Methods for Producing a Reliable APWP

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SUMMARY

First, new picking/weighting methods developed here and previously published picking/weighting methods are compiled together to generate 168 different paleomagnetic APWPs. Then, the APWP similarity measuring tool is used to find which method$s$ is(are) good or bad.

Key words: Moving Average – Weighting – APWP – Paleomagnetism.

1 INTRODUCTION

APWPs are generated by combining paleomagnetic poles for a particular rigid block over the desired age range to produce a smoothed path. See the Supplementary Material for some examples how the pole datasets are constrained first.

1.1 Not All Data Are Created Equal

However, uncertainties in the age and location of paleomagnetic poles can vary greatly for different poles.

1.1.1 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 paleomagnetic data 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.

1.1.2 Position Error

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

1.1.3 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. Sometimes, this is the case. Sometimes we have further separated poles with close ages.

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

`Lithology`

For poor consistency of data, 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 (Tauxe et al. 2018). 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.

`Local Rotations`

Local deformation between two paleomagnetic localities invalidates the rigid plate assumption and could lead to inconsistent VGP directions. So if discordance is due to local deformation, and we would ideally want to exclude such poles from our APWP calculation.

`Other Factors`

In most cases, mean pole age (centre of age error) has just been binned. If any of the poles have large age errors, they could be different ages from each other and sample entirely different parts of

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the APWP. Conversely, if any of the poles 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.

1.1.4   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. 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 North American Craton (NAC), but few poles exist for Greenland and Arabia. Based on mean age (mean of lower and upper magnetic ages), for 120–0 Ma, the **Global Paleomagnetic Database** (GPMDB) version 4.6b (Pisarevsky 2005) has more than 130 poles for NAC, but only 17 for Greenland and 24 for Arabia.

1.1.5   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 paleomagnetic poles are created equal, which leads to an important question: how to best combine poles of varying quality into a coherent and accurate APWP?

1.2   Existing Solutions and General Issues

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 (van der Voo 1990) and the BC02 selection criteria provided by Besse & Courtillot (2002). Briefly, the V90 criteria for paleomagnetic results includes seven criteria: (1) Well determined age; (2) At least 25 samples with Fisher (Fisher 1953) precision κ greater than 10 and $\alpha 95$ 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 (Torsvik et al. 1992). The total criteria satisfied (0–7) is then used as a measure of a paleomagnetic result's overall reliability, which is known as Q (quality) factor (Torsvik et al. 1992). Q factor is indeed a very straightforward way to get a quantitalized reliability score. Also it then can be conveniently used in the later calculations of APWPs (Torsvik et al. 1992). But at the same time this is a fairly basic filter that lumps together criteria that may not be equally important. 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 $\alpha 95$ less than $10°$ in the Cenozoic and $15°$ in the Mesozoic. B02 is also straightforward and convenient to use, but some useful data may be filtered out and wasted especially for a period where there are only limited number of data. In addition, there has been

limited study of how effective these marking/filtering 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.

Above all, there haven't been any real attempts to study how APWP fits may be improved by filtering/weighting data. This paper is presented to address these issues.

2   METHODS

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. After about 170 Ma, multiple data sources can help constrain plate motions in more accurate ways. One of the most developed and studied plate kinematics models is the Fixed Hotspot Model (FHM) (Müller et al. 1993; Müller et al. 1999), which assumes the Atlantic and Indian hotspots are relatively fixed. Such a model like the Fixed Hotspot can predict APWPs for main continents, e.g. the North America.

2.1   Reference Path: The Hotspot Model Predicted

The oldest pole that can be predicted from the FHM is about 120 Ma. The North American 120–0 Ma APWP predicted from this rotation model and latest published spreading ridge rotations (collected data will be shared as a supplementary material) will be taken as a reference path (Fig. 1), which will be compared with paleomagnetic APWPs for the same plate or continent.

2.2   120–0 Ma North American Paleomagnetic APWP

The GPMDB 4.6b (Pisarevsky 2005), data source used here, includes 9514 paleopoles for ages of 3,500 Ma to the present published from 1925 to 2016. A polygon can be drawn around a set of data, whose sampling sites we believe belong to a specific plate or rigid block. Then the *Spatial Join* technique (Jacox & Samet 2007) helps join attributes from the polygon to the paleomagnetic data based on the spatial relationship allowing data within this polygon to be extracted from the whole raw large dataset without splitting a subset just for a specific plate. That allows us to quickly select subsets of the database based on geographic constraints just as easily as for age. Of course, the boundary of this polygon must be reasonably along a tectonic boundary (see the details about data filtering for North America in the Supplementary Material). The temporal distribution of North American 120–0 Ma poles is shown in Fig. 4.

2.3   Picking Data for A Certain Time Window

2.3.1   Moving Average

The moving average method, also called "running mean" or "moving window" (Torsvik et al. 2008) method, calculates the average of values between a certain data (age in our case) range; the average is then recalculated as the limits of the bin are repeatedly incremented upwards. In addition to the traditional moving windows averaging algorithm, a newly developed moving average method is also used, referred to here as the "Age Position Picking (APP)" method. The difference of this moving average method from the one built in GMAP (Torsvik & Smethurst 1999; Torsvik et al. 2008) is that the whole magnetic age range is taken into account in each
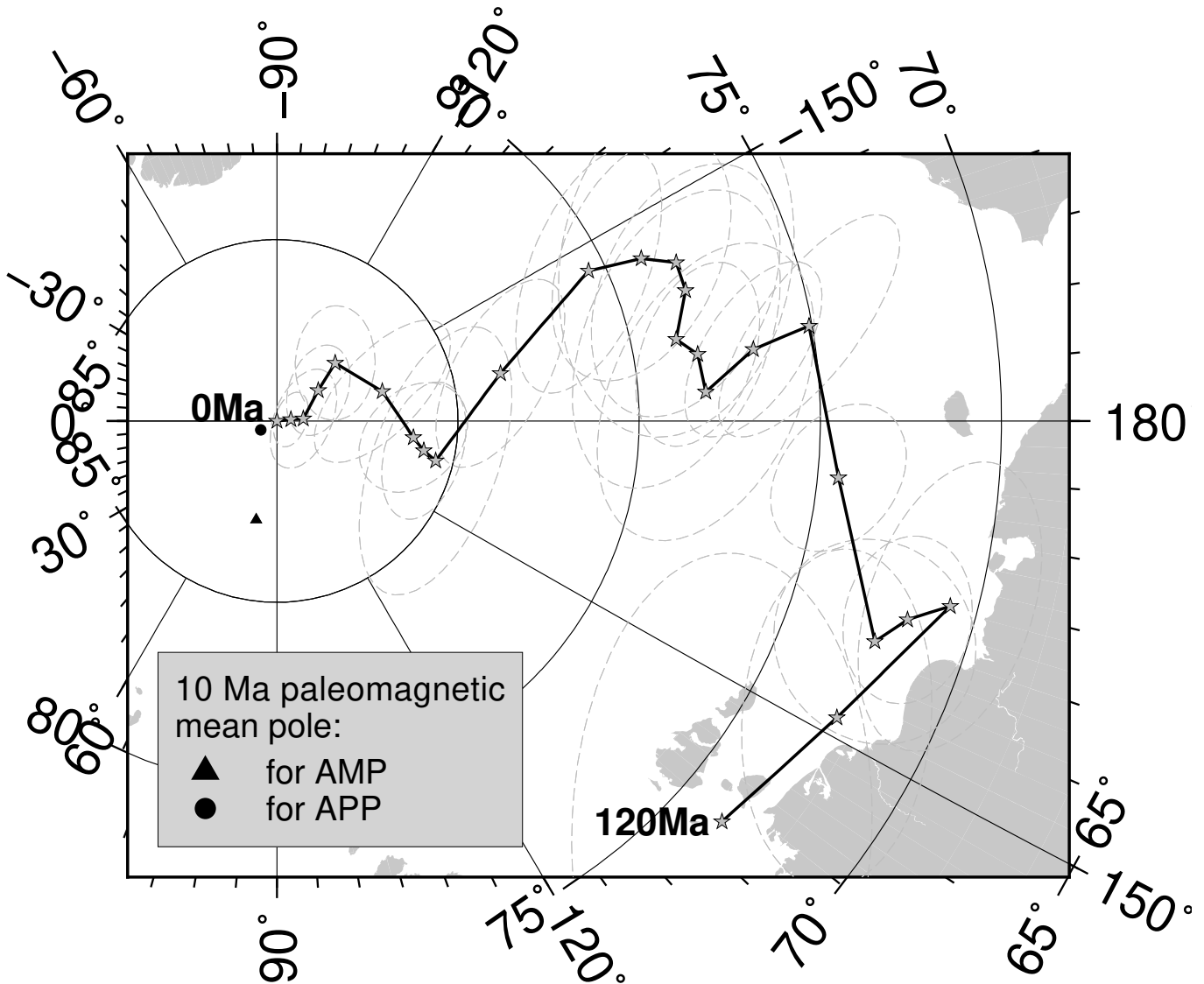
Figure 1. FHM predicted 120–0 Ma APWP for NAC through the North America–Nubia–Mantle plate circuit. Its age step is 5 Myr.

window, while GMAP only considers the mid-point of the low and high magnetic age of each pole, an algorithm referred to as the "Age Mean Picking (AMP)" method.

Normally each VGP in the paleomagnetic database is treated as a point with an age that is the mid-point between the upper and lower age limits, i.e. AMP, but this is problematic for paleomagnetic data with large age ranges (especially if they turn out to be primary magnetization that should plot at old end of age range). We are trying a method, APP, that includes a VGP in the moving average bin if any part of its specified age range falls within that bin. If, for example, we have a pole which is constrained to within 10 and 20 Ma of age, and we have a 2 Myr moving window with a 1 Myr age step, then it shouldn't just be in the 14–16 Ma bin (for the mid-point age of 15 Ma)—it should be in the 9–11,10–12,11–13,12–14 … 17–19,18–20, and 19–21 Ma bins. So the average poles are produced from each bin, and each original pole is represented over its entire possible acquisition age. Fig. 7 shows an example of moving average with a 10 Myr window and a 5 Myr step. So, for example, for the window of 15 Ma to 5 Ma (the light blue bin in Fig. 7), the AMP method calculates the Fisher mean pole of only 5 poles,

while the APP method calculates the mean pole of 9 poles. From comparison of mean poles of the picked poles for the light blue age window with the two different algorithms (the 10 Ma mean poles in Fig. 1), the mean pole from the APP method is closer to the 10 Ma pole in the FHM predicted path.

2.3.1.1 Picking The 28 picking methods include AMP, APP and also those with filtering or corrections implemented onto the two (Table. 1).

Filtering through $\alpha95$ and Age Range For this specific filter, the poles are picked out through setting $\alpha95$ of $\leq\ 15°$ and age uncertainty of ≤ 20 Myr.

Filtering Out Non-igneous Derived Poles With this filter, the poles are mainly or only from igneous rocks with extrusive or intrusive type.

Filtering Out Igneous Unrelated Poles With this filter, the poles are from rocks that contain extrusive or intrusive igneous
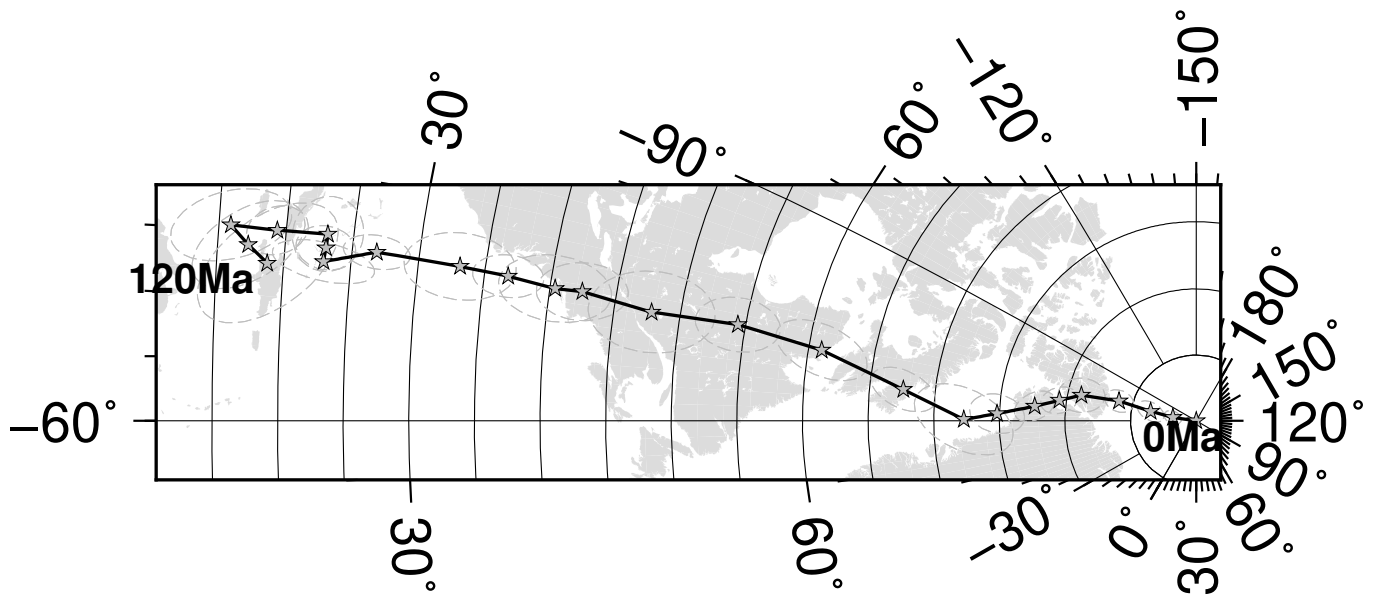
Figure 2. FHM predicted 120–0 Ma APWP for India through the India–Somalia–Nubia–Mantle plate circuit. Its age step is 5 Myr.
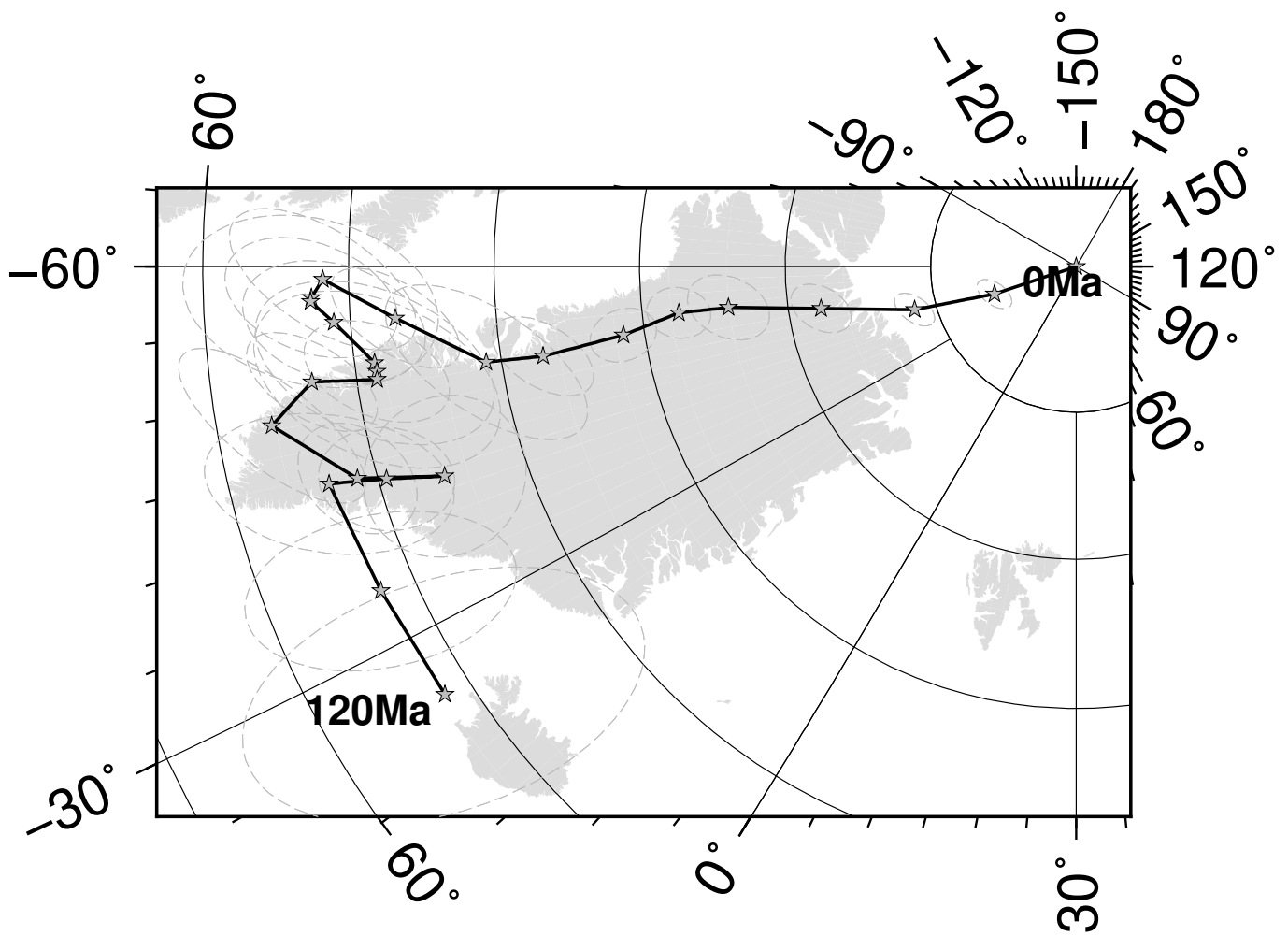
Figure 3. FHM predicted 120–0 Ma APWP for Australia through the Australia–East Antarctica–Somalia–Nubia–Mantle plate circuit. Its age step is 5 Myr.
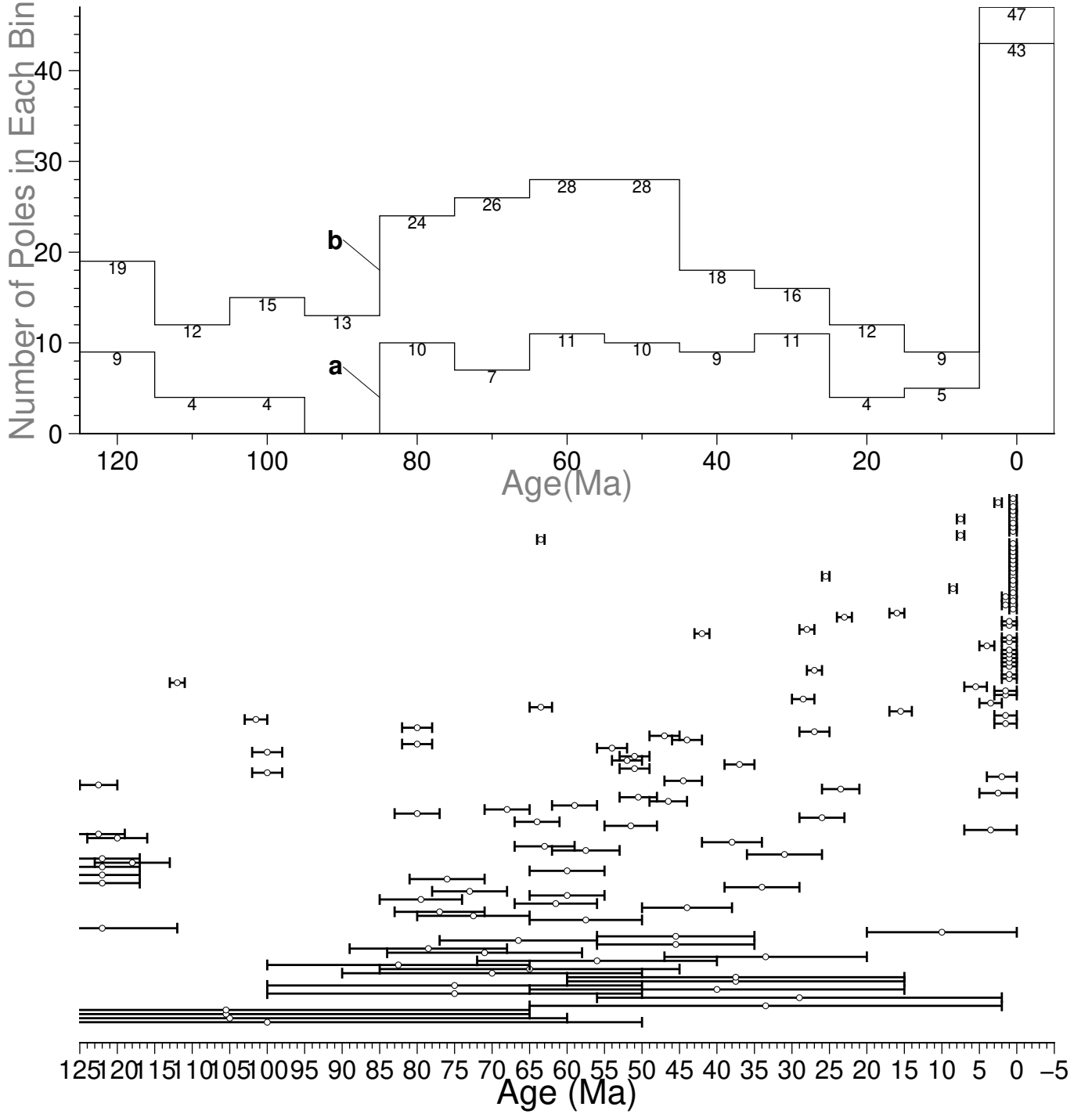
Figure 4. Temporal distribution of 120–0 Ma NAC (101) paleomagnetic poles. For distribution a, each bin (spanning 10 Myr here) only counts in the midpoints of pole error bars; For distribution b, as long as the bar intersects with the bin, it is counted in.

type. In other words, the rock type could be mainly sedimentary or metamorphic.

Inclination Shallowing and Unflattening   To test if unflattening possible inclination shallowing in sedimentary rocks can improve the APWP fitting outcomes, the flattening function (King 1955) $\tan I_o = f \tan I_f$ is used to unflatten assumed existing inclination shallowing in sedimentary-based or redbeds-based paleomagnetic data (No 5 and 7 in Table. 1), where I_o is the observed

inclination, I_f is the unflattened inclination, and f is the flattening factor (or shallowing coefficient) ranging from unity (no flattening) to 0 (completely flattened). Here $f = 0.6$ is used in our calculations, according to the previous experience (Torsvik et al. 2012).

Filtering Out Poles Related to Red-beds   Bias toward shallow inclinations is also observed in paleomagnetic data derived from red-beds (Tauxe & Kent 2004). For this filter, the poles derived from red-beds are simply removed.
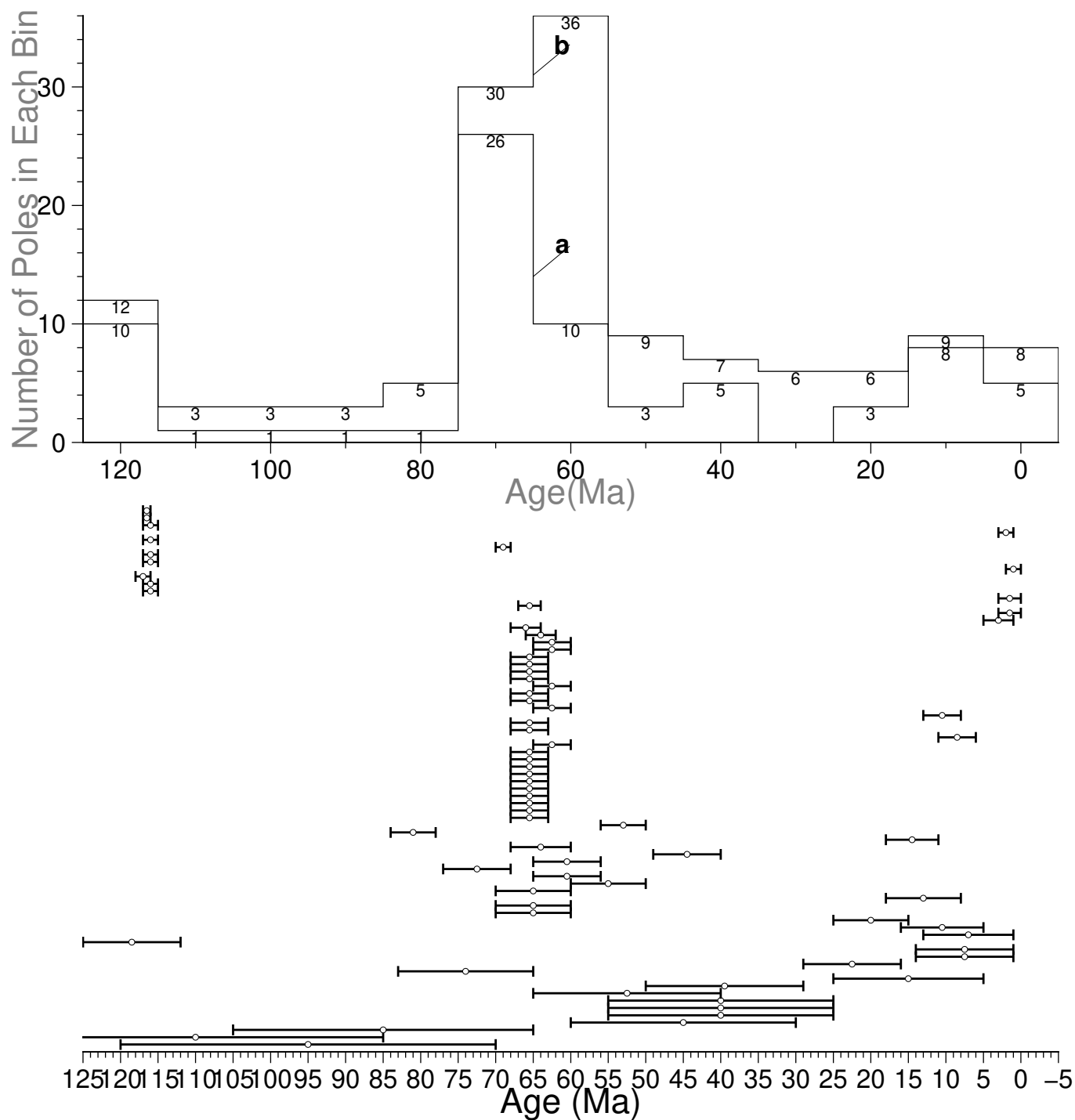
Figure 5. Temporal distribution of 120–0 Ma Indian (501) paleomagnetic poles. For distribution a, each bin (spanning 10 Myr here) only counts in the midpoints of pole error bars; For distribution b, as long as the bar intersects with the bin, it is counted in.

Filtering Out Poles Published Earlier or Later   It is also worthy to see if recently published data is able to produce a more reliable APWP than relatively older data. Here 1983 is chosen as the division, because the mean of the data publication years is about 1983.

Filtering Out Poles Influenced by Local Rotations or Secondary Print   Some publications of paleomagnetic data suggest the data has probably been affected by local rotations or secondary overprints. So for this filter, this type of data are removed.

Filtering Out Poles Influenced by Local Rotations or Correcting Them if Suggested   Some publications suggest the data has been through local rotation and propose a solution of correction. With this filter, if there is a correction suggestion, the data is corrected; if no, the data is simply removed.
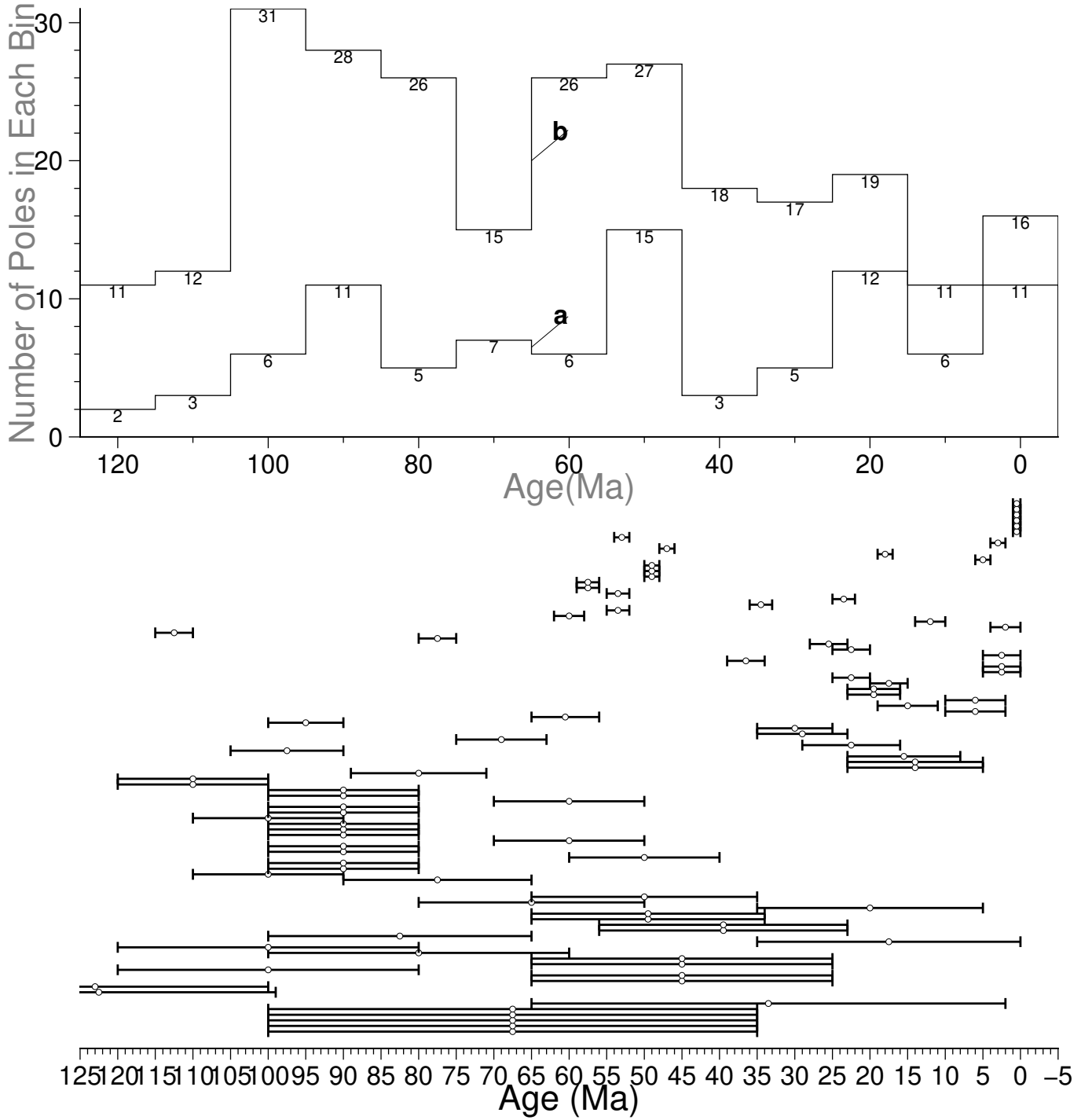
Figure 6. Temporal distribution of 120–0 Ma Australian (801) paleomagnetic poles. For distribution a, each bin (spanning 10 Myr here) only counts in the midpoints of pole error bars; For distribution b, as long as the bar intersects with the bin, it is counted in.

Filtering Using SS05 Liability Criteria SS05 (Schettino & Scotese 2005) provided their criteria of picking paleomagnetic data for producing their APWPs. This filter is reproducing their criteria by setting $\alpha 95$ of $\leq 15°$, age uncertainty of ≤ 40 Myr, sampling sites' quantity of ≥ 4, samples' quantity of at least 4 times of the sites, and laboratory analytical procedure code of at least 2.

Filtering Out Superseded Data In this filter, those superseded data already included in other newer results are excluded.

2.3.1.2 Weighting Because all data is not created equal, we want to calculate a weighted mean pole for a time interval with 'better' (more likely to be reliable) poles counting more than 'worse'. For example, a pole with small $\alpha 95$ and very well constrained age is more likely to reflect APWP position at the selected age point than a pole with large $\alpha 95$ and very broad age range. There are many potential ways to weight this data set which can obviously greatly influence the final result, and we want to test this.

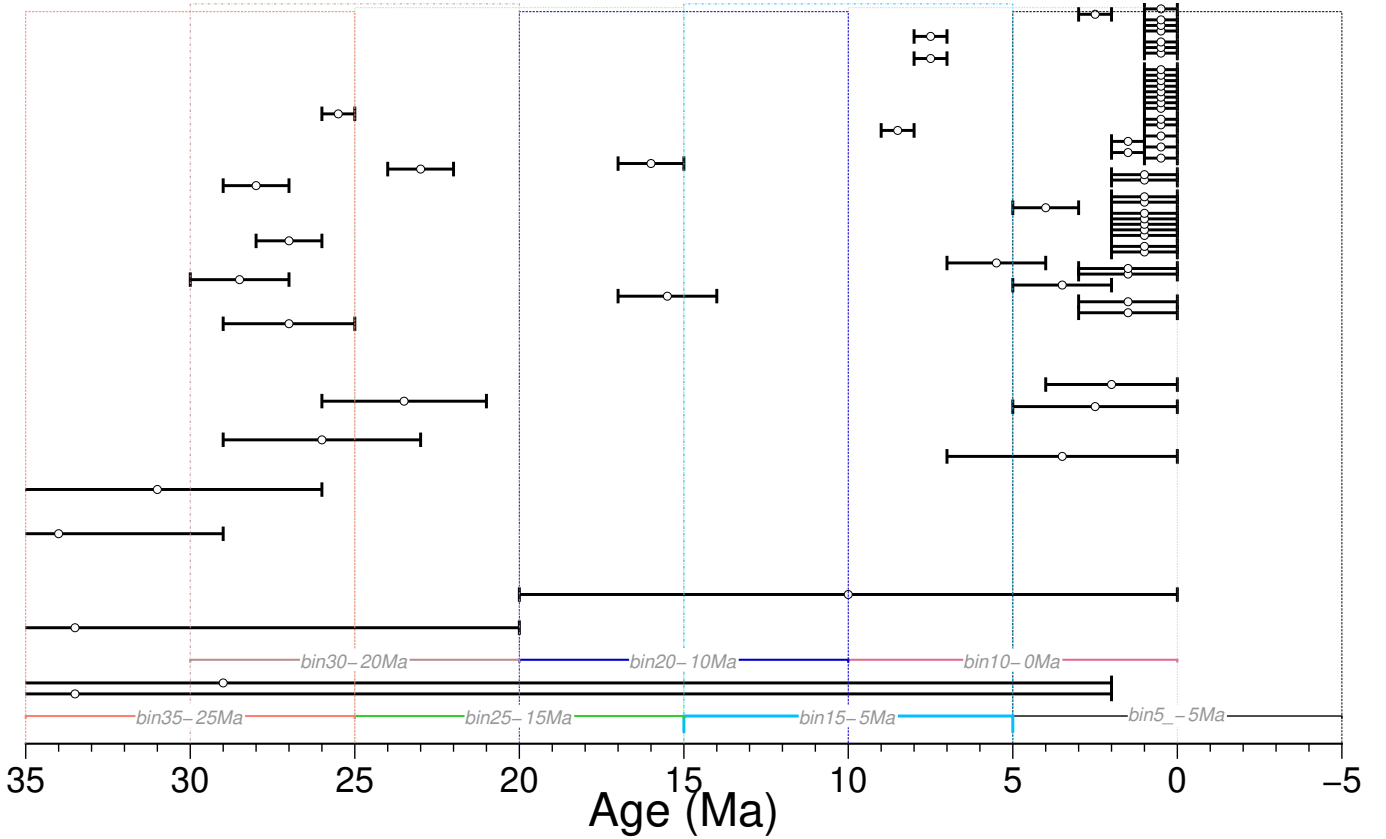Six weighting algorithms (Table. 2) have currently been devel-

Figure 7. An example of 10 Myr moving window and 5 Myr step in the moving average method, based on poles of the NAC. Every age window has a different color. Red points are the midpoints of low and high magnetic ages. The vertical axis has no specific meaning here.

oped or reproduced according to published work to give different weights to data with different qualities.

In order to average errors in orientation of the samples and scatter caused by secular variation, a "sufficient" number of individually oriented samples (observations) from "enough" sites must be satisfied (Tauxe et al. 2018; van der Voo 1990; Besse & Courtillot 2002). So for the "Numbers of sites (B), Observations (N)" weighting (No 1 in Table. 2), larger B and N mean stronger weighting. Through knowing the pattern of all B and N in the database, the proposed solutions are as follows. If both B and N are more than 1, weight=$(1-\frac{1}{B})*(1-\frac{1}{N})$. There are data in GPMDB with only the number of sampling sites (at least greater than 1) given, but no number of samples or only one sample given, so for this case, if B>1 and N $\leq$ 1, weight=$(1-\frac{1}{B})*0.5$. If only the number of samples (at least greater than 1) is given, and the number of sampling sites is missing or only one, i.e. B$\leq$ 1 and N>1, weight=$(1-\frac{1}{N})*0.5$. If B $\leq$ 1 and N $\leq$ 1 (there are only 23 datasets for the whole GP-MDB 4.6b, including 18 with both B and N informations missing), weight=0.2.

As for the "Age uncertainty" weighting (No 2 in Table. 2), a well-constrained age should be known to within a half of a geological period (e.g., Quaternary, Neogene, Triassic) for Phanerozoic data (van der Voo 1990; Tauxe et al. 2018). Generally, this work follows this principle. However, for the periods of Paleogene, Cretaceous, and Jurassic, their halves are all beyond a time span of at least 20 Myr, which is relatively large for these relatively young geologic periods. So for these three periods, a tighter age constraint is set using age uncertainties of $\leq$ 15 Myr. So, for example, for NAC's Neogene (23.03–2.58 Ma according to GSA Geologic Time

Scale) data, if age uncertainty (the high magnetic age − the low magnetic age) $\leq$ 10.225 (from 0.5* (23.03−2.58)) Myr, its weight = 1; if age uncertainty > 10.225 Myr, its weight = 10.225 / (high magnetic age − low magnetic age). For the periods spanning Jurassic to Paleogene, if age uncertainty $\leq$ 15 Myr, it get its weight of 1; if age uncertainty > 15 Myr, a weight of 15 / (high magnetic age − low magnetic age) is assigned instead.

For the "$\alpha 95$" weighting (No 3 in Table. 2), smaller radius of circle of 95% confidence about mean remanence direction means less error, so should get larger weight. Here, weight is from a Gaussian distribution centered on 0 with standard deviation of 10, i.e., when $\alpha 95 \leq 10$, weight=1; when $\alpha 95 > 10$, weight<1. It is also worthwhile to mention that if samples, where two poles are derived, are exactly from the same place and same rock, and one $\alpha 95$ is completely inside the other $\alpha 95$, a zero is assigned as the weight of the data with the larger $\alpha 95$. Here, the same procedure can be applied on A95 (circle of 95% confidence about mean pole) instead of $\alpha 95$.

For the "Age error Position to window" weighting (No 4 in Table. 2), if window intersects with young/old end of age bracket or whole window overlaps with a part of age range, weight= (overlapping part) / (age range width); if whole age range is within window, weight= (window width) / (age range width) (note that when weight > 1, it is set back to 1).

The "Age error Position to window, and $\alpha 95$" weighting (No 5 in Table. 2), is a combination of No 3 and No 4.

Table 1. List of all Picking (i.e. Binning) algorithms developed in this paper. AMP, Age Mean Picking (See Section "Moving Average"); APP, Age Position Picking.

No.	Picking Algorithm
0	AMP
1	APP
2	AMP ("α95/Age range" no more than "15/20")
3	APP ("α95/Age range" no more than "15/20")
4	AMP (mainly or only igneous)
5	APP (mainly or only igneous)
6	AMP (contain igneous and not necessarily mainly)
7	APP (contain igneous and not necessarily mainly)
8	AMP (unflatten sedimentary)
9	APP (unflatten sedimentary)
10	AMP (nonredbeds)
11	APP (nonredbeds)
12	AMP (unflatten redbeds)
13	APP (unflatten redbeds)
14	AMP (published after 1983)
15	APP (published after 1983)
16	AMP (published before 1983)
17	APP (published before 1983)
18	AMP (exclude commented local rot or secondary print)
19	APP (exclude commented local rot or secondary print)
20	AMP (exclude local rot or correct it if suggested)
21	APP (exclude local rot or correct it if suggested)
22	AMP (filtered using SS05 palaeomagnetic reliability criteria)
23	APP (filtered using SS05 palaeomagnetic reliability criteria)
24	AMP (exclude superseded data already included in other results)
25	APP (exclude superseded data already included in other results)
26	AMP (comb of 22 and 24)
27	APP (comb of 23 and 25)

Notes: SS05, (Schettino & Scotese 2005)

3 RESULTS AND DISCUSSIONS

(i) Only from the results with both space and shape tested of North American (101) paleomagnetic APWPs comparing with its projected APWP from FHM through the North America–Nubia–Mantle plate circuit (Fig. 8), we can see generally (1) the APP methods (adding data to a time window with overlapping age selection criterion) produce better similarities than the AMP methods; (2) the picking methods (Table. 1) influence the similarity more than the weighting methods (Table. 2); (3) weighting also seems to make things worse (for many of the methods, no weighting is the best performer); (4) the groups of picking-method-no 25 (APP with those superseded studies filtered out), 1 (APP) and 15 (APP with older-than-1983 studies excluded) (Table. 1) are the best, while the groups of picking-method-no 16 (AMP with only earlier-than-1983 studies), 2 (AMP with "α95/Age range" no more than "15°/20 Myr"), 22 (AMP with SS05 palaeomagnetic reliability criteria) and 26 (AMP with SS05 palaeomagnetic reliability cri-

Table 2. List of all weighting algorithms developed in this paper.

No.	Weighting Algorithm
0	None
1	Numbers of sites (B), Observations (N)
2	Age uncertainty
3	α95
4	Age error Position to bin
5	comb of 3 and 4

teria and also excluding superseded data already included in other results) (Table. 1) are the worst.

(ii) Only from the results with both space and shape tested (Fig. 8, Fig. 10 and Fig. 12), for both North America (101) and Australia (801), the groups of picking-method-no 25 and 1 (Table. 1) are the best; however, for India (501), picking-method-no 26 is the best; interestingly, picking-method-no 26 is one of the worst for both North America (101) and Australia (801).

(iii) For both North America (101) and Australia (801), both the results with space and shape tested (Fig. 8 and Fig. 12) and the results with only space tested (Fig. 9 and Fig. 13) show that the groups of picking-method-no 25 and 1 (Table. 1) are the best.

(iv) For both North America (101) and India (501), both the results with space and shape tested (Fig. 8 and Fig. 10) and the results with only space tested (Fig. 9 and Fig. 11) show that more recent studies give better results than older studies. However, this is not true for Australia (801) (Fig. 12 and Fig. 13).

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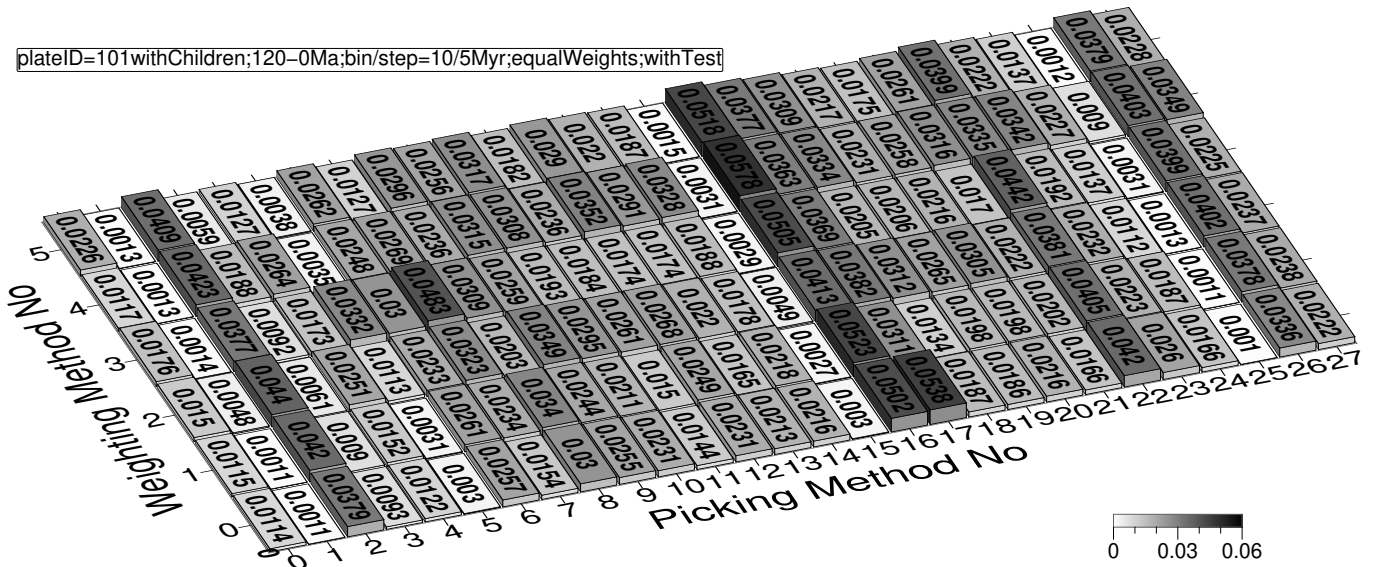
Figure 8. Difference values with test between North American (101) paleomagnetic APWPs and its predicted APWP from FHM and related plate circuit.

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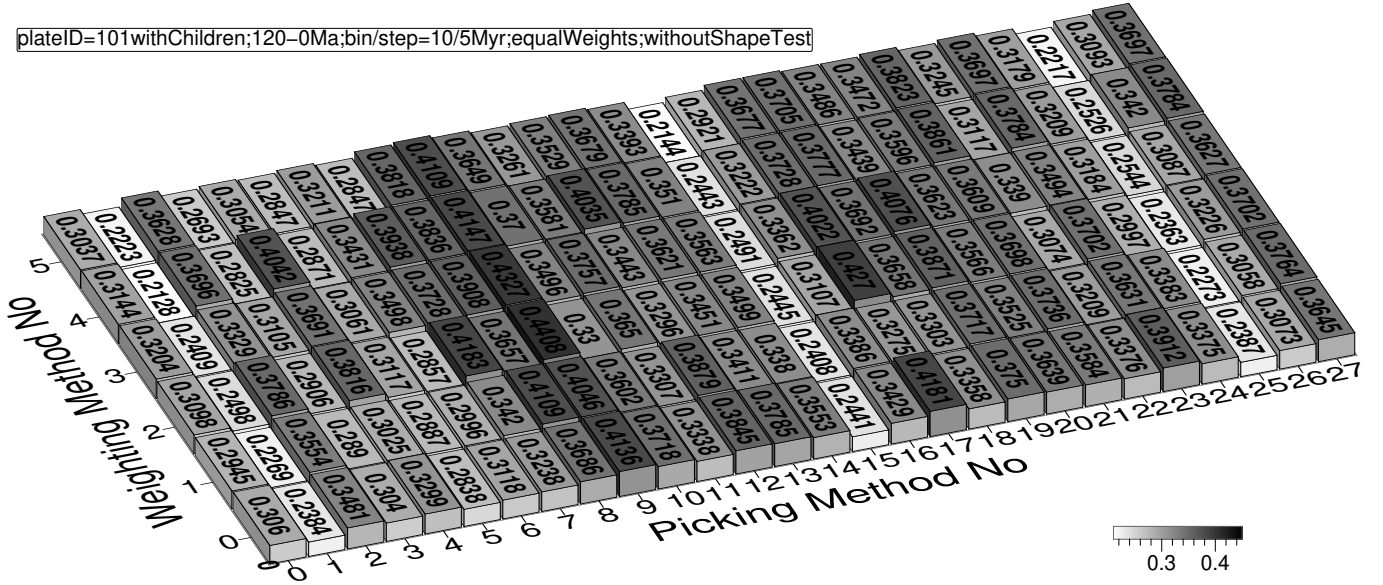
Figure 9. Difference values without shape test between North American (101) paleomagnetic APWPs and its predicted APWP from FHM and related plate circuit.
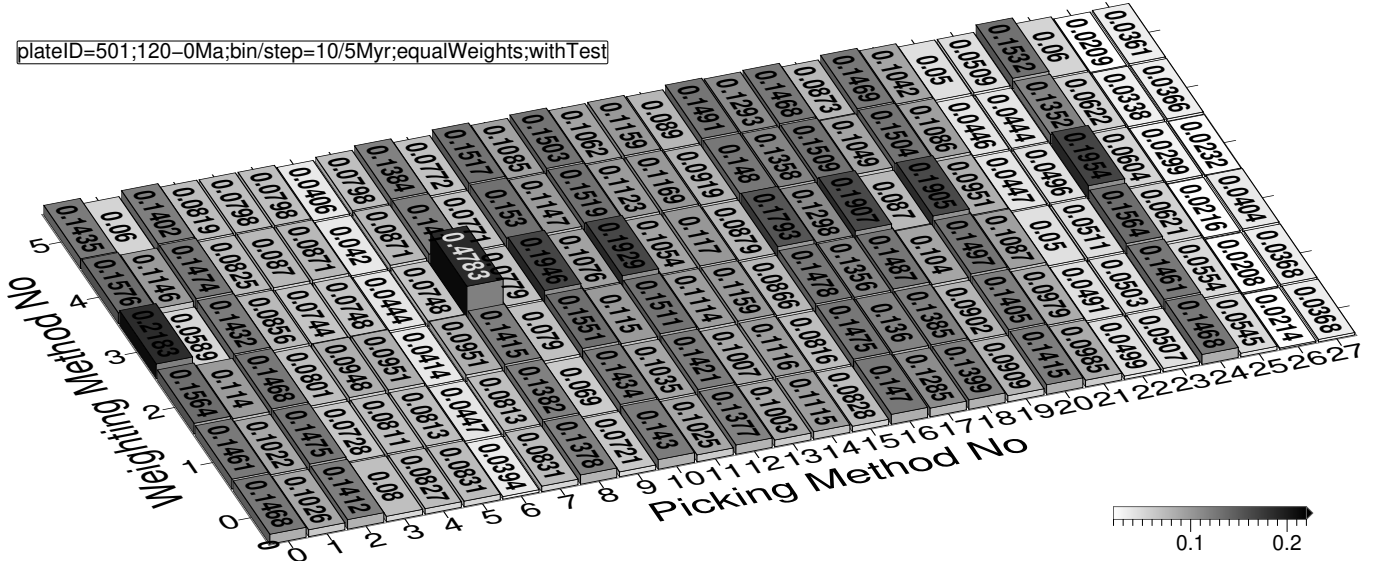

Figure 10. Difference values with test between Indian (501) paleomagnetic APWPs and its predicted APWP from FHM and related plate circuit.
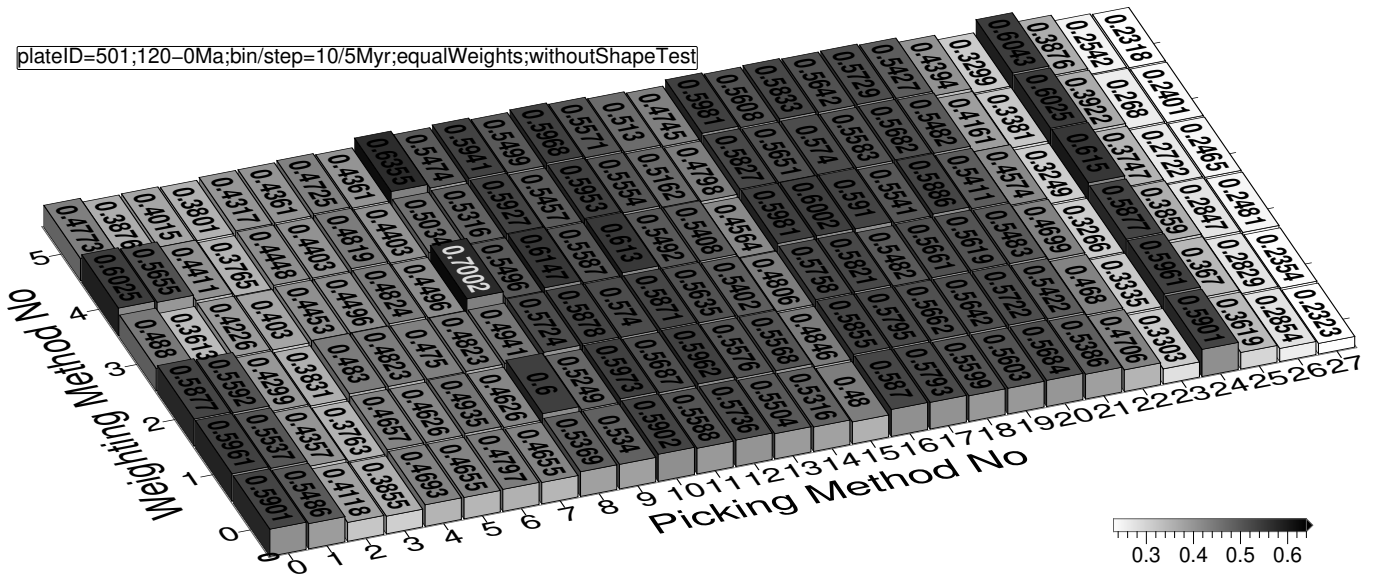
Figure 11. Difference values without shape test between Indian (501) paleomagnetic APWPs and its predicted APWP from FHM and related plate circuit.
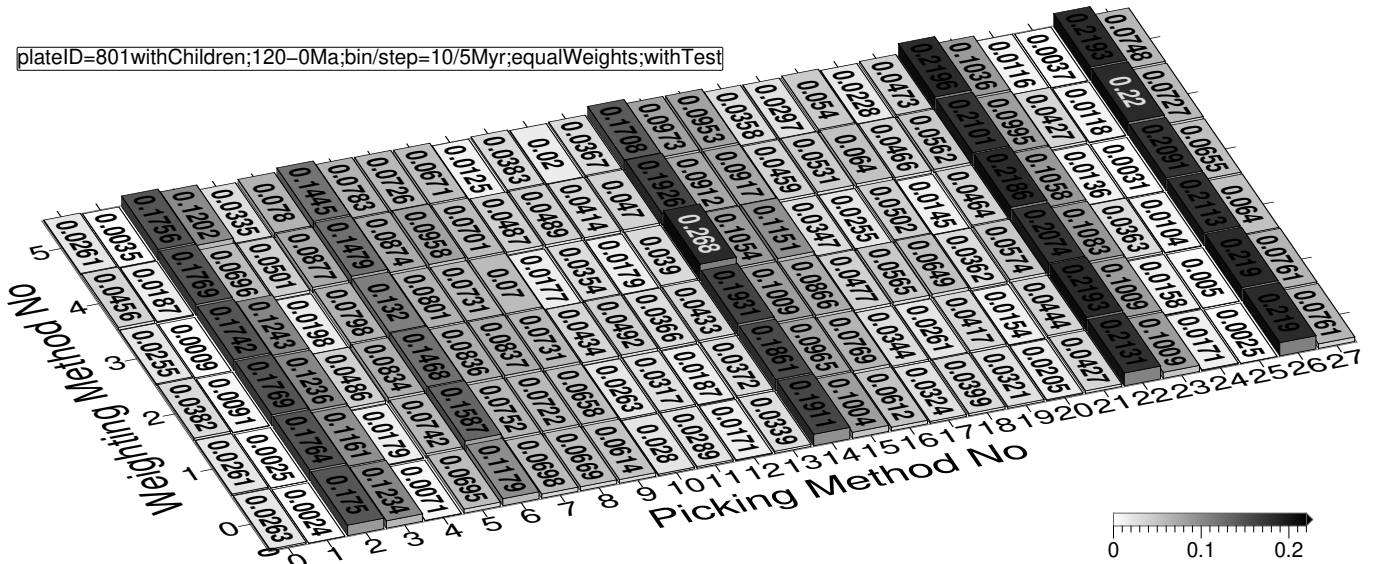

Figure 12. Difference values with test between Australian (801) paleomagnetic APWPs and its predicted APWP from FHM and related plate circuit.
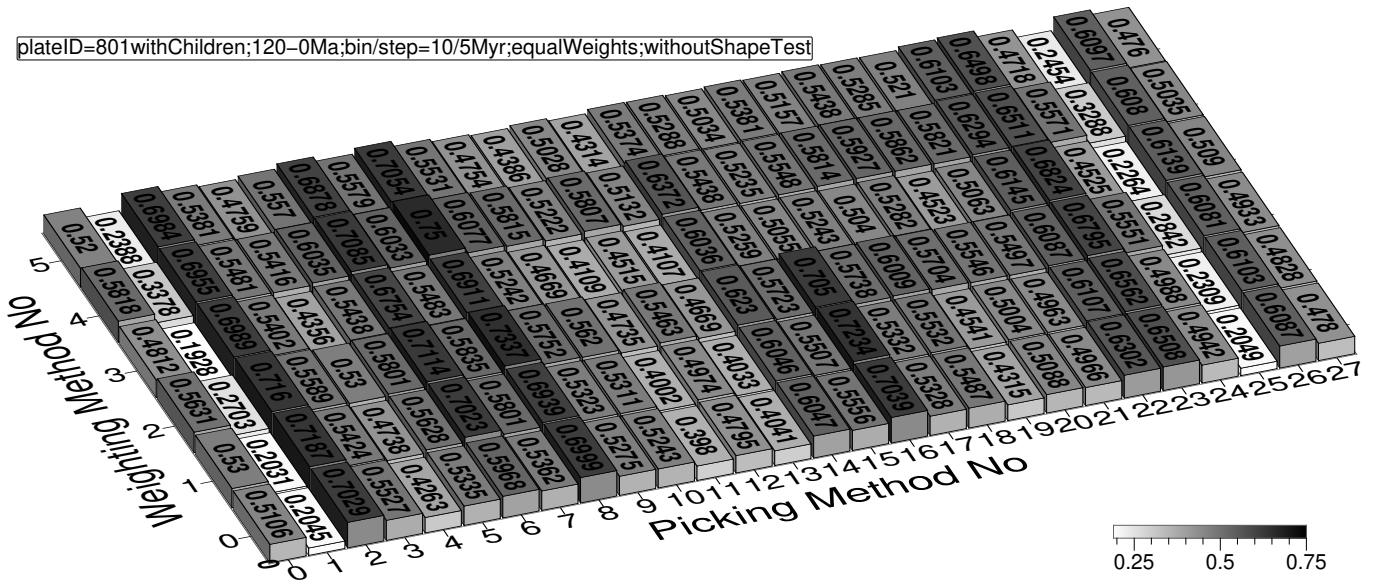
Figure 13. Difference values without shape test between Australian (801) paleomagnetic APWPs and its predicted APWP from FHM and related plate circuit.