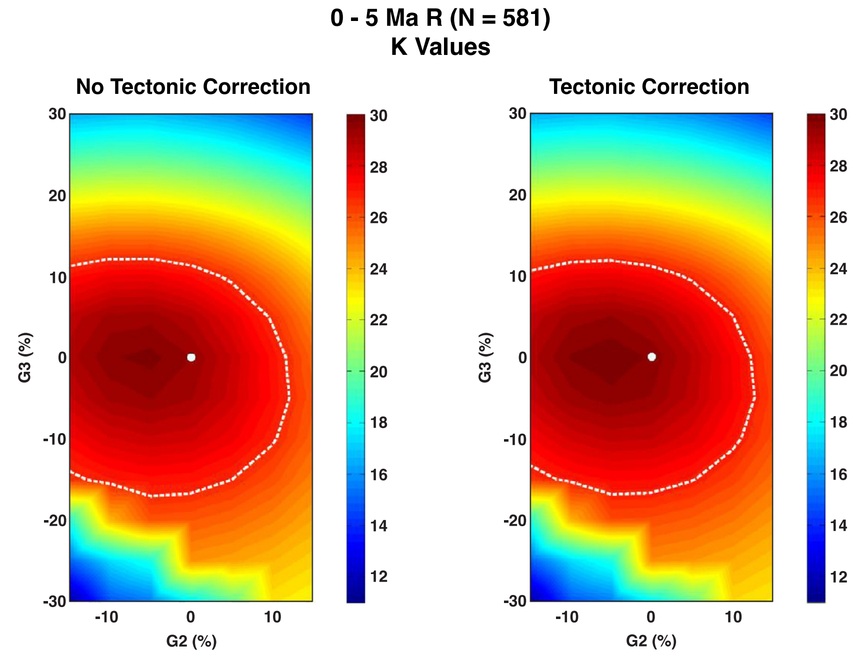

Fig. 4. Comparison of Fisher K values on mean paleomagnetic poles according to field geometries for 0–5 Ma reverse polarity data either *in situ* (left) or with corrections for Neogene plate-tectonic motions (right). Symbols as in Fig. 3.

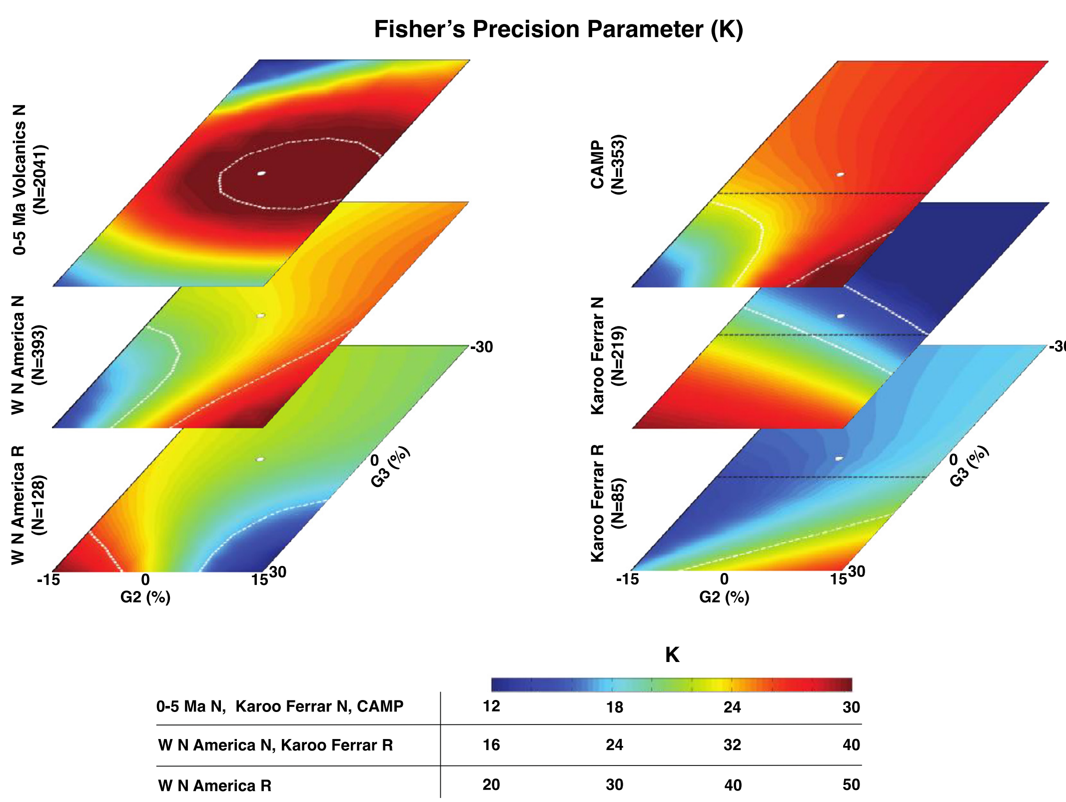

Fig. 5. Comparison of results for the complete 0–5 Ma normal polarity dataset, as well as a subset covering the western USA and Central America for normal and reverse polarity (left) with the results from CAMP and Karoo–Ferrar (right). The GAD geometry (circle), Torsvik and Van der Voo geometry (Torsvik and Van der Voo, 2002), and $p = 0.05$ significance levels relative to GAD (white, dashed line) are included for result reference.

the 2470–2445 Ma Matachewan dikes (Heaman, 1997; Evans and Halls, 2010), the 1270 Ma Mackenzie dikes (LeCheminant and Heaman, 1989; Heaman et al., 1992), and the 720 Ma Franklin dikes (Heaman et al., 1992; Denyszyn et al., 2009). These targets were chosen because of their paleolatitudinal expanse and/or large sampling by earlier paleomagnetic studies. Although the Matachewan dikes are geographically more limited than the others, they are sampled by a sufficient number of sites to yield statistically robust paleomagnetic poles. The data were quality filtered using the same criteria as described above. The Matachewan swarm has abundant sampling in both remanence polarities, which have been arbitrarily designated '*R*' and '*N*' with possibly as much as a 20-million-year

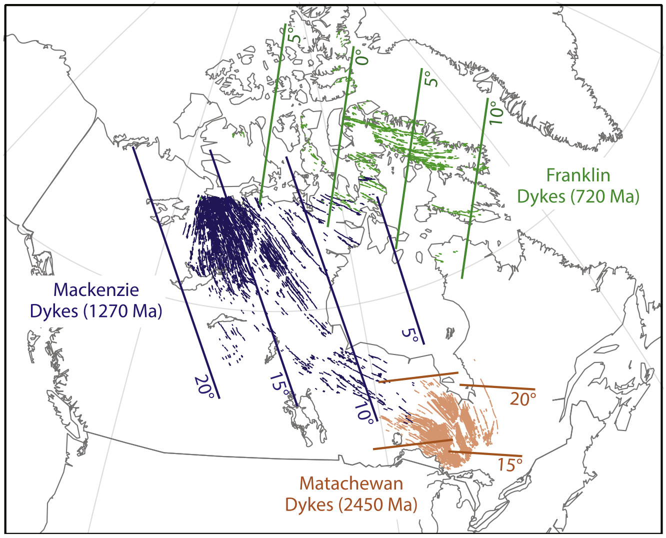

Fig. 6. Locations of the Franklin (green), Mackenzie (blue), and Matachewan (orange) dike swarms in Canada. The lines going through each dike swarm designate the approximate paleolatitudes of each, assuming GAD. The offset in the Matachewan swarm paleolatitudes is due to tectonic rotations prior to the assembly of North America, at ca. 1900 Ma (Heaman, 1997). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

difference in age (Evans and Halls, 2010). Matachewan sites and remanence directions have been restored to paleotectonic positions prior to ca. 1900 Ma deformation across the Kapuskasing structural zone (Evans and Halls, 2010). The Mackenzie LIP is sampled entirely within a single rigid block of Laurentia, but only Franklin data from the autochthonous Canadian Shield were considered, because of additional (though minor) uncertainties in Cenozoic restoration of the Ellesmere and Greenland plates (Denyszyn et al., 2009). In all instances of the Proterozoic LIPs investigated, the pattern of results conforms to those of regional rather than global data, with maxima and minima of VGP clustering toward the extreme values of the parameter space investigated. In other words, the clustering of each Proterozoic mean of VGPs (Figs. 7–10) more closely resembles those of western North American data from 0 to 5 Ma, or the mid-Mesozoic LIPs (Fig. 5) than any global site coverage (Figs. 3, 4).

4. Discussion

The results of this study show that large igneous provinces (LIPs) do not have the appropriate areal coverage to adequately constrain global geomagnetic field geometry during the Proterozoic (Figs. 7–10). Even if the test were shown to be valid at these spatial scales, the geometries proposed by previous studies invoking large, persistent ∼25–29% octupolar components (Kent and Smethurst, 1998; Williams and Schmidt, 2004; Evans, 2006), typically have the poorest fit to one dataset or another. *F* variance tests of significant departures in precision of VGPs (McElhinny, 1964), relative to GAD, demonstrate that each of the previously proposed high-octupolar models is contradicted at the 95% confidence level by at least one of the dike swarm datasets.

Results from dike swarms with two polarities of paleomagnetic remanence can provide insights into the nature of any possible small-scale departures from a pure GAD field. The data

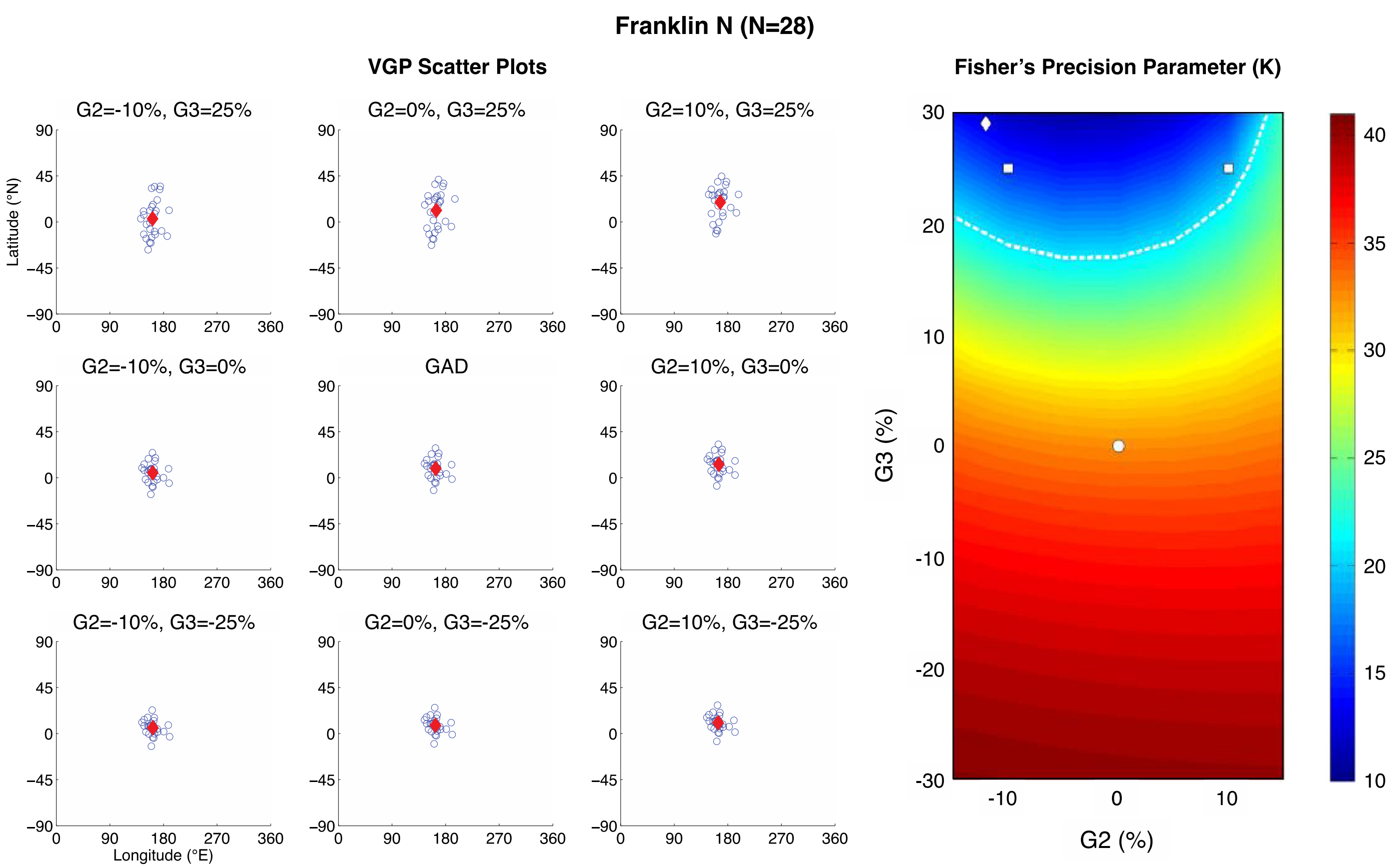

Fig. 7. [Left] The scatter in the virtual geomagnetic pole (VGP) positions of nine geomagnetic field geometries for the Franklin dike swarm "*N*" polarity data with site VGP locations (blue circles) and mean VGP locations (red diamond), [Right] and the Fisher precision parameter results for each model geometry with the geometry of pure GAD (circle), Kent and Smethurst (1998; squares), Williams and Schmidt (2004; diamond), and 95% significance from GAD (dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

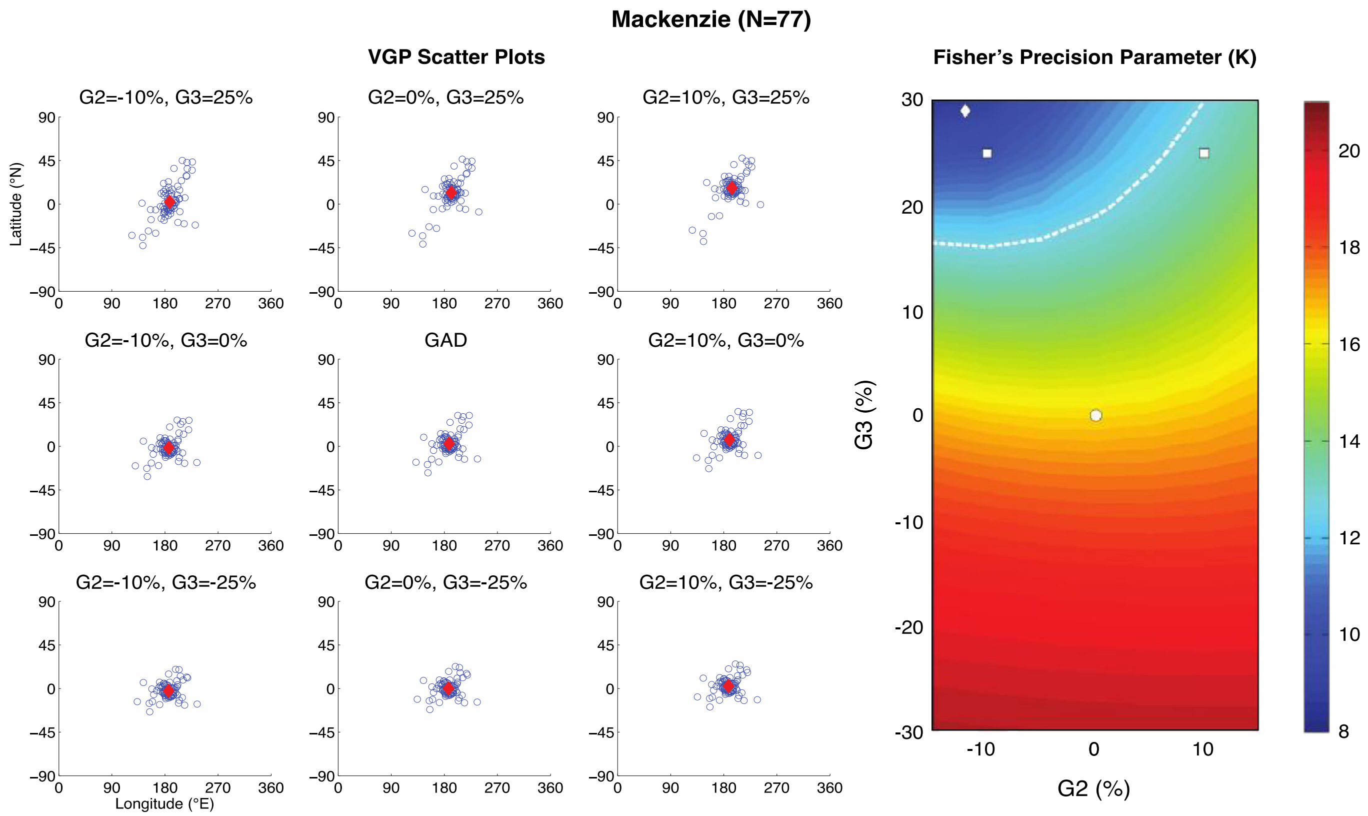

Fig. 8. [Left] The scatter in the virtual geomagnetic pole (VGP) positions of nine geomagnetic field geometries for the Mackenzie dike swarm data with site VGP locations (blue circles) and mean VGP locations (red diamond), [Right] and the Fisher precision parameter results for a range of G_2 and G_3 values. Symbols as in Fig. 7. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

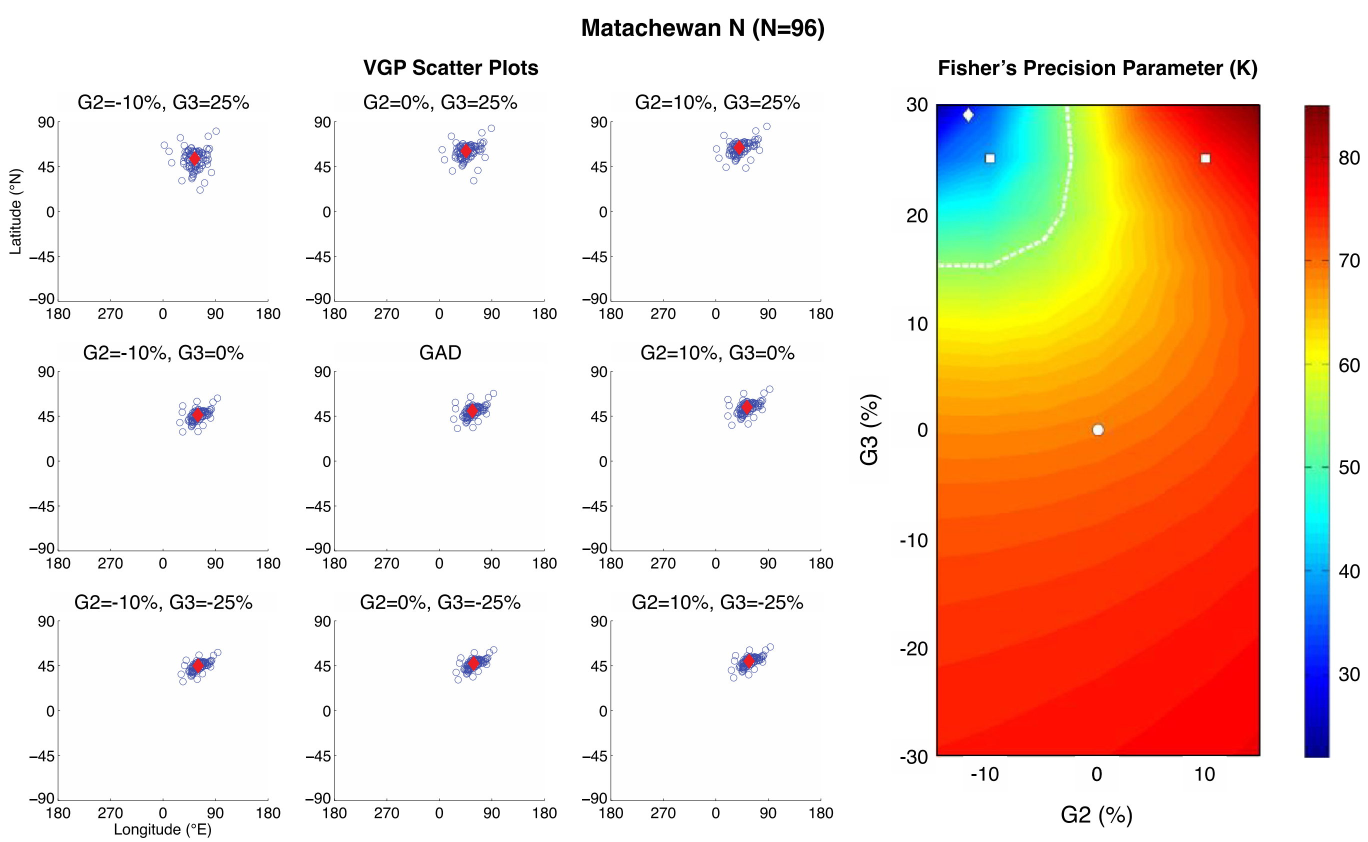

Fig. 9. [Left] The scatter in the virtual geomagnetic pole (VGP) positions of nine geomagnetic field geometries for the Matachewan dike swarm "*N*" polarity data with site VGP locations (blue circles) and mean VGP locations (red diamond), [Right] and the Fisher precision parameter results for a range of G_2 and G_3 values. Symbols as in Fig. 7. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

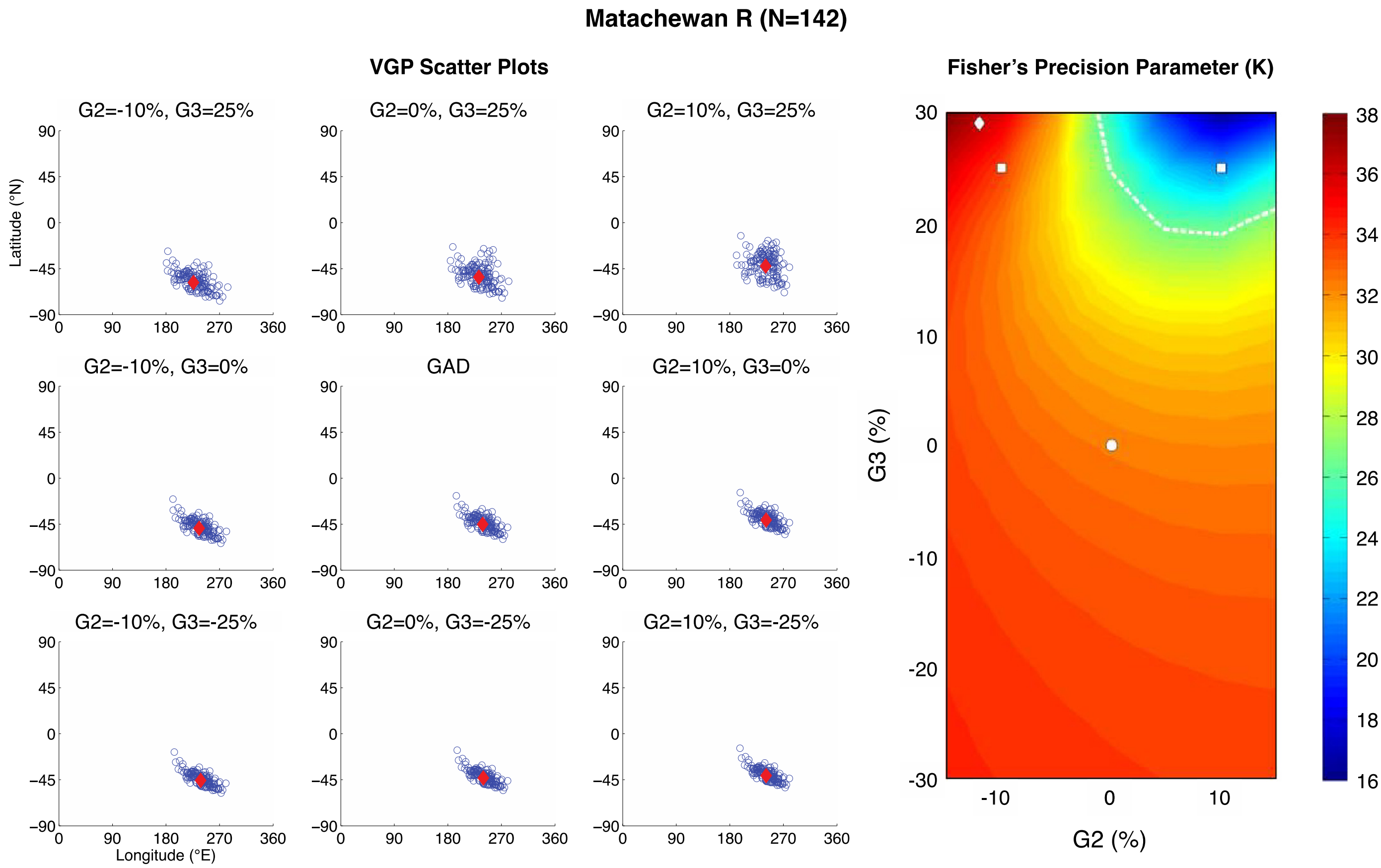

Fig. 10. [Left] The scatter in the virtual geomagnetic pole (VGP) positions of nine geomagnetic field geometries for the Matachewan dike swarm "*R*" polarity data with site VGP locations (blue circles) and mean VGP locations (red diamond), [Right] and the Fisher precision parameter results for a range of G_2 and G_3 values. Symbols as in Fig. 7. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

from opposing polarities of Matachewan dikes show patterns of VGP clustering that have approximate mirror symmetry about the $G_2 = 0$ axis (Figs. 9, 10). This result suggests that despite a possible age difference as great as ca. 25 million years between the two polarities of remanence, small departures from GAD, at least at a regional scale, may have been non-reversing in the earliest Proterozoic, as they appear to be for the 0–5 Ma interval (Johnson and Constable, 1995), and also, less confidently, for the Karoo–Ferrar dataset. The Franklin dike data are insensitive to such analysis because their sites are closer to the paleoequator (Fig. 6), thus VGP distribution is distorted equally by quadrupolar components regardless of their sign. Mackenzie data, unfortunately for this analysis, are restricted to a single polarity of remanence.

If a stationary (and reversing) field geometry is to be assumed for the entire Proterozoic, then GAD appears reasonable based on the results from the Franklin, Mackenzie, and Matachewan dike swarms. However, as shown above, the use of data at merely a continental scale of investigation is insufficient is describing global geomagnetic field geometry. More advanced tests of this nature will require larger regions of geographic extent, extending from one craton to another in a valid paleogeographic framework. Such global-scale paleogeographic reconstructions of the Proterozoic world are nascent, but developing rapidly (Zhang et al., 2012). In the meantime, the present analysis indicates that the LIP-based geomagnetic field geometry test devised by Williams and Schmidt (2004) provides no significant support for substantial (∼25–29%) non-dipole components in Proterozoic time. For now, a stationary GAD model remains the most reasonable conceptual framework for interpreting the time-averaged Proterozoic paleomagnetic record.

Acknowledgements

We would like to thank Catherine Johnson for providing the 0–5 Ma paleomagnetic database compilations, and Dennis Kent for helpful initial discussions.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2014.09.007.

References

Bloxham, J., 2000. Sensitivity of the geomagnetic axial dipole to thermal core–mantle interactions. Nature 405 (6782), 63–65.

Carlut, J., Courtillot, V., 2002. How complex is the time-averaged geomagnetic field over the past 5 Myr? Geophys. J. Int. 134 (2), 527–544. http://dx.doi.org/10.1046/j.1365-246x.1998.00577.x.

Denyszyn, S.W., Halls, H.C., Davis, D.W., Evans, D.A.D., 2009. Paleomagnetism and U–Pb geochronology of Franklin dykes in High Arctic Canada and Greenland: a revised age and paleomagnetic pole constraining block rotations in the Nares Strait region. Can. J. Earth Sci. 46 (9), 689–705. http://dx.doi.org/10.1139/E09-042.

Evans, D.A.D., 2006. Proterozoic low orbital obliquity and axial-dipolar geomagnetic field from evaporite palaeolatitudes. Nature 444 (7115), 51–55. http://dx.doi.org/10.1038/nature05203.

Evans, D.A.D., Halls, H.C., 2010. Restoring Proterozoic deformation within the Superior craton. Precambrian Res. 183, 474–489.

Evans, M.E., 1976. Test of the dipolar nature of the geomagnetic field throughout Phanerozoic time. Nature 262, 676–677.

Evans, M.E., Hoye, G.S., 2007. Testing the GAD throughout geological time. Earth Planets Space 59, 697–701.

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

Grower, M., 2005. Closing Pandora's box: additional insights on inclination bias using a random walk approach. UF J. Undergrad. Res. Pap. 6 (6), 1–16.

Heaman, L., LeCheminant, A., Rainbird, R., 1992. Nature and timing of Franklin igneous events, Canada: implications for a Late Proterozoic mantle plume and the break-up of Laurentia. Earth Planet. Sci. Lett. 109, 117–131.

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

Hospers, J., 1955. Rock magnetism and polar wandering. J. Geol. 63 (1), 59–74.

Johnson, C., pers. comm.

Johnson, C.L., Constable, C.G., 1995. The time-averaged geomagnetic field as recorded by lava flows over the past 5 Myr. Geophys. J. Int. 122 (2), 489–519. http://dx.doi.org/10.1111/j.1365-246X.1995.tb07010.x.

Kent, D.V., 2005. Corrected late Triassic latitudes for continents adjacent to the North Atlantic. Science 307 (5707), 240–244. http://dx.doi.org/10.1126/science.1105826.

Kent, D.V., Smethurst, M.A., 1998. Shallow bias of paleomagnetic inclinations in the Paleozoic and Precambrian. Earth Planet. Sci. Lett. 160 (3), 391–402.

Kosterov, A., Perrin, M., 1996. Paleomagnetism of the Lesotho basalt, southern Africa. Earth Planet. Sci. Lett. 139, 63–78.

LeCheminant, A.N., Heaman, L.M., 1989. Mackenzie igneous events, Canada – middle Proterozoic hotspot magmatism associated with Ocean opening. Earth Planet. Sci. Lett. 96, 38–48.

McElhinny, M.W., 1964. Statistical significance of the fold test in palaeomagnetism. Geophys. J. Int. 8, 338–340.

McElhinny, M.W., McFadden, P.L., Merrill, R.T., 1996. The time-averaged paleomagnetic field 0–5 Ma. J. Geophys. Res. 101 (B11), 25007–25027. http://dx.doi.org/10.1029/96JB01911.

McFadden, P.L., 2004. Is 600 Myr long enough for the random palaeogeographic test of the geomagnetic axial dipole assumption? Geophys. J. Int. 158, 443–445. http://dx.doi.org/10.1111/j.1365-246X.2004.02321.x.

Meert, J.G., Tamrat, E., Spearman, J., 2003. Non-dipole fields and inclination bias: insights from a random walk analysis. Earth Planet. Sci. Lett. 214 (3–4), 395–408. http://dx.doi.org/10.1016/S0012-821X(03)00417-5.

Pesonen, L.J., Nevanlinna, H., 1981. Late Precambrian Keweenawan asymmetric reversals. Nature 294, 436–439.

Piper, J.D.A., Grant, S., 1989. A palaeomagnetic test of the axial dipole assumption and implications for continental distribution through geological time. Phys. Earth Planet. Inter. 55 (1–2), 37–53. http://dx.doi.org/10.1016/0031-9201(89)90232-X.

Schneider, D.A., Kent, D.V., 1990. Testing models of the Tertiary Paleomagnetic field. Earth Planet. Sci. Lett. 101, 260–271.

Swanson-Hysell, N.L., Maloof, A.C., Weiss, B.P., Evans, D.A.D., 2009. No asymmetry in geomagnetic reversals recorded by 1.1-billion-year-old Keweenawan basalts. Nat. Geosci. 2, 713–717. http://dx.doi.org/10.1038/NGEO622.

Torsvik, T.H., Van der Voo, R., 2002. Refining Gondwana and Pangea palaeogeography: estimates of Phanerozoic non-dipole (octupole) fields. Geophys. J. Int. 151 (3), 771–794.

Veikkolainen, T., Evans, D.A.D., Korhonen, K., Pesonen, L.J., 2014. On the low-inclination bias of the Precambrian geomagnetic field. Precambrian Res. 244, 23–32.

Williams, G.E., Schmidt, P.W., 2004. Neoproterozoic glaciation: reconciling low paleolatitudes and the geologic record. Geophys. Monogr. 146, 145–159.

Zhang, S., Li, Z.-X., Evans, D.A.D., Wu, H., Li, H., Dong, J., 2012. Pre-Rodinia supercontinent Nuna shaping up: a global synthesis with new paleomagnetic results from North China. Earth Planet. Sci. Lett. 353, 145–155. http://dx.doi.org/10.1016/j.epsl.2012.07.034.