Lectures in Paleomagnetism - DRAFT

Lisa Tauxe

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Chapter 16

Apparent Polar Wander Paths and tectonic applications

Suggested Supplemental Reading
For background:
Chapters 10 and 11: Butler (1992)
McElhinny and McFadden (2000)
To learn more:
Besse and Courtillot (2002)
http://www.scotese.com/

16.1 Introduction

No course in paleomagnetism would be complete without a lecture on apparent polar wander and tectonic applications of paleomagnetism. So what is apparent polar wander? The simplicity of the notion of a centered dipole giving rise to an observed direction at a given location on the surface of the Earth led to the definition of an equivalent pole position (the VGP of Lecture 2). In Lecture 14 we mentioned that averages of a number of VGPs sufficient to "average out" secular variation are known as paleomagnetic poles. When these are plotted on a map, they tend to "wander away" from the spin axis with increasing age of the rock unit sampled (e.g, Hospers, 1955; Irving, 1958). Data from a single continent can not distinguish between the wandering of the north pole (true polar wander) and the wandering of the continents (apparent polar wander). But data from multiple continents and a firm belief in the essential dipolar nature of the geomagnetic field (dating back to 1600!), convinced paleomagnetists in the 50s of the reality of continental drift. In this lecture we will consider how apparant polar wander paths for the various continents can be constructed and briefly discuss a few tectonic applications.

16.2 Some terminology

Before we dive into the details of paleomagnetic poles and the construction of Apparent Polar Wander Paths (APWPs), we need to review some basic terminology and establish working definitions for various terms in paleomagnetism. These are: specimen, sample, site, and the various poles.

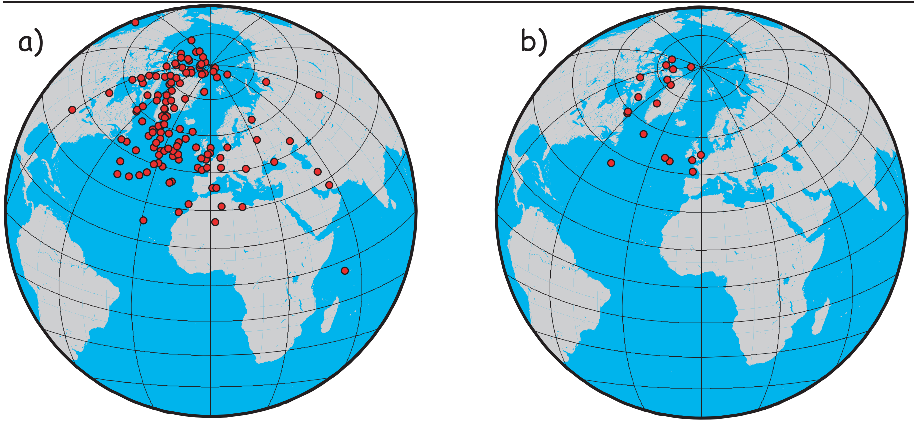

Figure 16.1: Paleomagnetic poles from Australia for the last 200 Ma from GPMDB. a) No selection criteria. b) The selection criteria of BC02.

These terms are used in different ways by different authors; for the purpose of this lecture series, we will use them in the following way:

Term	Definition
Specimen	Something that gets measured.
Sample	Something that gets taken either in the field or sub-sampling of a core, pot sherd, or other object. Samples can be prepared into for measurement as one or more specimens.
Site	A group of samples expected to be homogeneous with respect to the property to be measured (e.g., a single lava flow or a single sedimentary horizon).
VGP	The mapping of a direction from a spot reading of the geomagnetic field to an equivalent pole (see Lecture 2).
Paleomagnetic pole	An average of a number of VGPs sufficient to average out secular variation. Can also be the mapping of an average of a number of directions to the equivalent pole (see Lecture 14).

16.3 Paleomagnetic poles and apparent polar wander

There have been nearly 7000 paleomagnetic poles published since 1925. These range in age from the Archean to quite recent and in quality from excellent to highly questionable. Paleomagnetic poles have been assembled into the Global Paleomagnetic Database (GPMDB), a version of which is available for downloading at the the National Geophysical Data Center (NGDC) repository:

http://www.ngdc.noaa.gov/seg/geomag/paleo.shtml

As an example of the process of constructing APWPs, we will follow the work of Besse and Courtillot (2002) (hereafter BC02) who recently updated the apparent polar wander paths for the major continents for the last 200 Myr. We begin with the plot of all the paleomagnetic poles (regardless of quality) compiled in the GPMB for Australia for the last 200 Myr in Figure 16.1. These poles form a smear that extends in a broad arc away from the spin axis sown the Atlantic and then into Europe and Africa, although there are also isolated poles that are quite far away from the general trend.

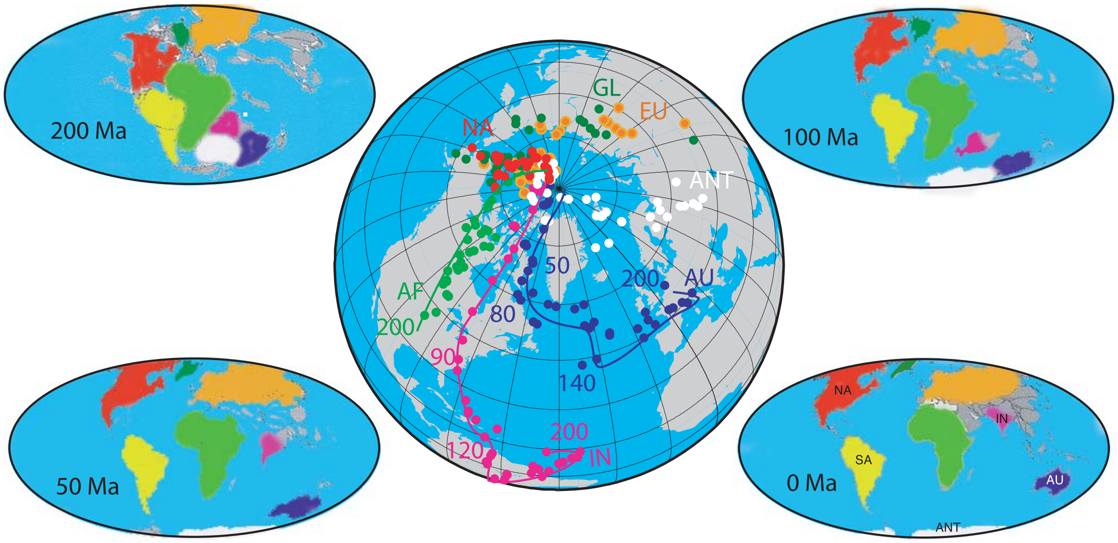

Figure 16.2: Maps of continental reconstructions for 200, 100, 50 and 0 Ma. The central map is of the apparent polar wander paths for the various continents for the last 200 million years, evaluated at five million year intervals. [Reconstructions from www.scotese.com and APWPs of Besse and Courtillot, 2002.]

Picking out the meaningful poles from the published data is the art of paleomagnetism. We have been building a tool kit for dealing with this problem throughout these lecture notes. There is some agreement in what constitutes a "good" pole among various workers. The basic selection criteria used by most workers are based those summarized by Van der Voo (1990). The "Voo Criteria" are:

1. The age of the formation must be known rather accurately. In the Voo criteria, the age should be known to within a half of period (see Lecture 15) or within a numerical age of ± 4% for Phanerozoic data. For Precambrian rocks, the age should be known to within ± 4 % or 40 Myr, whichever is smaller. BC02 demanded age uncertainties of ± 15 Myr.

2. In order to average errors in orientation of the samples and scatter caused by secular variation, there must be a sufficient number of individually oriented samples from enough sites. What constitutes "sufficient" and "enough" here is somewhat subjective and a matter of debate. The Voo Criteria recommend a minimum of 24 discrete samples of the geomagnetic field having a $\kappa > 10$. Some authors also compare scatter within and between sites in order to assess whether secular variation has been sufficiently sampled, but this relies on many assumptions as to what the magnitude of secular variation was (see Lecture 14). Butler (1992) suggested using the scatter of VGPs (S in Lecture 14) to decide whether secular variation has been averaged out or whether there is excess scatter in the data set. BC02 used only poles with at least six sites and 36 samples, each site having a 95% confidence interval less than 10° in the Cenozoic and 15° in the Mesozoic.

3. It must be demonstrated that a coherent characteristic remanence component has been iso-

lated by the demagnetization procedure. McElhinny and McFadden (2000) attempt to standardize the description of the demagnetization status of a dataset using a demagnetization code (DC) (see Table 16.1). BC02 use only poles with a DC of at least 2.

4. The age of the magnetization relative to the age of the rock should be constrained using field tests (fold test, conglomerate test, baked contact test, see Lecture 9). BC02 reject poles that fail a fold test or a reversals test.

5. There should be agreement in the pole position from units of similar age from a broad region and adequate knowledge of any structural corrections necessary. BC02 reject poles from "mobile regions", or incorporate data from regions that have undergone only vertical axis rotation by using inclination only data (see Lecture 13).

6. Both polarities should be represented and the two data sets should be antipodal.

7. Pole positions should not fall on a younger part of the pole path or on the present field direction. Such poles should be viewed with suspicion.

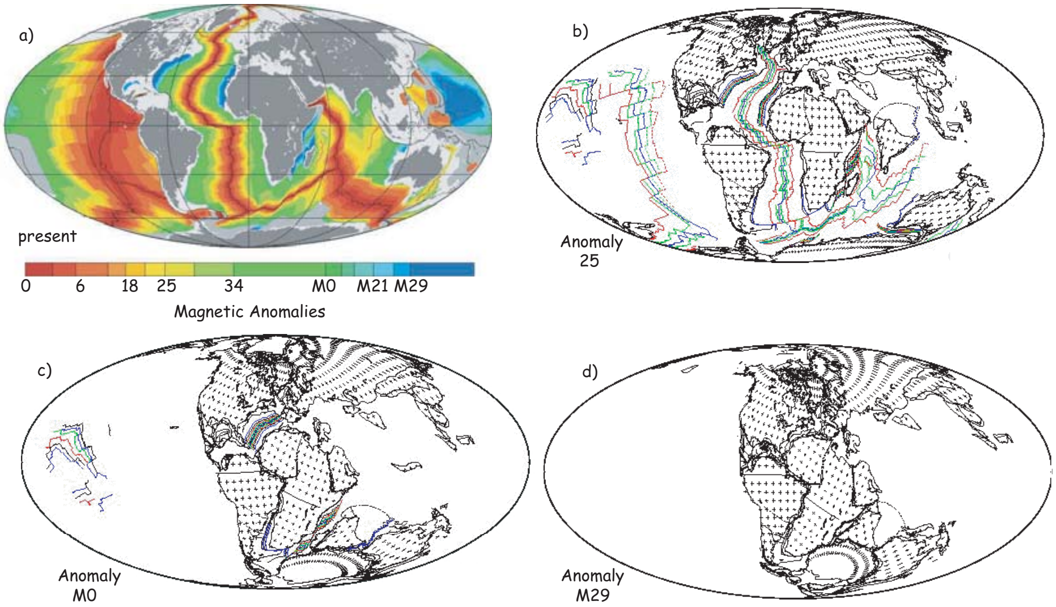

Figure 16.3: a) Position of the major anomalies and inferred age of the sea floor. [Figure modified from http://www.geosci.usyd.edu.au/research/marinegeophysics/Resprojects/ and Müller et al. (19997).] b-d) Reconstructions based on fitting of matching magnetic anomalies for selected times. [Figures from http://gdcinfo.agg.nrcan.gc.ca/app/utig_report_e.html and Royer et al. (1992).]

In the Voo criteria, each pole gets a point for every criterion that it passes. The sum of the points is the quality factor Q which ranges from 0 to 7. It is not expected that every pole satisfy all seven criteria (very few would!). Most authors use poles with $Q > 2$. BC02 on the other hand use critieria 1-5 (must have all of them) but do not require 6 or 7.

Table 16.1: Demagnetization Codes (DC) summarized by McElhinny and McFadden (2000).

DC	Description
0	Only NRM values reported. No evidence for demagnetization.
1	Only NRM values reported. Demagnetization on pilot specimens suggest stability.
2	Demagnetization at a single step on all specimens. No demagnetograms shown.
3	Demagnetograms shown that justify demagnetization procedure chosen.
4	Principal component analysis (PCA) carried out from analysis of Zijderveld diagrams. (see Lecture 9)
5	Magnetic vectors isolated using two or more demagnetization methods with PCA. e.g., thermal and AF demagnetization (see Lecture 9).

Of the 137 poles from Australia in the GPMDB plotted in Figure 16.1a, only 18 meet the BC02 criteria (see Figure 16.1b). These form a sparse track which would be the basis for the Apparent Polar Wander Path (APWP) for Australia. A similar story plays out on all the major continental blocks, so the pole paths for the continents are not very well constrained using this approach. This is why most authors use less stringent demands on their poles. However, BC02 had a plan. They argue that if the rotation parameters between continents are well known as a function of age, then poles from one continent can be transferred to the coordinate system of another. In fact, all the poles could be transferred to a single continent and used to compose a single "master" apparent polar wander path. This master path could then be re-exported back to the contributing continents. This plan works in principle if the correct poles of rotation are used, hence the demands for accurate age control of the individual paleomagnetic poles.

BC02 argue that the poles of rotation among the seven continents of Africa, Antarctica, Australia, India, North America, South America and Europe are well enough known for the last 180 Myr or so. The basis for their optimism is the fact that the magnetic anomaly patterns in the intervening oceans have been carefully mapped (see, e.g., Figure 16.3) The finite rotation poles that "roll up" the sea floor, superimposing magnetic anomalies on opposite sides of the ridge crest, can be used to transform paleomagnetic poles from one continent to another (see Appendix for details). The exported (synthetic) APWPs for the seven continents are shown in Figure 16.2.

The BC02 approach works well for the last 180 Myr or so. Prior to that, however, the rotation parameters are not as well constrained, independent of the paleomagnetic data themselves. Both the quality and quantity of the available poles decline with increasing age. The assumptions of the GAD hypothesis and amount and style of secular variation become increasingly problematic. Furthermore, most continents are composed of separate blocks whose relationships in ancient times are unknown or poorly known. An exception to this is supercontinents like Gondwana or its precursor Pangea, for which it is possible to combine data from different parts of the supercontinent with some confidence.

McElhinny and McFadden (2000) summarize the data from major continental blocks for the Phanerozoic and construct APWP using data with $Q > 2$. They claim that the APWP for Australia (see Figure 16.4a) is the best determined of all the continents. The portion from the present to about 200 Ma is similar (although of course not as detailed) as that of BC02 (blue dots in Figure 16.2. Beyond that the poles are sparse and the path is very jerky leading to the suspicion that it is somewhat aliased.

Because Australia was once part of Gondwana and the reconstruction of Gondwana is rather

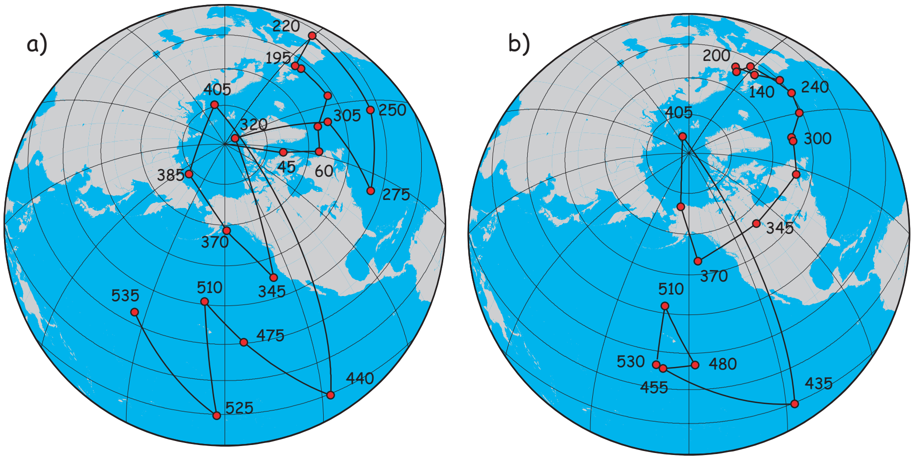

Figure 16.4: The Australian APWP for the Phanerozoic. a) Australian poles only (Table 6.14 of McElhinny and McFadden, 2000). b) Composite Gondwana path exported to Australia. [Table 7.3 of McElhinny and McFadden, 2000, rotated to Australian coordinates (see text).]

straight-forward, a similar approach to building a composite Gondwana APWP has long been taken by paleomagnetists. This was done by McElhinny and McFadden (2000) using the rotation parameters of Lottes and Rowley (1990) to transfer the Gondwana poles to NW African coordinates. Their composite APWP for Gondwana, rotated back to Austraian coordinates (using a finite rotation pole of 28.1S, 66.8W and -52.1° (clockwise) is plotted in Figure 16.4b. Some of the jerkiness of the Australian poles only plot has been removed, but more work is still needed.

16.4 Plate Reconstructions

One of the first uses of paleomagnetic data was as a test of the idea of *continental drift* (e.g., Wegener, 1915). Data from one continent, for example the data from Australia in Figure 16.1 could be interpreted to indicate either motion of the continent with respect to a fixed geomagnetic pole, or motion of the geomagnetic pole with respect to a fixed continent. To test the hypothesis of continental drift, data from at least two continents are required.

The synthetic APWPs from BC02 are not suitable for testing continental drift because that hypothesis (in the form of sea-floor spreading) is a built-in assumption. Data from each continent separately are required, as is some reconstruction not based on the idea of sea floor spreading (e.g., the fit of the continental shelves). Such APWPs can in fact be used to test particular reconstructions as we will show using data from the North America and Europe.

In Figure 16.5, we plot the data compiled by van der Voo (1990) for North America and Europe which meet his minimum standards of reliability (i.e., $Q > 2$). In Figure 16.5a, the poles are plotted with respect to present-day coordinates: the poles clearly fall on two separate tracks. This indicates that either the field was not at all dipolar, or that the two continents have moved, not only with respect to the geomagnetic pole, but also with respect to each other.

Many people who have contemplated the globe have had the desire to fit North and South America against Europe and Africa by closing the Atlantic Ocean. One such attempt, known as the *Bullard fit* (Bullard et al., 1965), fits the continents together using misfit of a particular

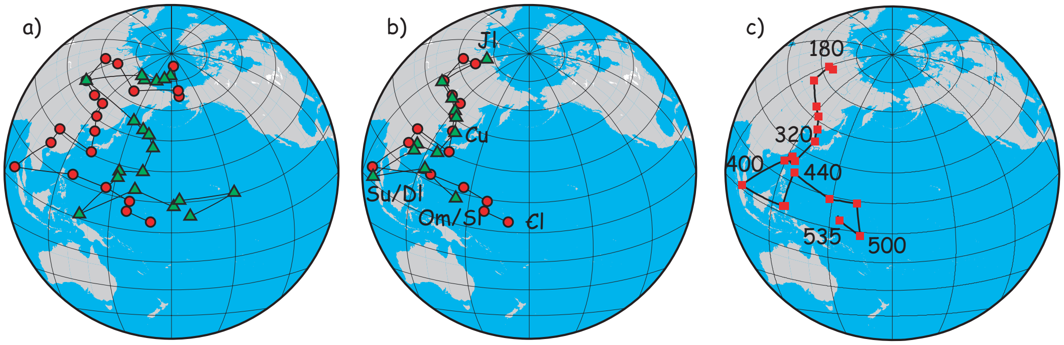

Figure 16.5: Poles from North America (circles) and Europe (triangles). (Data from van der Voo, 1990.) a) in present day coordinates. b) after rotation of Europe to close the Atlantic Ocean using the so-called "Bullard" fit (Bullard, 1965). c) APWP made by combining all the data from Laurentia and Europe in a master curve, in North American coordinates. [Poles from McElhinny and McFadden, 2000.]

contour on the continental shelves as the primary criterion. Following van der Voo (1990) (and many before him), we rotate the European poles, using the Bullard fit, into North American coordinates in Figure 16.5b. After closing the Atlantic, the curves overlap rather well, and, if the ages of the poles are also taken into account, the match is convincing. The agreement provides strong support of the continental drift hypothesis and also of the Bullard fit. Other reconstructions could be tested for a superior fit (see McElhinny and McFadden, 2000). Finally, combining poles from Europe and North America to create a master Laurussia curve and transferring it to North American coordinates yields the track shown in Figure 16.5c.

Please note that longitude of the reconstructions is not constrained, so the continents could be at any longitude and still have poles that fit identically. Some reconstructions of Pangea take advantage of this fact in order to accommodate overlap among continental masses in the early Mesozoic (see e.g., Irving, 1977).

16.5 Discordant poles and displaced terranes

Regions with paleomagnetic directions that are significantly different from the direction expected from the appropriate reference pole of the APWP may have rotated or translated from their original positions as an independent entity (a tectonostratigraphic terrane of *microplate*). As workers began investigations in the western parts of North America, it soon became apparent that many of the poles were well off the beaten track for the rest of North America (see, e.g., Irving, 1979). To illustrate this, we plot the data from North America that meet minimum van der Voo standards ($Q > 2$). The poles from "cratonic" North America (from van der Voo, 1993) are plotted as circles in Figure 16.6. Also shown as triangles is a small selection of so-called *discordant poles* (from van der Voo, 1981). What is immediately obvious is that the discordant poles do not fall anywhere near the APWP. Most are from western North America and indicate some clockwise rotations (the poles are rotated to the right of the expected poles). When taking into account the age of the formations, many also seem to have directions that are too shallow, which suggests possible northward transport of 1000's of kilometers. The validity and meaning of these discordant directions is still under debate, but it is obvious that most of the western Cordillera is not *in situ*.

Figure 16.6: Circles are "reliable" poles from cratonic North America. (Data from van der Voo, 1990). So-called "discordant poles" from western North America are plotted as triangles (data from van der Voo, 1981).

16.6 Testing GAD

One of the most useful assumptions in paleomagnetism is that the geomagnetic field is on average closely approximated by a geocentric axial dipole (GAD). As discussed in Lecture 14, the GAD hypothesis has been found to be true for at least the last 5 million years with the largest non-GAD contribution to the spherical harmonic expansion generally being of the order of 5%. For the more ancient past, it is difficult to test the GAD (or any other field) hypothesis owing to plate motions, accumulating problems of overprinting, and difficulty in reconstructing paleo-horizontal. Although most paleomagnetic studies make the implicit assumption of a GAD field, several recent studies have called the essential GAD nature of the ancient field into question. These studies fall into two groups: those that use reference poles and plate tectonic reconstructions to predict directions (e.g., Si and van der Voo, 2001) and those that compare observed statistical distributions of directions to those predicted by different field models (e.g., Kent and Smethurst, 1998). The inescapable conclusion from these and other studies is that there is often a strong bias toward shallow inclinations and many studies have called on non-dipole field contributions, in particular large (up to 20%) average axial octupole (g_3^0)contributions (see Lectures 2 and 14). We will explore these ideas in the rest of this lecture.

16.6.1 Predicted directions and the Asian inclination anomaly

Earlier in the lecture, we discussed the BC02 APWPs for the major continents. These can be used to predict directions for a given time and place using the spherical trigonometric tricks covered in the Appendix to Lecture 2. Despite the general success of the BC02 APWPs for predicting directions, comparison of predicted directions with those observed in many data sets from red beds in Central Asia led many authors to the conclusion that the GAD hypothesis failed. We show an example of such a data set in Figure 16.7, although it is atypical in that there are an unusually large number of directions. These have a mean of $\bar{D} = 356.1°$, $\bar{I}$ =43.7°. Assuming that the location of the study (presently located at 39.5°N, 94.7°E) has been fixed to the European coordinate system and taking the 20 Myr pole for Europe from BC02 (81.4°N, 149.7°E), the inclination is predicted to be 63° (see dashed line in Figure 16.7). These sediments are typical of Asian sedimentary units in having an inclination relative to the predicted values that is some 20° too shallow.

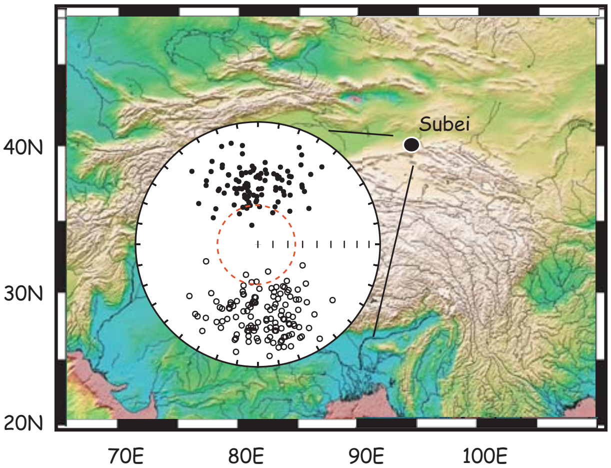

Figure 16.7: Paleomagnetic directions of Oligo-Miocene redbeds from Asia in equal area projection (stratigraphic coordinates). [Redrawn from Tauxe and Kent, 2004; data from Gilder et al., 2001.]

From Lecture 14 we know that paleomagnetic directions from the last five million years are, if anything, elongate in the North-South plane. However, the data in Figure 16.7 are distinctly elongate east-west. Tauxe and Kent (2004) pointed out that sedimentary inclination flattening not only results directions that are too shallow, but also whose N-S elongations are reduced in favor of elongations that are more east-west. This effect is shown in Figure 16.8 whereby Figure 16.8a is an equal area projection of 100 realizations of the TK03.GAD model evaluated at 30°N latitude (see Lecture 14). Figure 16.8b are the same directions but put through the flattening formula $\tan I_o = f \tan I_f$ (see Lecture 5) with a value for f of 0.6 and Figure 16.8c is the same but for $f = 0.4$.

The "elongation-inclination" (E/I) method of detecting and correcting inclination shallowing of Tauxe and Kent (2004) simply "unflattens" observed directional data sets using the inverse of the flattening formula and values for f ranging from 1 (no unflattening) to 0.3. At each unflattening step, they calculate inclination and elongation (τ_2/τ_3 of the orientation matrix, see Lecture 9) and plot these as in Figure 16.9a. In Figure 16.9b, elongation is plotted against inclination to form a curve. We know from Lecture 14 that elongation decreases from the equator to the pole, while inclination increases; A best-fit polynomial through the inclination - elongation data from model TK03.GAD is: $E = 2.88 - 0.0087I - .0005I^2$ shown as dashed line in Figure 16.9b. There is a unique pair of elongation and inclination that is consistent with the TK03.GAD field model (circled in Figure 16.9b) with an inclination of 64°.

To obtain confidence bounds on the "corrected" inclination, the E/I method performs a bootstrap. E/I curves from twenty such bootstrapped data sets are shown as thin lines in Figure 16.9b. A histogram of 1000 crossing points of bootstrap curves with the model elongation-inclination line

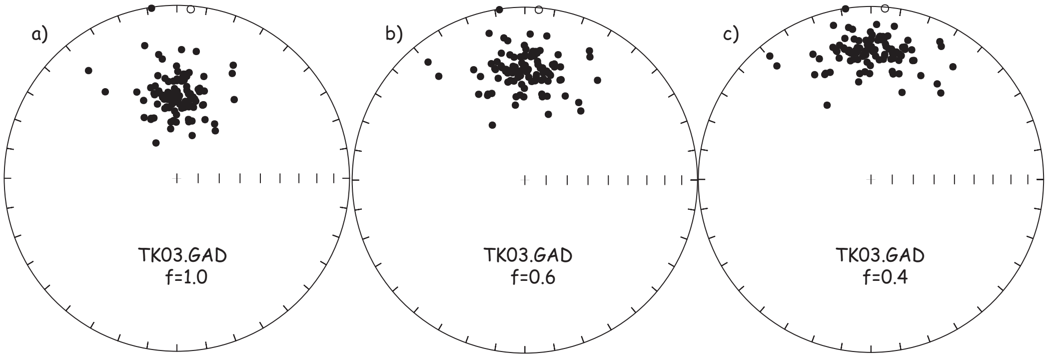

Figure 16.8: a) 100 realizations from the TK03.GAD statistical field model evaluated at 30°N. b) Same as a) flattened with an $f = 0.6$. c) Same as b) but with $f = 0.4$.

are plotted in Figure 16.9d. The mode of the bootstrapped crossings is at an inclination of 63° with 95% of the crossings falling between 56 and 69°, consistent with that predicted by the BC02 path for stable Europe.

Tan et al. (2003) performed the AARM correction (see Lecture 13) on the Tarim red beds and found an identical correction factor. Hence AARM correction (which is labor intensive in the lab) and EI correction (which is labor intensive in the field) give similar results. Both methods strongly suggest that inclination shallowing in the Asian red beds is indeed caused by sedimentary inclination shallowing of the type described in Lecture 5.

16.6.2 The "Statistical distribution" method and the Paleozoic/Pre-Cambrian geomagnetic field

The "statisitcal distribution method" of Evans (1976) for characterizing the time averaged ancient geomagnetic field requires no *a priori* assumptions about the structure of the ancient geomagnetic field. It relies instead on a large data set spanning sufficient time for the plates to have moved over the surface of the globe. The frequency of inclinations can be compared with that expected from some arbitrary magnetic field, e.g., a GAD field. It assumes that enough paleomagnetic sites have been sampled with sufficient spatial and temporal coverage that the entire ancient geomagnetic field will have been represented. Kent and Smethust (1998; KS98) employed the method on data extracted from the GPMDB data base. We follow their approach here using the compilation of paleomagnetic pole positions contained in GPMDBv.3.1. We have excluded only data that the authors themselves disavowed and separated the data by age (Cenozoic [0-65], Mesozoic [65-250 Ma], Paleozoic [250-550], PreCambrian [550-3500]). In order to overcome sampling biases in which certain areas at certain times are over represented in the database, Evans (1976) and KS98 bin the data by age and geographic area. We repeat the analysis of KS98 for the Cenozoic data set in Figure 16.10. The sampling sites are shown in Figure 16.10a and the frequency plots are in Figure 16.10b. The data appear to be consistent with a dominantly GAD field as was found by previous studies.

When KS98 (Kent & Smethurst 1998) examined the data from the Paleozoic and Pre-Cambrian, however, they found a strikingly different pattern as shown in Figure 16.10d. They concluded

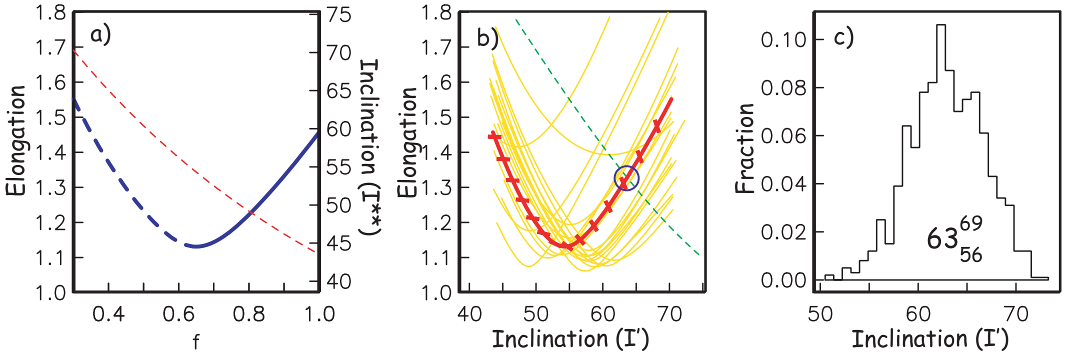

Figure 16.9: a) Plot of elongation (heavy solid and dashed line) and inclination (dashed) as a function of unflattening by the parameter f. Elongation is E-W (N-S) when heavy line is solid (dashed) b) Plot of elongation versus inclination for the data in a) (solid) and for the TK03.GAD model (dashed). Also shown are results from 20 bootstrapped datasets. The crossing points represents the inclination/elongation pair most consistent with the TK03.GAD model. c) Histogram of crossing points from 1000 bootstrapped datasets. The most frequent inclination (63°) is exactly that predicted from the Besse and Courtillot (2002) European APWP. The 95% confidence bounds on this estimate are 56-69°. [Figure modified from Tauxe and Kent, 2004.]

that the frequency distribution of Paleozoic and Pre-Cambrian inclination data are severely biased toward shallower directions and are not consistent with a GAD model.

KS98 (Kent & Smethurst 1998) discussed several possible causes of the bias: inclination "error" in sediments, non-random plate motion, and non-GAD fields, in particular, a time averaged geomagnetic field with a large ($\sim$ 20%) octupolar (g_3^0) contribution. In order to address the issue of sedimentary bias, KS98 separated the data into those of sedimentary origin and those of so-called "crystalline" origin, mostly extrusive and intrusive igneous rocks as shown in Figure 16.10c. Both types of rocks yield highly biased frequency plots.

The frequency distribution expected for sedimentary rocks exhibiting "inclination error" can be estimated by using the inclination error formula as before. We show the expected distribution of inclinations from such a process (using $f = 0.5$) in Figure 16.10d as the long dashed line. The sedimentary data (short dashed line) are quite consistent with this prediction. This result should come as no surprise perhaps because the overwhelming majority of the data come from so-called "red beds" with detrital hematite as a dominant carrier of remanence.

Because "crystalline" rocks do not suffer from depositional inclination error, the fact that they too were biased shallow was taken as support that the shallow bias was not solely the result of a sedimentary artifact. KS98 (Kent & Smethurst 1998) drew the conclusion that either the field was indeed biased with a large octupolar contribution, or that the continents had not drifted randomly, but had preferentially been near the equator.

There is another possibility. In the Paleozoic and the Pre-Cambrian, it is likely that most rock units have experienced some degree of tilting. For intrusive rocks, the amount of tilting could be unconstrained. Extrusives, however, generally have initial dips within some 30° of horizontal, depending on the type of volcano. Therefore, paleo-horizontal in even the extrusive units would not necessarily be known to better than 30° unless they are intercalated with sediments whose paleo-horizontal is much better constrained. The distribution of inclinations becomes increasingly

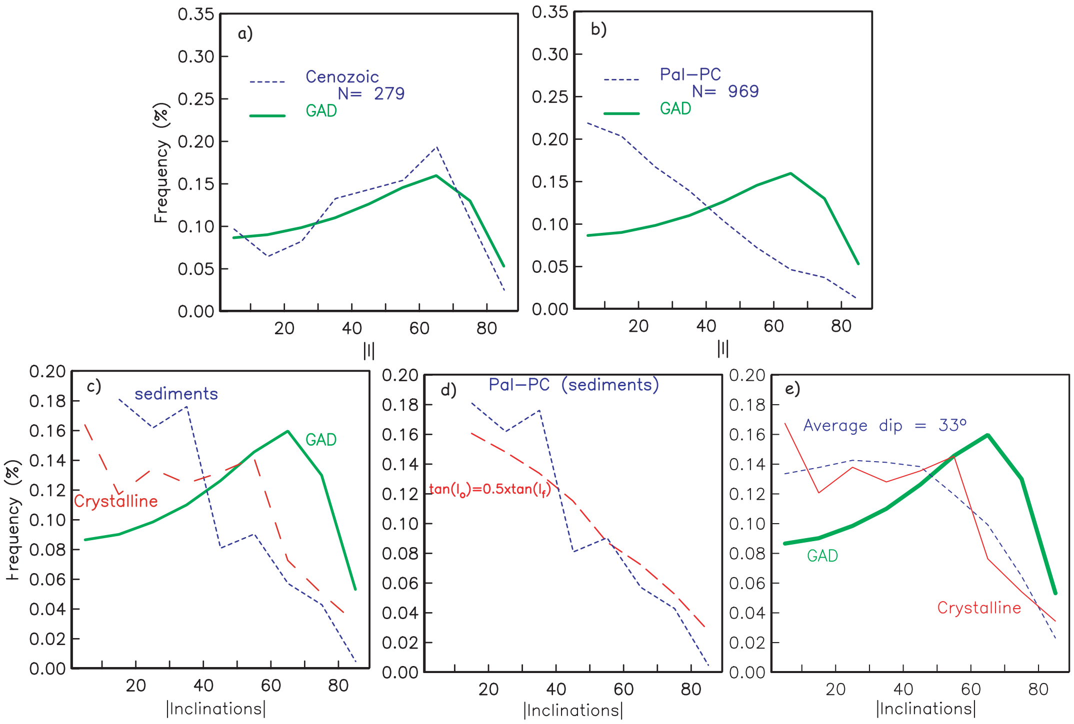

Figure 16.10: a) Frequency of inclinations. Dashed line is (binned) Cenozoic results. Solid line is expectation from GAD c) same as a) for Paleozoic-Precambrian results. b) Same as a) but for Paleozoic-Precambrian results. c) Same as b) but sediments shown as short dashed line and crystalline rocks shown as long dashed line. Also shown is the trend expected from GAD. d) same as c) but for sediments only. Also shown is trend expected GAD inclinations transformed by the inclination error formula. e) same as d) but for crystalline rocks. Also shown is the trend expected from random tilting of a GAD distribution of directions with an average dip of 33°.

skewed toward shallow directions as the amount of average tilting increases. In fact, it is perhaps surprising that simulations show that uncorrected tilt has a similar effect on the distribution of inclinations as the addition of a non-zero axial octupole.

The relevance to the structure of the ancient geomagnetic field of poorly constrained tilting is shown in Figure 16.10e in which we plot the frequency distribution obtained by tilting observations derived from the 1995 IGRF by random amounts with an average tilt of 33° and that obtained from the crystalline rocks in the database. Such tilts are not unexpected from a collection of Paleozoic/Pre-Cambrian intrusives and extrusives. We find that the poorly constrained tilt hypothesis explains the observations as well as the introduction of a large axial octupole contribution.

16.7 Concluding remarks

And so we return to where we started at the beginning of this course with an assumption that the geomagnetic field is essentially that of a centered dipole. There is no compelling evidence that the field has operated in a vastly different way in ancient times, apart from the puzzling change in reversal frequency. We are getting better at all aspects of paleomagnetic research from better designed field programs to better laboratory analyses to more sophisticated data analysis. There remains much to be done. Enjoy.

Appendix

A Method for rotating paleomagnetic poles using finite rotation poles

The following is based on the procedure described in Box 7.3 of Cox and Hart (1986). Given the coordinates of the paleomagnetic pole P_p with latitude λ_p, longitude ϕ_p the finite rotation pole P_f with latitude λ_f, longitude ϕ_f, the way to transform coordinates is as follows (you should also review Appendix A4 of Lecture 1 and Lecture 2).

Convert the latitudes and longitudes to cartesian coordinates by:

$$P_1 = \cos\phi\cos\lambda, P_2 = \sin\phi\cos\lambda, P_3 = \sin\lambda$$

where P is the pole of interest.

Set up the rotation matrix R as:

$$\begin{aligned}
R_{11} &= P_{f1}P_{f1}(1-\cos\Omega)+\cos\Omega\\
R_{12} &= P_{f1}P_{f2}(1-\cos\Omega)-P_{f3}\sin\Omega\\
R_{13} &= P_{f1}P_{f3}(1-\cos\Omega)+P_{f2}\sin\Omega\\
R_{21} &= P_{f2}P_{f1}(1-\cos\Omega)+P_{f3}\sin\Omega\\
R_{22} &= P_{f2}P_{f2}(1-\cos\Omega)+\cos\Omega\\
R_{23} &= P_{f2}P_{f3}(1-\cos\Omega)-P_{f1}\sin\Omega\\
R_{31} &= P_{f3}P_{f1}(1-\cos\Omega)-P_{f2}\sin\Omega\\
R_{32} &= P_{f3}P_{f2}(1-\cos\Omega)+P_{f1}\sin\Omega\\
R_{33} &= P_{f3}P_{f3}(1-\cos\Omega)+\cos\Omega
\end{aligned}$$

The coordinates of the transformed pole (P_t) are:

$$\begin{aligned}
P_{t1} &= R_{11}P_{p1}+R_{12}P_{p2}+R_{13}P_{p3}\\
P_{t2} &= R_{21}P_{p1}+R_{22}P_{p2}+R_{23}P_{p3}\\
P_{t3} &= R_{31}P_{p1}+R_{32}P_{p2}+R_{33}P_{p3}
\end{aligned}$$

which can be converted back into latitude and longitude in the usual way (see Lecture 2).

Bibliography

Besse, J. & Courtillot, V. (2002), ‘Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 myr’, *J. Geophys. Res* **107**, doi:10.1029/2000JB000050.

Bullard, E. C., Everett, J. E. & Smith, A. G. (1965), ‘A symposium on continential drit - iv. the fit of the continents around the atlantic’, *Phil. Trans. Roy. Soc.* **258**, 41–51.

Butler, R. F. (1992), *Paleomagnetism: Magnetic Domains to Geologic Terranes*, Blackwell Scientific Publications.

Cox, A. & Hart, R. (1986), *Plate Tectonics: How it Works*, Blackwell Scientific, Oxfort.

Evans, M. (1976), ‘Test of the dipolar natrue of the geomagneitc field throughout phanerozoic time’, *Nature* **262**, 676–677.

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

Irving, E. (1958), ‘Paleogeographic reconstruction from paleomagnetism’, *Geophys. Jour. Roy. astr. Soc.* **1**, 224–237.

Irving, E. (1977), ‘Drift of the major continental blocks since the devonian’, *Nature* **270**, 304.

Irving, E. (1979), ‘Paleopoles and paleolatitudes of north america and speculations about displaced terrains’, *Can. J. Earth Sci.* **16**, 669–694.

Kent, D. & Smethurst, M. (1998), ‘Shallow bias of paleomagnetic inclinations in the paleozoic and precambrian’, *Earth Planet. Sci. Lett.* **160**, 391–402.

Lottes, A. & Rowley, D. (1990), Early and late permian reconstructions of pangaea, *in* W. McKerro & C. Scotese, eds, ‘Paleozoic Paleogeogrpahy and Biogeography’, Vol. 12, Geol. Soc. London Meme, pp. 383–395.

McElhinny, M. & McFadden, P. (2000), *Paleomagnetism: Continents and Oceans*, Academic Press.

Mueller, R., Roest, W., Royer, J., Gahagan, L. & Sclater, J. G. (1997), ‘A digital age map of the ocean floor’.

Royer, J., Mueller, R., Gahagan, L., Lawver, L., Mayes, C., Nuernberg, D. & Sclater, J. G. (1992), ‘A global isochron chart’, *Univ. Texas Inst. Geophys. Tech. Rept.* **117**.

Si, J. & Van der Voo, R. (2001), ‘Too-low magnetic inclinations in central asia: an indication of a long-term tertiary non-dipole field?’, *Terra Nova* **13**, 471–478.

Tan, X. D., Kodama, K. P., Chen, H. L., Fang, D. J., Sun, D. J. & Li, Y. A. (2003), 'Paleomagnetism and magnetic anisotropy of cretaceous red beds from the tarim basin, northwest china: Evidence for a rock magnetic cause of anomalously shallow paleomagnetic inclinations from central asia', *Journal of Geophysical Research-Solid Earth* **108**(B2).

Tauxe, L. & Kent, D. V. (2004), A simplified statistical model for the geomagnetic field and the detection of shallow bias in paleomagnetic inclinations: Was the ancient magnetic field dipolar?, *in* e. a. Channell, J.E.T., ed., 'Timescales of the Paleomagnetic field', Vol. 145, American Geophysical Union, Washington, D.C., pp. 101–116.

Voo, R. V. d. (1981), 'Paleomagnetism of north america-a brief review', *Paleoreconstruction of the Continents, Geodynamic Series Amer. Geophys.* **2**, 159–176.

Voo, R. V. d. (1990), 'Phanerozoic paleomagnetic poles from europe and north-america and comparisons with continental reconstructions', *Rev. of Geophysics* **28**, 167–206.

Wegener, A. (1915), *Die Entstehung der Kontinente.*