Global Paleomagnetic Data Analysis:

Improved Methods of Reconstructing Plate Motions Using Paleomagnetic Data

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Contents

List of Figures

Chapter 1

Introduction

The first chapter introduces paleomagnetism-based paleogeographic reconstruction technique and highlights the motivation of the research conducted in the dissertation

1.1 Background and Motivation

Reconstructing past paleogeographies, especially the motion of plates and their interactions through time, is a key component of understanding the Earth's geological history, including deciphering tectonics (e.g. supercontinent reconstruction), paleoclimate history, and the evolution of life. Since the advent of plate tectonics, it has been the background for nearly all geologic events. In addition, plate reconstructions form the basis of global or regional geodynamic models.

1.1.1 Techniques Used in Relative and Absolute Plate Motion Studies

The earliest quantitative effort to model plate kinematics was fitting conjugate passive margins of the Atlantic [3, 28]. They showed that the Atlantic could be closed using a single Euler pole (using Euler's theorem on rotation). Then it became fitting conjugate isochrons based on best-fitting marine magnetic anomaly and fracture zone data [11], which minimizes the misfit area between two isochrons. The *Hellinger* method [8] is a more advanced and generalised method which also fits conjugate isochrons based on best-fitting marine magnetic anomaly and fracture zone data, which however minimizes the sum of the misfits of conjugate data points that belong to a common isochron segment [28] instead. These techniques mainly through fitting conjugate lines mentioned above are relatively accurate for quantitative analysis. However they give relative, not absolute, motions between plates, because plate motions can't be tied into absolute location on Earth's surface, since both plates are likely moving. In addition, they are limited to survey data from the seafloor, with a maximum age of no more than c. 200 Ma [14].

Reference frames are a means of describing the motion of geologic features (e.g. tectonic plates) on the surface of the Earth, relative to a common point or "frame" [19]. An absolute reference frame is a frame that can be treated as fixed relative to the Earth's geographic reference frame. In reality, it's impossible to find a truly absolute reference frame, so we are actually looking for a frame that has limited (and hopefully known) motion, which approximates as "fixed" over geologically useful timescales and provides the most complete descriptions of plate motions. A commonly used absolute reference frame is the "Fixed Hotspot model" [13, 12], covering ages from about 132 Ma to present-day, which assumes that the linear volcanic chains found on most oceanic plates are artifacts of absolute plate motions over a upwelling plume from the deep mantle, which is assumed to be relatively fixed. The advantage of this "Fixed hotspot model" is that it is fairly straightforward if the assumption of fixed hotspots is correct. However, this model is limited to plates with well-dated volcanic hotspot chains (e.g. the Ninetyeast Ridge on the Indian Ocean floor and the Walvis Ridge in the southern Atlantic Ocean; [15]) and dating can be difficult (e.g. diffuse volcanic centers possibly related to large diameter plume conduits could cause the existence of time reversals; [15]). As for not well-dated hotspot tracks, for example, only about 5‰ of the seamounts (thought to be volcanic) in the Pacific are thought be be related to hotspot volcanism and radiometrically dated (39 per cent of these ages are less than 10 Ma; [9]). In addition, the fixed hotspot model is mostly confined to existing oceanic or thin continental crust because older oceanic lithosphere has been largely destroyed by subduction and old, thick continental crust mostly removed by erosion [5]. Last, but not least, hotspots can be susceptible to drift that may be caused by changes in sub-lithospheric mantle flow [20]. Generally, however, the drift rate is considered to be an order of magnitude less than the rate of plate motions, so only becomes significant over timescales of c. 50 Myr or more [15, 21]. To overcome this source of error, the "Moving hotspot model" [15] uses mantle convection modeling to predict hotspot drift. Some are apparent success, e.g. by getting motions in the Indo-Atlantic and Pacific hotspot clusters to agree with each other, but it's very dependent on the mantle model. Hybrid models attempt to overcome the shortcomings of each reference frame by combining them, e.g. combining a fixed hotspot frame from 100 Ma to 0 Ma [13] with a moving hotspot frame from c. 132–100 Ma [15] (Hybrid hotspot model [19]), combining a moving hotspot frame from 100–0 Ma [15] with a paleomagnetic model (reflect plate motion relative to the magnetic dipole axis but cannot provide paleolongitudes because of the axial symmetry of the Earth's magnetic dipole field) [23] from 140–100 Ma (Hybrid paleomagnetic model [19]), and combining a moving hotspot frame from 120–100 Ma [15] with a True Polar Wander (TPW) corrected paleomagnetic model [1] from 100–0 Ma (Hybrid TPW-corrected model [19]).

Recently another absolute reference frame "Subduction reference model" [25] tries to connect orogenies/sutures/subduction complexes' on the Earth surface with their corresponding subducted slabs in the mantle. Assuming that these remnants sank vertically through the mantle, the absolute location at which they were subducted can be reconstructed. In this way, this model mainly imposes a longitude correction on the above mentioned "Hybrid TPW-corrected model", and can theoretically give past absolute locations of plates back to about 260 Ma based on the estimated age of the oldest slab remnants that can be reliably located in the mantle. While the

"Subduction reference model" allows for reconstructions between about 260 Ma and 140 Ma, older than the other absolute models can predict, the model is strongly dependent on the vertical subduction assumption and resolution of seismic tomography models, so its uncertainty is high. Above all, importantly, if we can describe the absolute motion of one or a few key plates, the techniques for establishing the relative plate motions described in the second paragraph above can be used to construct plate circuits that allow a full kinematic description of plate tectonics to be developed.

As we can see, all of these above reconstruction methods are limited to recent geological history. For most of Earth history, concretely for times before c. 170 Ma, the age of the oldest magnetic anomaly identification, paleomagnetism is the only accepted quantitative method for reconstructing plate motions and past paleogeographies.

1.1.2 Application of Paleomagnetism to Plate Tectonics

The geomagnetic field is generated by the convective flow of a liquid iron-nickel alloy in the outer core of the Earth. It is largely dipolar and can be represented by a dipole that points from the north magnetic pole to the south pole. However, the geomagnetic field varies in strength and direction over decadal–millennial timescales due to quadropole and octopole components of the field. The most spectacular variations in direction are occasional polarity reversals (normal polarity: the same as the present direction of the field; or the opposite, i.e. reverse polarity). Over a period of a few thousand years, the magnetic axis slowly rotates/precesses around the geographic axis and the Earth's rotation axis (secular variation), but when averaged over 10,000 year timescales, higher order components of the field are thought to largely cancel out and the position of the magnetic poles aligns with the geographic poles. This is the geocentric axial dipole (GAD) hypothesis. In a GAD field, at the north magnetic pole the inclination (angle with respect to the local horizontal plane, see Fig. 1.1) of the field is +90° (straight down), at the Equator the field inclination is 0° (horizontal) pointing north and at the south magnetic pole the inclination is -90° (straight up) (Fig. 1.1). Another direction parameter of the Earth's magnetic field is declination. It is the angle with respect to the geographic meridian, which is 0° everywhere in a time-averaged GAD field.

Magnetic remanence is the magnetization left behind in a ferromagnetic substance in the absence of an external magnetic field [22]. The remanent magnetisation of rocks can preserve the direction and intensity of the geomagnetic field when the rock was formed, e.g. in the process of cooling, ferromagnetic materials in the lava flow are

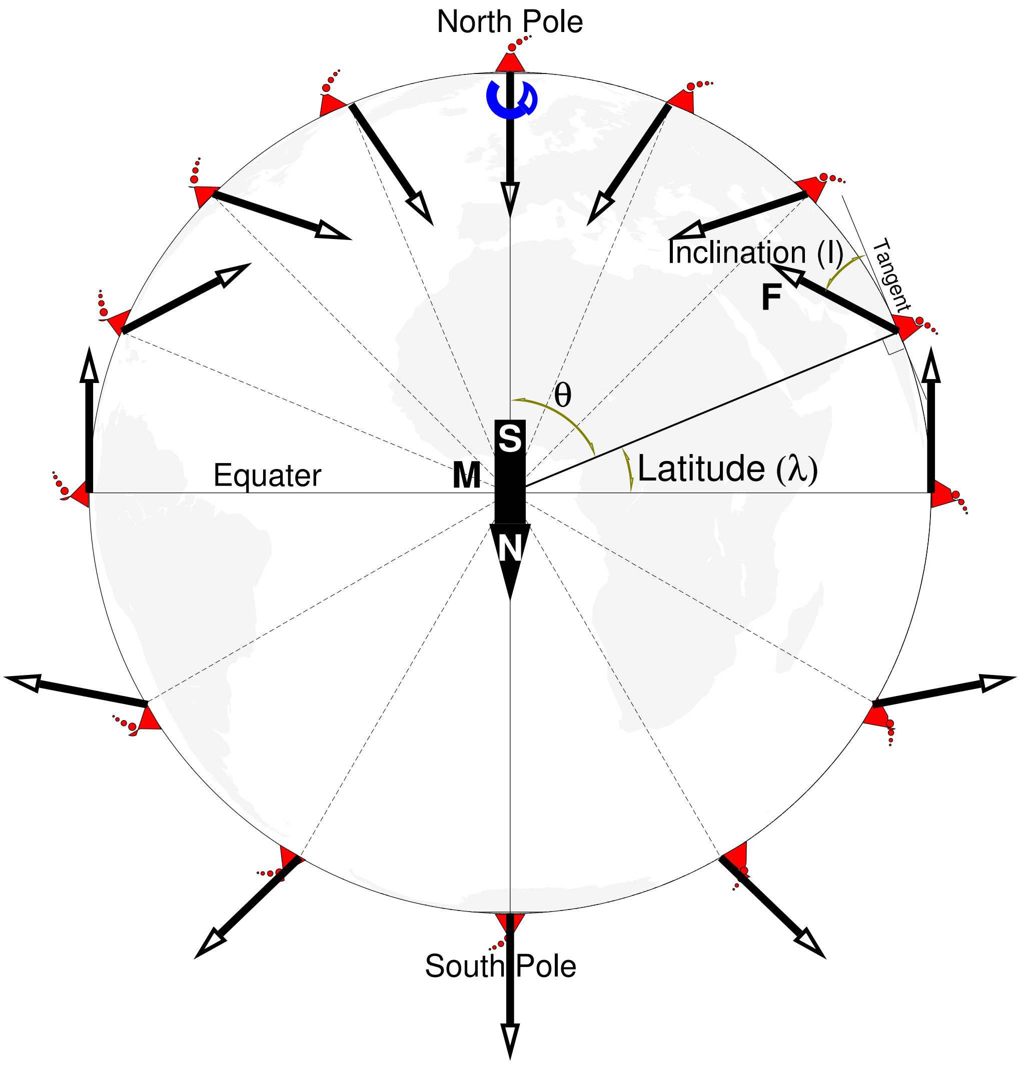


Figure 1.1: GAD model: Inclination (angle $\mathrm{I} = tan^{-1}(2tan\lambda)$) of the Earth's magnetic field and how it varies with latitude, redrawn from [4, 22, 23]. Magnetic dipole M is placed at the center of the Earth and aligned with the rotation axis; λ is the geographic latitude, and θ is the colatitude.

magnetized in the direction of the Earth's magnetic field, so the local direction of the field vector is locked in solidified lava. We are often interested in whether the geomagnetic pole has changed, or whether a particular plate/terrane has rotated with respect to the geomagnetic pole [22]. By measuring the direction of the remanent magnetisation, we can calculate a virtual geomagnetic pole (VGP) to represent the geomagnetic pole of an imaginary geocentric dipole which would give rise to the observed remanent declination and inclination. Collection of VGPs (or site-mean directions) allow calculating a "paleomagnetic pole", also known as paleopole, at the formation level. Commonly a paleopole is a Fisherian mean [6] with a spatial uncertainty. A paleopole that plots away from the present geographic poles is assumed to be due to plate motions since the lava was solidified, which causes the paleopole to move with the plate [23]. Based on measurements of the remanent inclination, the ancient latitude for a plate can be calculated when the rock formed from the dipole formula $\tan(I) = 2 * \tan(latitude)$. In addition, the remanent declination provides information about the rotation of a plate. Ideally, as a time average, a paleopole (which can be calculated from declination, inclination and the current geographic location of the sampling site) for a newly formed rock will correspond with the geographic north or south pole. To perform a reconstruction with paleopoles we therefore have to calculate the rotation (Euler) pole and angle which will bring the paleopole back to the geographic north or south pole, and then rotate the plate by the same amount of angle using the same Euler pole. This is how paleomagnetism can be used to reconstruct past positions of a plate. In our example (Fig. 1.2), a c.155 Ma paleopole (latitude=52.59°N, longitude=91.45°W) will be restored to the geographic pole by an Euler rotation of pole (0°, 178.55°E) with angle 37.41°, which rotates the sampling site from its present position of (0°, 25°E) to the Africa paleo-continent at (15.6998°S, 20.1121°E). So Africa must have drifted northwards since the Late Jurassic.

However, there are 2 problems with using paleomagnetic poles for constraining finite rotations [22]. First, if only one paleomagnetic pole is given alone without any geologic context, its polarity can be ambiguous, i.e. an upward inclination may be due to being located in the southern hemisphere during a normal polarity chron, or in the northern hemisphere during a reversed polarity chron (cf. the solid blue and solid green Africa in Fig. 1.2). In other words, we can't know if it's North pole or South pole, especially for paleomagnetic data with the Precambrian and early Paleozoic ages. Returning to the example above, if the c. 155 Ma paleomagnetic pole (52.59°N, 91.45°W) was formed during a period of reversed polarity, then it needs to be rotated to the South pole rather than the North pole. The necessary

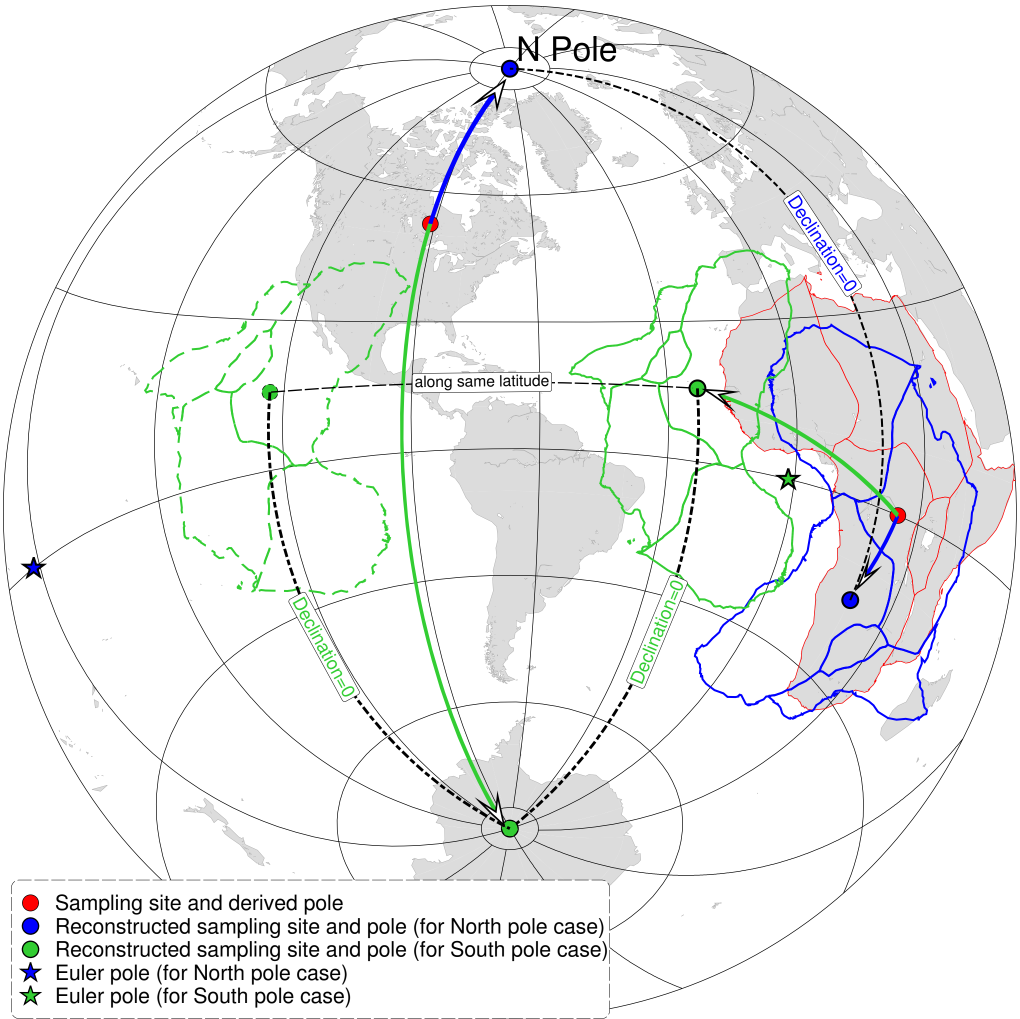


Figure 1.2: Reconstruction of Africa with its c. 155 Ma paleomagnetic pole. The red polygon is today's position of Africa, while the blue and green ones shows its reconstructed position at c. 155 Ma, if the pole was North and South pole, respectively. Dashed green polygon illustrates the ambiguity of paleolongitude from paleomagnetic data alone (sites at same latitude but different longitudes record the same Declination and Inclination in a GAD field).

Euler rotation of pole (0°, 1.45°W) and angle 142.59° rotates the sampling site (0°, 25°E) on Africa to (15.6998°N, 23.0121°W) indicating southward motion since the Late Jurassic. Second, because in a GAD field the declination equals zero everywhere (Fig. 1.2), paleomagnetic data doesn't register longitudinal motions of plates (the Euler pole for a plate moving purely to the east or west is at the geographic poles, so preserved paleomagnetic poles will experience zero rotation), which means we can position a plate at any longitude we wish subject to other geological constraints (cf. the solid and dashed green Africa in Fig. 1.2).

The data source used in this dissertation is *Global Paleomagnetic Database* (GPMDB) Version 4.6b [17, updated in 2016 by the Ivar Giaever Geomagnetic Laboratory team, in collaboration with Pisarevsky], which includes 9514 paleopoles for ages of 3,500 Ma to the present published from 1925 to 2016. GPMDB has been published in two ways: (1) IAGA GPMDB 4.6 online query: *http://www.ngu.no/geodynamics/gpmdb/*, which is now closed; (2) Microsoft Access system in *.mdb* format at NOAA's National Geophysical Data Center *https://www.ngdc.noaa.gov/geomag/paleo.shtml* [18] and CESRE's Paleomagnetism and Rock Magnetism project *https://wiki.csiro.au/display/cmfr/Palaeo*
which is later updated by Ivar Giaever Geomagnetic Laboratory *http://www.iggl.no/resources.html*

An apparent polar wander path (APWP) is composed of poles of different ages from different sampling sites on the same stable (non-deforming) continent, chained together to form a record of motion relative to the fixed magnetic pole over geological time. It represents a convenient way of summarizing paleomagnetic data for a plate instead of producing paleogeographic maps at each geological period [23]. As a preliminary study, the *North American Craton* (NAC) is chosen as a research object to develop techniques we want to think about. The NAC is one of best studied cratons in paleomagnetism with the GPMDB containing 2160 poles published since 1948 (Fig. 1.3). If we observe the latitudes, longitudes and age distribution of the NAC poles (Fig. 1.3), we actually can identify the general trend of its APWP. However, converting this data into a reliable, well-defined APWP can be challenging, due to the following issues:

1.1.3 Fact 1: Not All Regions on the Earth Surface Are Solid

If we consider the modern North America continent, the region west of the Rockies is actively deforming. Paleomagnetic data from such areas are likely to reflect local tectonic processes such as block rotation rather than rigid plate motions, and should be excluded. For example, the Rockies Mountain area was not included as my data selecting polygon (the transparent yellow area in Fig. 1.3). In order to investigate a

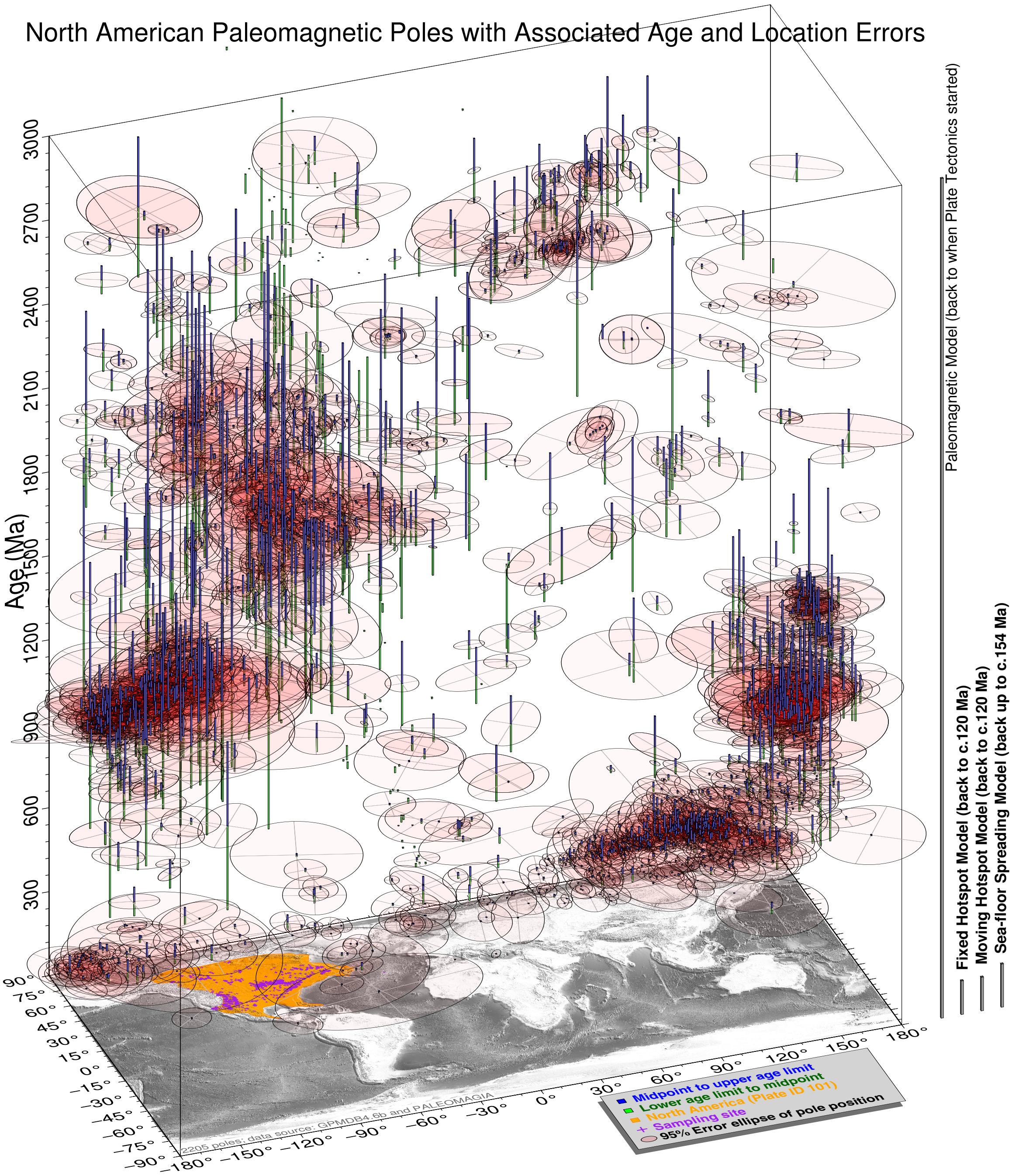


Figure 1.3: Much paleomagnetic data has been collected from the North American Craton. For younger geologic times, do we really need so much data to reconstruct accurately just like modern-day plate motions? The image shows distribution of all published paleomagnetic poles of the NAC over time, which are compiled from GPMDB 4.6b [17] and PALEOMAGIA [27].

specific craton or terrane or block's past paleogeographic motion, choosing an appropriate subregion without active tectonic activities, e.g. rotation or uplifting or rifting, to select data is often required. Such tectonics-free regions are usually called rigid. However, the difficulty of defining such tectonic boundaries makes appropriate spatial and temporal choices very difficult, particularly further in the geological past when cratonic configurations and active plate boundaries were very different to today. This leads to a question: What is the best way to constrain the data for a specific plate or block? My present solution is described in Chapter 2.

1.1.4 Fact 2: Not All Data Are Created Equal

APWPs are generated by combining paleomagnetic poles for a particular rigid block over the desired age range to produce a smoothed path. However, the NAC dataset illustrates that uncertainties in the age and location of paleomagnetic poles in the GPMDB can vary greatly for different poles.

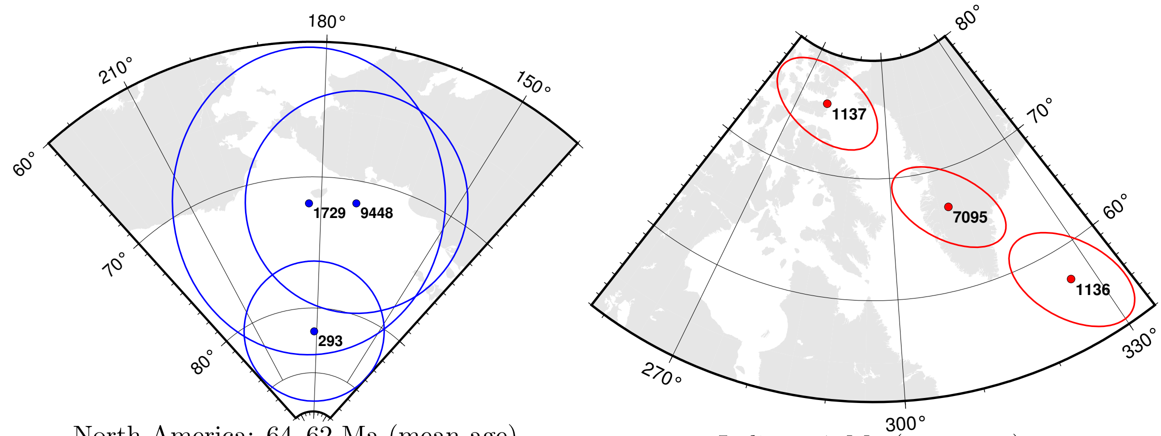
1.1.4.1 Age Error

Although remanent magnetizations are generally assumed to be primary, many events can cause remagnetisation (in which case the derived pole is 'younger' than the rock). If an event that has occurred since the rock's formation that should affect the magnetisation (e.g. folding, thermal overprinting due to intrusion) can be shown to have affected it, then it constrains the magnetisation to have been acquired before that event. Recognising or ruling out remagnetisations depends on these field tests, which are not always performed or possible. Even a passed field test may not be useful if field test shows magnetisation acquired prior to a folding event tens of millions of years after initial rock formation.

The most obvious characteristic we can observe from NAC paleomagnetic data (Fig. 1.3) is that some poles have very large age ranges, e.g. more than 100 Myr. The magnetization age should be some time between the information of the rock and folding events. There are also others where we have similar position but the age constraint is much narrower, e.g. 10 Myr window or less. Obviously the latter kind of data is more valuable than the one with large age range.

1.1.4.2 Position Error

The errors of pole latitudes and longitudes are plotted as 95% confidence ellipses (Fig. 1.3), which also vary greatly in magnitude. All paleomagnetic poles have some



North America: 64–62 Ma (mean age)

India: 9–7 Ma (mean age)

Figure 1.4: Overlapping and further separated paleomagnetic poles of NAC and India. The oval ellipses are their 95% confidence errors. The labels are their result number given in GPMDB 4.6b.

associated uncertainties due to measurement error and the nature of the geomagnetic field. More uncertainties can be added by too few samples, sampling spanning too short a time range to approximate a GAD field, failure to remove overprints during demagnetisation, etc.

1.1.4.3 Data Consistency

Paleomagnetic poles of a rigid plate or block should be continuous time series. For a rigid plate, two poles with similar ages shouldn't be dramatically different in location. We want to look at the consistency of NAC and India's data over smaller time periods, so the data is binned over a small time interval (e.g. 2 Myr) to see whether the paleopoles in each time interval overlap within their error ellipses, as they should. Sometimes, this is the case (Fig. 1.4a). Sometimes we have further separated poles with close ages (Fig. 1.4b).

There are a number of possible causes for these outliers, including:

Lithology For this poor consistency of data (Fig. 1.4b), it is potentially because of different inclinations or declinations. The first thing we should consider about is their lithology. We want to check if the sample rock are igneous or sedimentary, because sediment compaction can result in anomalously shallow inclinations [22]. In addition, we also can check if the rock are redbeds or non-redbeds. Although whether redbeds record a detrital signal or a later chemical remanent magnetization (CRM) is still somewhat controversial, both sedimentary rocks and redbeds could lead to inconsistency in direction compared to igneous rocks. For this case, all the three poles (Fig. 1.4b) are from sedimentary rocks. In addition, pole 1136 and 1137 (Result

Number in GPMDB 4.6b)'s source rocks also contain redbeds [16], although the authors did not mention about the potential inclination shallowing. For pole 7095, although the source rocks do not contain redbeds, the authors did mention about possible inclination shallowing due to haematite grains [7].

Local Rotations As discussed previously, local deformation between two paleomagnetic localities invalidates the rigid plate assumption and could lead to inconsistent paleopole directions. All the three poles (Fig. 1.4b) contain signals of local rotations [16, 7], e.g. pole 7095 has a signal which suggests the presence of a counter-clockwise local rotation of the Tinau Khola section [7], and therefore do not reflect motions of the whole rigid India plate in this case. So the discordance is likely due to local deformation (Fig. 1.4b), and we would ideally want to exclude or correct such poles from our APWP calculation.

Other Factors In Fig. 1.4, mean pole age (centre of age error) has just been binned. If any of the paleopoles have large age errors, they could be different ages from each other and sample entirely different parts of the APWP. Conversely, if any of the paleopoles have too few samples, or were not sampled over enough time to average to a GAD field, a discordant pole may be due to unreduced secular variation, because in order to average errors in orientation of the samples and scatter caused by secular variation, a "sufficient" number of individually oriented samples from "enough" sites must be satisfied [22, 26, 2]. For example, pole 1136 (Fig. 1.4b) is from only 4 sampling sites, pole 1137 from only 3 sites and pole 7095's site number not even given in the GPMDB 4.6b.

1.1.4.4 Data Density

As we go back in time, we have lower quality and lower density (or quantity) of data, for example, the Precambrian or Early Paleozoic paleomagnetic data are relatively fewer than Middle-Late Phanerozoic ones, and most of them are not high-quality, e.g. larger errors in both age and location (Fig. 1.3). The combination of lower data quality with lower data density means that a single 'bad' pole (with large errors in age and/or location) can much more easily distort the reconstructed APWP, because there are few or no 'good' poles to counteract its influence.

Data density also varies between different plates. E.g. we have a relatively high density of paleomagnetic data for NAC, but few poles exist for Greenland and Arabia.

Based on mean age (mean of lower and upper magnetic ages), for 100–0 Ma, GPMDB 4.6b has 198 NAC poles, but only 17 for Greenland and 24 for Arabia.

1.1.4.5 Publication Year

The time when the data was published should also be considered, because magnetism measuring methodology, technology and equipments have been improved since the early 20th century. For example, stepwise demagnetisation, which is the most reliable method of detecting and removing secondary overprints, has only been in common use since the mid 1980s.

In summary, not all paleopoles are created equal, which leads to an important question: how to best combine poles of varying quality into a coherent and accurate APWP? Paleomagnetists have proposed a variety of methods to filter so-called "bad" data, or give lower weights to those "bad" data before generating an APWP, e.g. two widely used methods: the V90 reliability criteria [26] and the BC02 selection criteria [2]. Briefly, the V90 criteria for paleomagnetic results includes seven criteria: (1) Well determined age; (2) At least 25 samples with Fisher [6] precision κ greater than 10 and $\alpha95$ less than 16°; (3) Detailed demagnetisation results reported; (4) Passed field tests; (5) Tectonic coherence with continent and good structural control; (6) Identified antipodal reversals; (7) Lack of similarity with younger poles [24]. Compared with V90, the BC02 criteria suggests stricter filtering, e.g. using only poles with at least 6 sampling sites and 36 samples, each site having $\alpha95$ less than 10° in the Cenozoic and 15° in the Mesozoic. There are many potential ways to weight the data set which could obviously greatly influence the final result, and we want to test this. But there has been limited study of how effective these filtering/weighting methods are at reconstructing a 'true' APWP, and for most studies after a basic filtering of 'low quality' poles, the remaining poles are, in fact, treated equally.

1.2 Objectives

Our overarching aims are to develop rigorous, consistent and well-documented methods of reconstructing plate motions using paleomagnetic data, and to investigate the limits of paleomagnetic data on reconstructing individual plate motions, supercontinents, and global tectonic parameters like average rate of plate motion.

1.2.1 Motivation and General Approach

How has plate tectonics evolved over geologic history, in terms of average plate velocities, numbers of plates and so on? The only quantitative data we have prior to about 170 Ma are paleomagnetic data. We know there are limitations, because we can't constrain the longitudes of paleo-plates very well. When we look back through geologic history, how much good paleomagnetic data do we have, and how well does it reconstruct 'true' plate motions? We don't know well the effects of data quality and density, which generally degrades further back in geologic history, on producing reliable APWPs. For the past c. 130–200 Myr we have the highest density of paleomagnetic data and also independent plate motion data from reconstructions of ocean spreading combined with hotspot reference frames. These independent data sources can help constrain plate motions in more accurate ways. This allows us to ask the question: How much paleomagnetic data do we need actually to reconstruct accurately known modern-day plate motions? If we can handle that, we can go back in time. For a certain density of paleomagnetic data that we have, how reliably can we talk about what's going on in the past given the much lower data distribution? It might turn out we don't need very much data to say something reasonably and reliably. We can test this by looking at the last 0–120 Ma where we can compare paleomagnetically derived plate motions with other methods of paleogeographic reconstruction. This does not only include the work of developing tools and algorithms to generate those paleomagnetically derived plate motions (to use paleomagnetic data to reconstruct APWP parameters that are known from other sources like ocean basins and hotspots), but also need us to know how good these tools are or which one is the best algorithm (to compare paleomagnetic APWPs with the known data sources predicted APWP). This can give insights into how well we can 'know' plate motions back in the past, and what data quality and density are necessary to reliably reconstruct a 'true' APWP.

As a preliminary analysis, some algorithms were made to separate/calculate out so-called good paleomagnetic data (at any particular time period for a particular craton, like here from 100 Ma to the present day for NAC). We are interested in what makes 'good' data, how we can identify it and filter it from the database, and how sometimes 'bad' data is only bad in the sense that it is poorly constrained in age or position or any other parameter, in which cases it might be possible to include it by e.g., weighting. A weighted mean pole can be calculated for a time interval with 'better' (more likely to be reliable) poles counting more than 'worse'. For example, a pole with small $\alpha95$ and very well constrained age is more likely to reflect APWP position at the selected age point than a pole with large $\alpha95$ and very broad age range.

1.2.2 Research Questions or Hypotheses

Questions 1–4 focus on method development, whereas 5 and 6 start using them for plate tectonic research, especially in deep times.

1.2.2.1 Question 1

What is the best way to turn a collection of individual poles, with different age constraints and uncertainties, into a smoothed APW path? This question, in fact, is about how to (1) choose a data-constraining polygon that represents a solid continent during a certain period; (2) pick (or bin) data within a certain window for Fisher statistical [6] calculation; (3) do weighting for picked data according to different uncertainties or other kinds of standards of qualifications; (4) if the derived APWP is still not smoothed enough when compared with a reference path, is further smoothing necessary? Our goal here actually is to get a reliable result, i.e. a path generated to approximate the 'real' APWP with appropriate uncertainties.

1.2.2.2 Question 2

Based on the consequences from the algorithms we developed, we can do research on why some algorithms are good, others bad for all plates? Why some algorithm performs well for a plate or two but not others?

1.2.2.3 Question 3

How much paleomagnetic data do we need actually to accurately reconstruct known modern known plate motions? What insights does this give us into the reliability of reconstructions from earlier in geologic history?

1.2.2.4 Question 4

Based on our analysis above, can we develop algorithms that look for matching segments of APWPs from different cratons, that might indicate they were part of the same continent or supercontinent?

1.2.2.5 Question 5

What kind of dataset (in terms of data density and quality) is needed to accurately reconstruct a known APWP, or a shared APWP between two cratons? If we can establish some criteria for this, does it provide any insights into past reconstructions of plate motions (e.g., Rodinia)?

1.2.2.6 Question 6

Can we develop algorithms that use APWPs from multiple continents to estimate global average plate motion rates? Can we get a good sense of how much information is lost due to lack of data on longitudinal motions? Can we use this to draw any conclusions about long term trends (or lack thereof) in the style and vigour of global plate tectonics? (Possible further question: can data on relative continental motion acquired from matching APWP curves be incorporated to improve these estimates?)

In summary, this dissertation will not be able to help answer all the above questions. However, in the end the completion of this dissertation and solving the first three questions are hoped to be helpful solving the later questions in the future.

Chapter 2

Methodologies

This chapter mainly describes the development of a new APW path similarity measuring tool used throughout the dissertation

(This chapter is appended as a paper draft with its supplementary material after the Bibliography. It is also openly accessible from *https://github.com/f-i/APWP_similarity*. Text: *https://github.com/f-i/APWP_similarity/blob/master/2.pdf*; Figures: *https://github.com/f-i/APWP_similarity/blob/master/2_figures.pdf*; Supplementary: *https://github.com/f-i/APWP_similarity/blob/master/2Supp.pdf*)

Chapter 3

Finding the Way(s) to Make a Reliable APWP

This chapter mainly describes how to generate paleomagnetic APWPs in different ways, and then the application of the new APW path similarity measuring tool used in finding the best APWP generating method(s)

(This chapter is appended right after the paper draft for Chapter 2; Chapter 3 is also openly accessible from *https://github.com/f-i/making_of_reliable_APWPs*.)

Chapter 4

How Much Data Needed to Make a Reliable APWP

This chapter mainly describes how the mean poles with their original paleopoles at random reduced densities can make a reliable APWP. Further we will see how much data (raw paleopoles) are needed on earth to make a reliable APWP, and how the "bad" paleopoles influence the final result when we have less data. Are we be able to make a final determination of best number of paleopoles in each sliding window in average for moving-averaging out an APWP? (No, different situations for different continents.)

In the past, especially in deep time, the density and quality of paleomagnetic data are lower, compared with younger geological times. Reducing the data density can help see if our methodology is still able to reliably give reasonable results from data aged in deep times.

4.1 Reference Path

The fixed hotspot model and related plate circuit predicted APWPs are used as references. In fact, as mentioned in the last chapter, choosing FHM or MHM does not make much difference at all.

4.2 Extration Fraction

Sub-sampling (extracting part of raw paleopoles) is implemented before moving-averaging with filtering/correcting and weighting at four percentages, 80%, 60%, 40% and 20%, which mean 20, 40, 60 and 80 per cent of raw paleopoles are removed. This means not all sub-samples at, for example, 80% are going to be generating a path from the same number of paleopoles after filtering. In some cases a large number might be removed, in others much less, depending on the properties of the sub-sampled population. This is definitely an additional factor that would affect the difference score.

We can see that the best picking and weighting methods are statistically always better than the worst ones even if only 20 percent of thei 120–0 Ma paleopoles are used to compose the APWPs (Fig. 4.1) for the three continents, North America, India and Australia.

For the worst methods applied onto Indian and Australian data, the equal-weight $\mathcal{CPD}$ surprisingly decreases when the percentage of extracted data decreases (Fig. 4.1). This is because after the data density is reduced the left data are not always enough to cover all the time range of 120–0 Ma but only part, or even though the 120 and 0 Ma mean poles (two ends) exist, the number of intermediate mean poles between 120 Ma and 0 Ma is much less than the APWP from data without reducing density.

4.2.1 Number of Samples

Here because the thousands of times of testing for each percentage of data removal and each picking and weighting method is rather expensive, 30 samples (a rule of thumb; e.g. [10] says "greater than 25 or 30") are obtained. In fact, the 25th percentiles (Q_1),

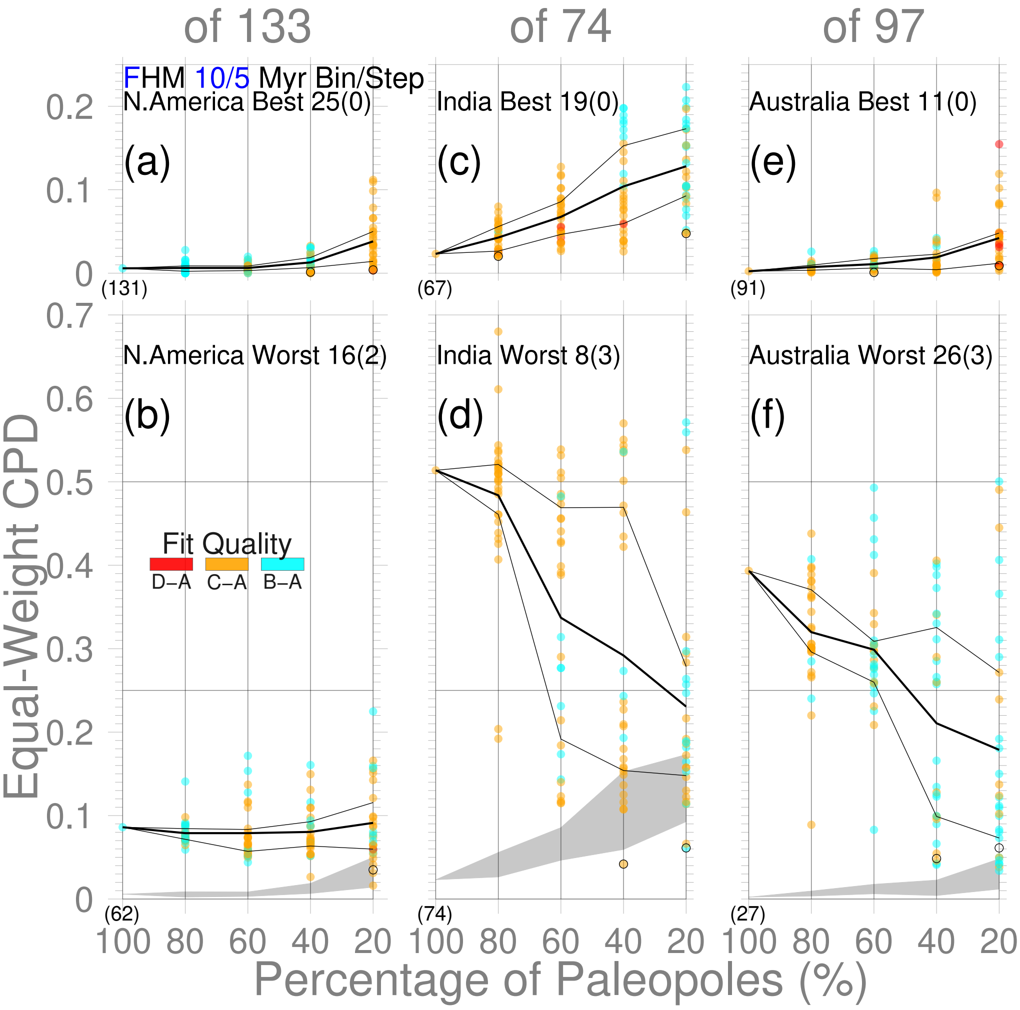


Figure 4.1: Random paleopole samplings (30 times) for the best and worst results for the 10 Myr window and 5 Myr step paleomagnetic APWPs vs FHM & plate circuit predicted APWP. The lower and upper bound lines connect the 1st and 3th quantiles (Q_1 and Q_3) of the 30 samples. The bold line connects their means. The numbers in small parentheses are actual quantity of paleopoles after filtered by the corresponding picking methods for the case with no data removal. The Q_1–Q_3 interquartile range from best method is also shown (shadowed) in the plot of the worst method for clarity. Black rings are the lowest value for each method or the lowest for the 20% case.

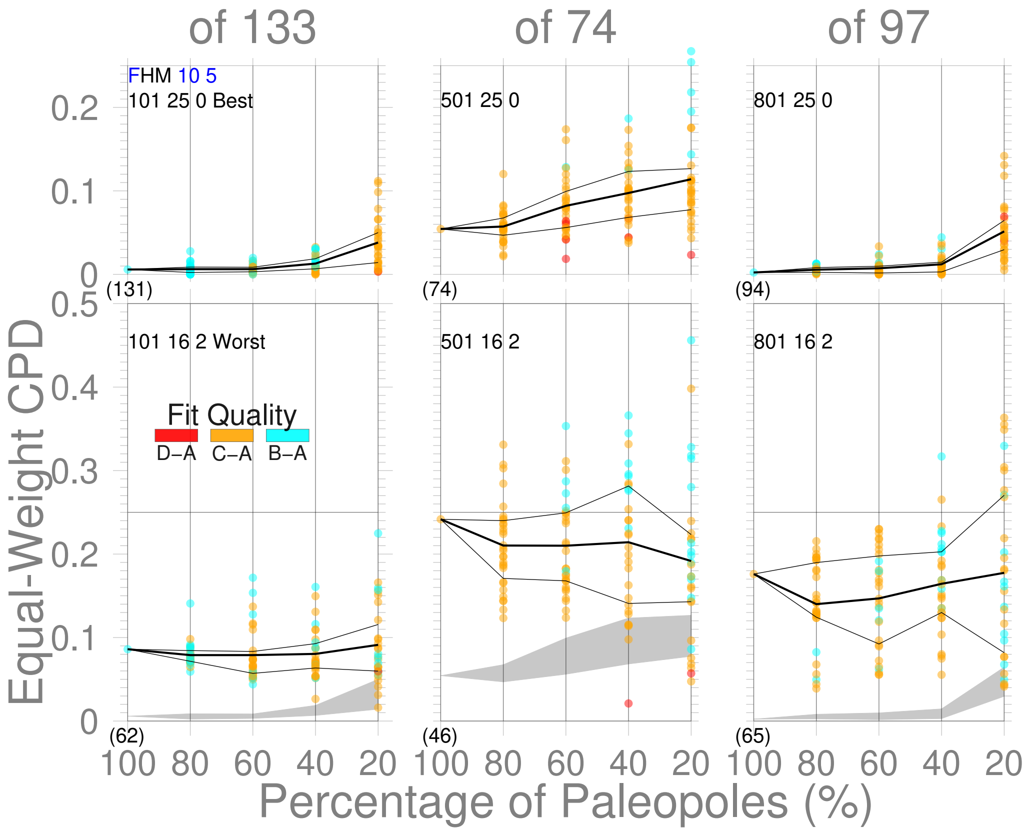


Figure 4.2: Comparisons of results from the best and worst methods for North America (101), also applied on the other two continents (501 and 801). The Q_1–Q_3 interquartile range from Picking No. 25 is also shown (shadowed) in the plot of Picking No. 16 for clarity.

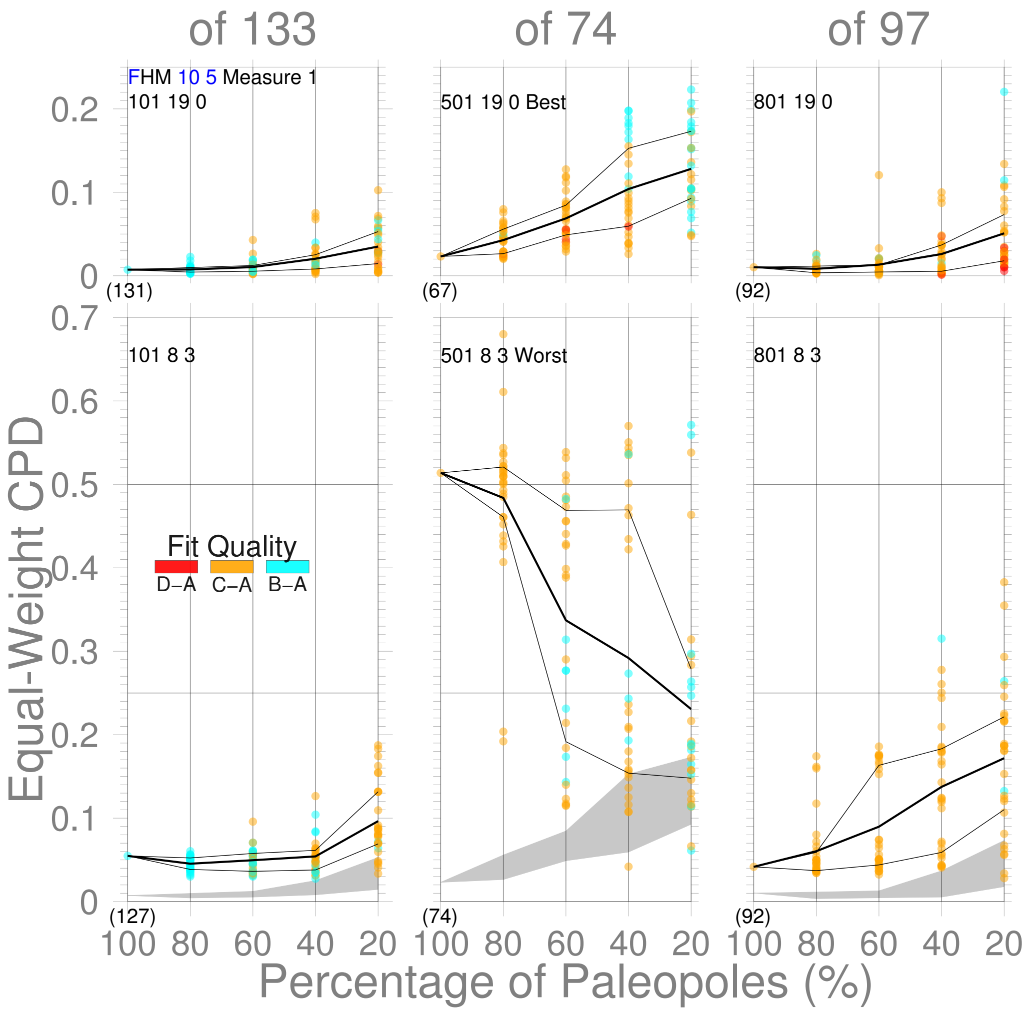


Figure 4.3: Comparisons of results from the best and worst methods for India (501), also applied on the other two continents (101 and 801). The Q_1–Q_3 interquartile range from Picking No. 19 is also shown (shadowed) in the plot of Picking No. 8 for clarity.

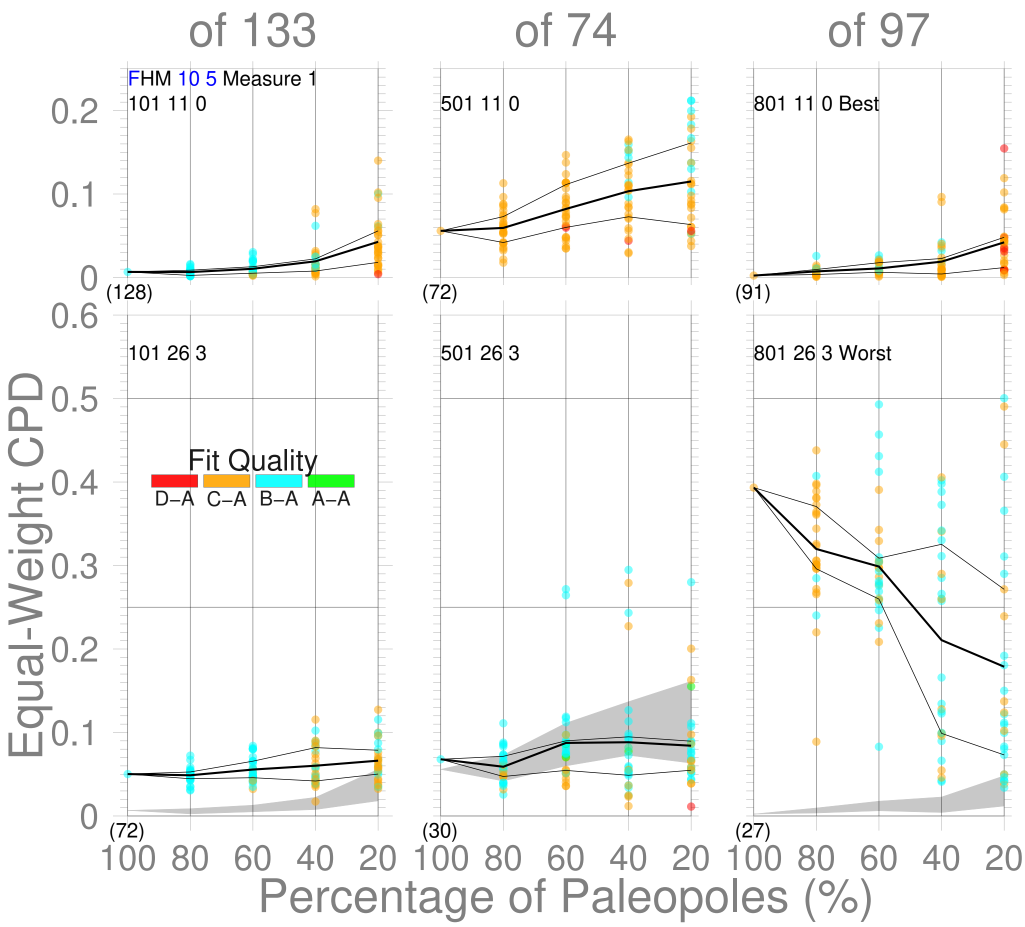


Figure 4.4: Comparisons of results from the best and worst methods for Australia (801), also applied on the other two continents (101 and 501). The Q_1–Q_3 interquartile range from Picking No. 11 is also shown (shadowed) in the plot of Picking No. 26 for clarity.

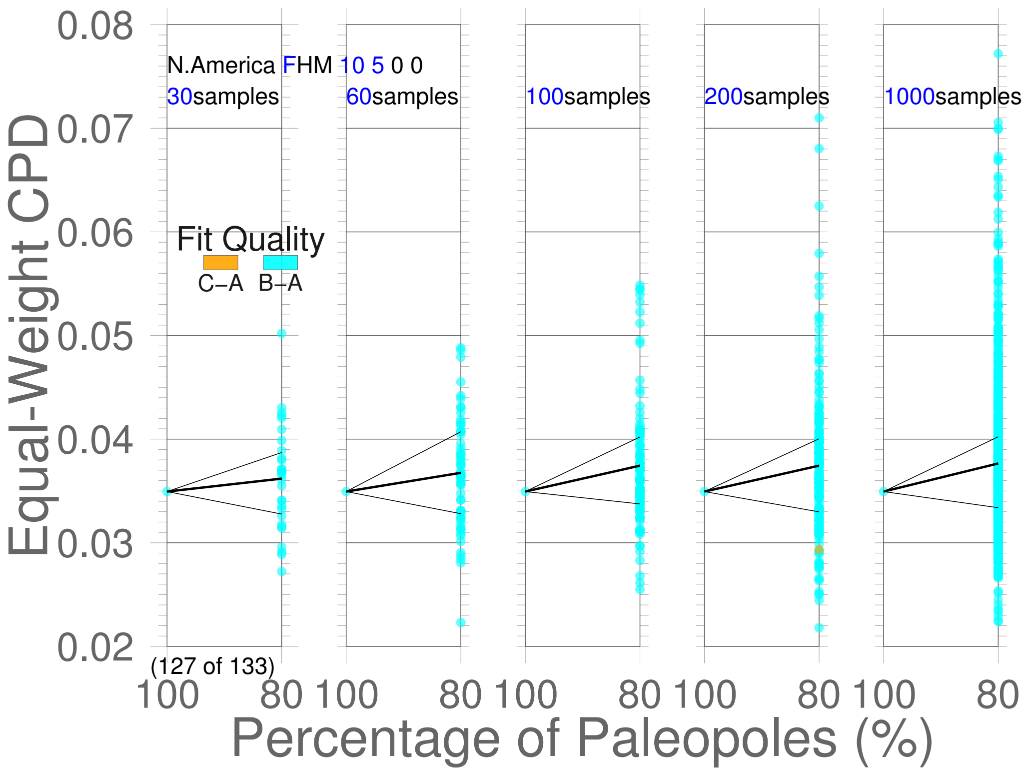


Figure 4.5: Testing differences of results from different numbers of samples. See Fig. 4.1 for more details.

75th percentiles (Q_3) and the means of 30, 60, 100, 200 and 1000 samples are not quite different (Fig. 4.5), although 200 seems a better and relatively cheaper option.

4.2.2 Extreme Value Study: Suggestions on Algorithm, especially on large uncertainties

It is easy for us to think that less paleomagnetic data means poorer similarity between paleomagnetic APWPs and the reference path. However, it is noticeable that even though the data density is tremendously reduced (e.g. by 80%), it seems still possible to have a better similarity for paleomagnetic APWPs and the reference, even better than for the paleomagnetic APWP with all original datasets (e.g. the black rings in Fig. 4.1). For example, for the case (a) (Fig. 4.1), even though 60% of the paleopoles are removed, we still can get a better similarity using the paleomagnetic APWP composed of the left 40% of the paleopoles than the original. Although this 40% data generated paleomagnetic APWP owns the same number of mean poles as the 100% data generated paleomagnetic APWP, the number of paleopoles for each mean pole is actually much less. The main reason why this 40% data generated paleomagnetic APWP is more similar to the reference path is that this APWP's spatial uncertainties (FQ: C-A) are much larger than those (FQ: B-A) of the 100% data generated

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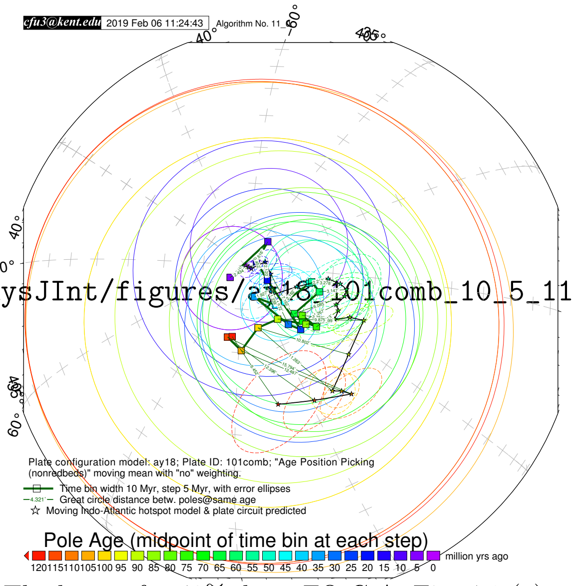

100% data, FQ B-A; Fig. 4.1 (a) The lowest for 40% data, FQ C-A; Fig. 4.1 (a)

Figure 4.6: Comparing the 100% North American 120–0 Ma paleomagnetic data derived result with the best of the only 40% data (giving even better similarity) derived results (the lowest yellow dot in Fig. 4.1 (a)).

paleomagnetic APWP (Fig. 4.6). Even only 20% of the paleopoles could also give a better similarity (the lowest red dot in Fig. 4.1 (a)). Unfortunately, the reason why this 20% data generated paleomagnetic APWP is more similar to the reference path is the same as for the 40% data generated path: extremely large spatial uncertainties (FQ: D-A). So we need to be cautious about the similarity score when we do not have enough paleomagnetic data for making an APWP, which tends to generate large spatial uncertainties for mean poles. The situation is the same for the lowest difference given by the 60% Australian paleomagnetic data (the lowest green dot in Fig. 4.1(e)).

For the case (b) (Fig. 4.1), the main reason why the only 20% data could give better result than the 100% data does is that not only, for example, for the lowest cyan dot the 20% data gives less mean poles, but also a few larger spatial uncertainties appear for this 20% case (Fig. 4.7).

For the case (c) (Fig. 4.1), the reason why the 80% data is able to give better result than the 100% data does is that the 10 Ma mean pole of the 80% data derived path is a bit closer to reference, because both the 10 Ma pole pair in Fig. 4.8 are distinguishable. Although the 80% data derived paleomagnetic APWP (Fig. 4.8b) generally owns relatively larger spatial uncertainties, the related pole pairs are distinguishable for both path pairs in Fig. 4.8.

Still for the case (c) (Fig. 4.1), of the 30 samples for the 20% data, none is able to give better result compared with the 100% data, but the lowest difference value we can get from these 30 samples (20% in Fig. 4.1 (c)) indicates that 20% data is still

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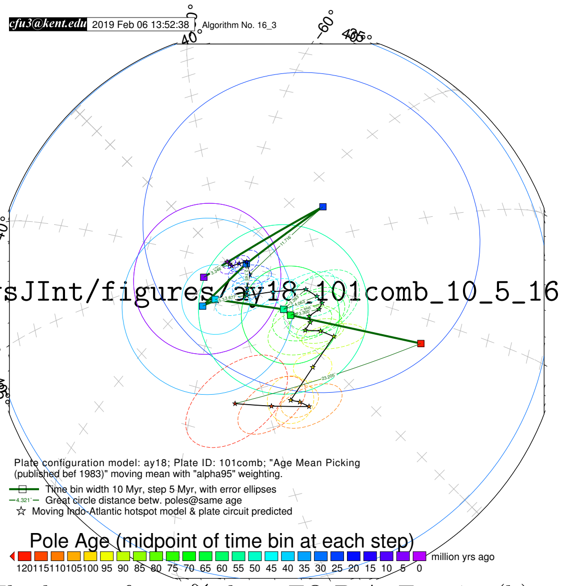
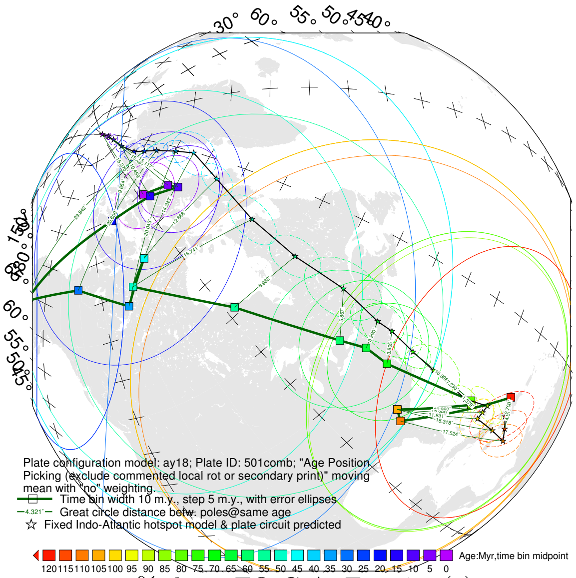
100% data, FQ B-A; Fig. 4.1 (b)

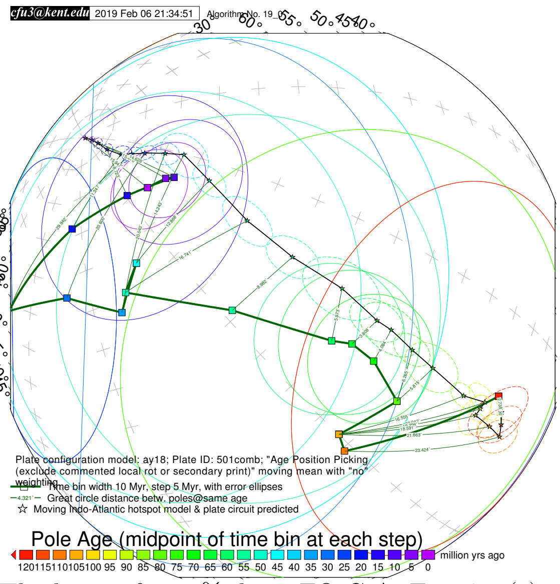


The lowest for 20% data, FQ B-A; Fig. 4.1 (b)

Figure 4.7: Comparing the 100% North American 120–0 Ma paleomagnetic data derived result with the best of the only 20% data (giving even better similarity) derived results (the green dot in Fig. 4.1 (b)).

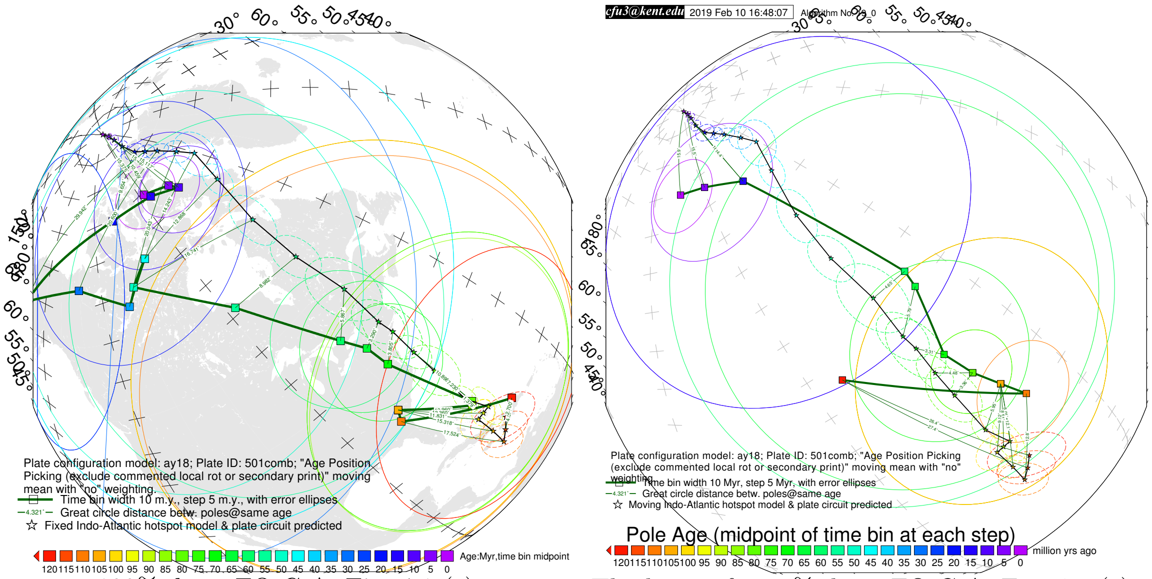


100% data, FQ C-A; Fig. 4.1 (c)



The lowest for 80% data, FQ C-A; Fig. 4.1 (c)

Figure 4.8: Comparing the 100% Indian 120–0 Ma paleomagnetic data derived result with the best of the only 80% data (giving even better similarity) derived results (the green dot in Fig. 4.1 (c)).



100% data, FQ C-A; Fig. 4.1 (c) The lowest for 20% data, FQ C-A; Fig. 4.1 (c)

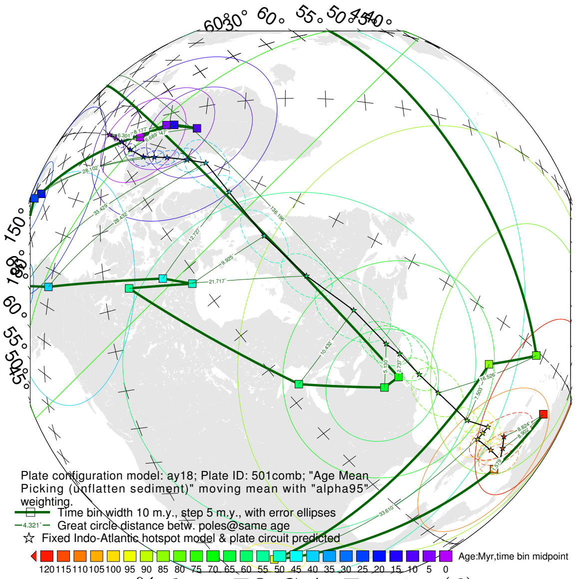
Figure 4.9: Comparing the 100% Indian 120–0 Ma paleomagnetic data derived result with the best of the only 20% data (giving even better similarity) derived results (the dark green dot in Fig. 4.1 (c)).

able to give good (not dramatically different from that 100% data gives) similarity (Fig. 4.9b).

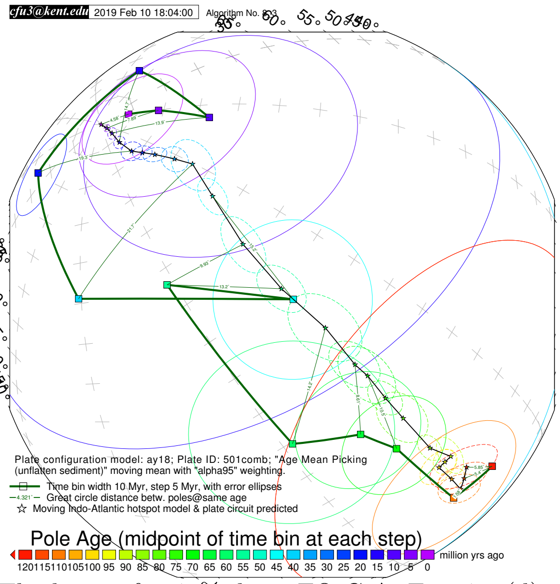
For the case (d) (Fig. 4.1), the reason why the only 40% data could give better result than the 100% data does is that for the green dot (Fig. 4.1 (d)) not only the 40% data gives less mean poles (but two ends 120 Ma and 0 Ma still exist), but also the 40% data does not contain some “bad” paleopoles that are far away from the reference path (Fig. 4.10b). It’s the same for the lowest difference given by the 20% data samples (the dark green dot in Fig. 4.1 (d)).

For the case (e) (Fig. 4.1), although the 20% data derived paleomagnetic paths are not closer to the reference path than the 100% data derived one, the closest one (the dark green dot in Fig. 4.1 (e)) still performs well (Fig. 4.11b). This is mainly because the number of mean poles becomes less when there are only 20% of the paleopoles, especially for 120 Ma and 115 Ma, where the mean poles are far from the reference path for the 100% data (Fig. 4.11a), mean poles are missing for the dark green dot case (Fig. 4.1 (e)). The same situation happens to the green dot case (Fig. 4.1 (f)).

For the case (f) (Fig. 4.1), most of the 20% data derived paleomagnetic paths are closer to the reference path than the 100% data derived one, especially for the dark green dot case in Fig. 4.1 (f) (Fig. 4.12b). This is mainly because the number of mean poles becomes much less when there are only 20% of the paleopoles, especially two end mean poles missing.



100% data, FQ C-A; Fig. 4.1 (d)



The lowest for 40% data, FQ C-A; Fig. 4.1 (d)

Figure 4.10: Comparing the 100% Indian 120–0 Ma paleomagnetic data derived result with the best of the only 40% data (giving even better similarity) derived results (the green dot in Fig. 4.1 (d)).

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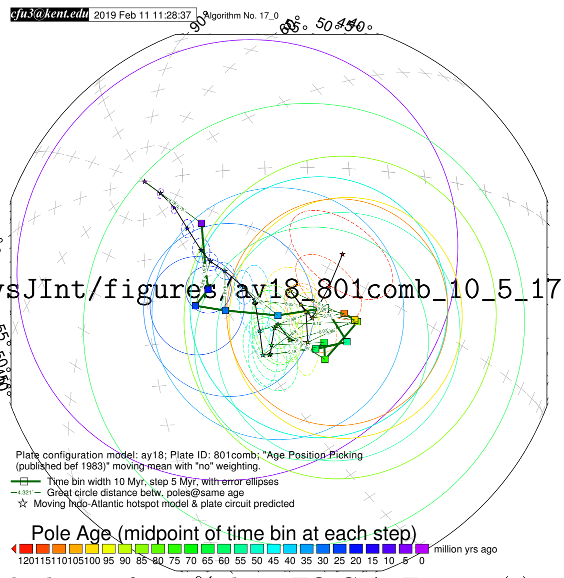

100% data, FQ C-A; Fig. 4.1 (e)

The lowest for 20% data, FQ C-A; Fig. 4.1 (e)

Figure 4.11: Comparing the 100% Australian 120–0 Ma paleomagnetic data derived result with the best of the only 20% data derived results (the dark green dot in Fig. 4.1 (e)).

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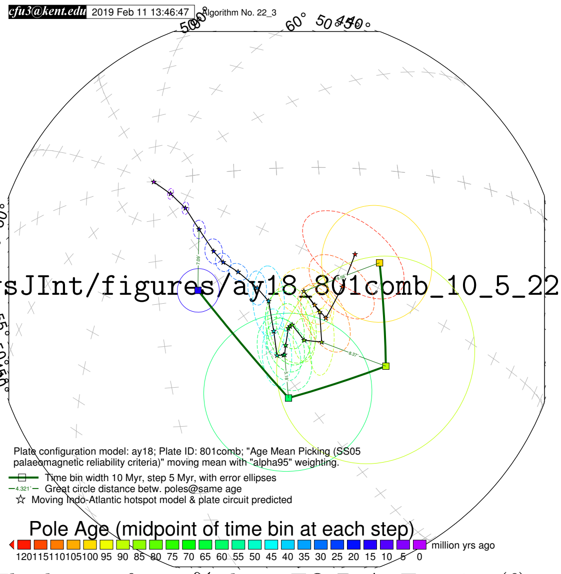

100% data, FQ C-A; Fig. 4.1 (f) The lowest for 20% data, FQ B-A; Fig. 4.1 (f)

Figure 4.12: Comparing the 100% Australian 120–0 Ma paleomagnetic data derived result with the best of the only 20% data derived results (the dark green dot in Fig. 4.1 (f)).

4.3 Are the rules we obtained in the last chapter are still true for less data?

First, that if APP is still better, and weighting is still not affecting for less dense paleomagnetic data, is needed to be tested.

From the perspective of checking if the Q_1–Q_3 intervals overlap, APP is indeed still better than AMP and weighting is indeed still not affecting for more than 15 paleopoles making a 10/5 Myr bin/step APWP (ideally composed of 25 mean poles for 120–0 Ma). For the 20% Indian data case, which contains not more than 15 paleopoles making a 120–0 Ma APWP, there is overlapping between APP's Mean–Q_3 interval and AMP's Q_1–Mean interval for weighted cases (i.e. for Weighting No. 1–5). Even so, APP's means are still lower than AMP's for this no-more-than-15-paleopoles case (Fig. 4.13). So here is the question: is 15 the threshold?

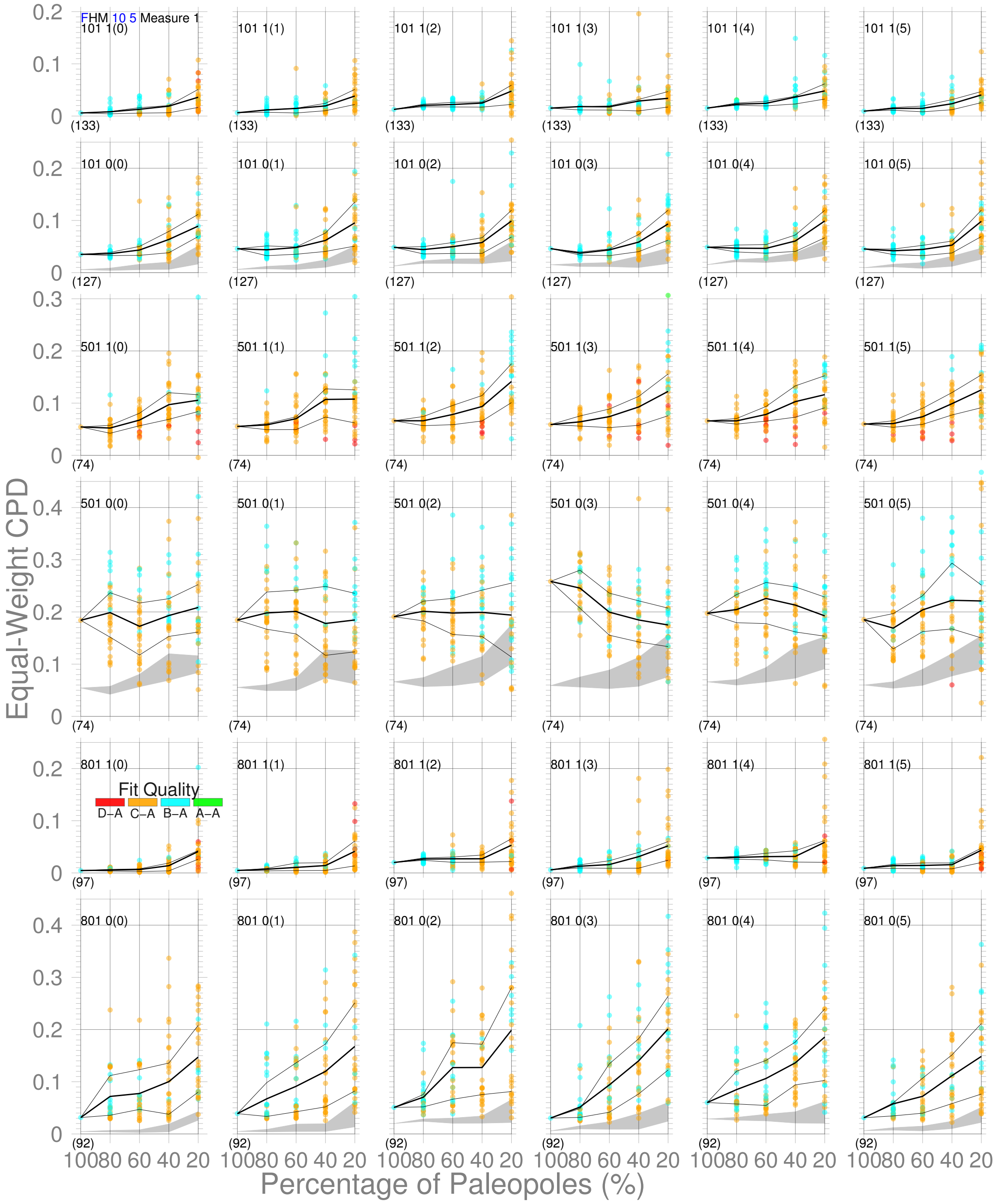

Figure 4.13: Comparisons of results from Picking No. 1 (APP) and Picking No. 0 (AMP) with all the listed weighting methods for three continents. The Q_1–Q_3 interquartile range from Picking No. 1 is also shown (shadowed) in the plot of Picking No. 0 for clarity.

Chapter 5

Conclusions

3–4 pages of summary of results, significance and future directions/work.

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