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The Magnificent Seven: A Proposal for Modest Revision of the Van der Voo (1990) Quality Index

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Abstract

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1. Introduction

Paleomagnetic studies were a crucial element in verifying continental mobility and the establishment of plate tectonics as the prevailing paradigm in Earth Sciences in the 1950's and 1960's (Cox and Doell, 1960; Opdyke, 1995 and references therein). Nowadays, paleomagnetic inquiry yields a quantitative assessment of plate motion and true polar wander over the bulk of geologic time, and is the primary evidence used in quantitative continental reconstructions. Furthermore, paleomagnetic data forms the basis for evaluating the evolution of the geodynamo. As the number of paleomagnetic results increased and techniques for isolating magnetic components were refined, it became apparent that not all studies were equally reliable. A number of 'filtering' techniques were proposed to assess the reliability of an individual result (Irving et al., 1976; Briden and Duff, 1981; May and Butler, 1986; Piper, 1987; Pesonen et al., 1989; Li et al., 1990; Buchan et al, 2000). Additional rejection/selection criteria were sometimes used on an ad-hoc basis (see for example Westphal and Pfaff, 1986), but it was not until Van der Voo's (1990) study that a schema for grading paleomagnetic poles was widely applied.

Three parallel developments made the Van der Voo (1990) criteria immediately relevant to the paleomagnetic community. The first "Nordic Paleomagnetic workshop" took place in Espoo, Finland, in 1986, and the second in Sweden in 1990 (Elming and Pesonen, 2009). These workshops brought together experts in paleomagnetism from the U.S.A. and Europe to review paleomagnetic poles and evaluate their quality and reliability. The first two workshops, though limited in scope to critical reviews of paleomagnetic data from Baltica and Laurentia, provided the framework for subsequent global expansion. The second important development to arise in this time frame was the hypothesis of the Precambrian supercontinent Rodinia (McMenamin and McMenamin, 1990; Dalziel, 1991; Moores, 1991; Hoffman, 1991). Precambrian paleomagnetic studies were relevant to the Rodinia hypothesis, but the quality of the database was viewed with skepticism (Van der Voo and Meert, 1991; Piper, 1987). Perhaps the most important impetus for advancing a grading scheme of paleomagnetic data was the creation of the Global Paleomagnetic Database (GPMDB, McElhinny and Lock, 1990; Lock and McElhinny, 1991). Global compilations of paleomagnetic data were available prior to the GPMDB (for example Irving, 1960; McElhinny, 1968; Khramov, 1971), but they were neither digital nor easily searchable. McElhinny and Lock (1990) purposely avoided grading individual poles, but the compilation provided an easily queried database for critically evaluating published paleomagnetic data. Rob Van der Voo was involved in all three prongs of these overlapping research foci and had the forethought to develop a scheme for evaluating data leading to a critical appraisal of our scientific approach to paleomagnetic studies.

2. The Magnificent Seven

Van der Voo (1990) proposed seven criteria to evaluate individual paleomagnetic studies, given in a simplified form in Table 1. The original criteria were fleshed out by Van der Voo (1993) in a discussion of (largely Cambrian and younger) paleomagnetism and paleogeography. The following review of those criteria is couched within the knowledge base of the early 1990s.

The first criterion is met when the age of the magnetization is the same as the age of the rock to within a half-period (or ±4%, whichever is larger) for the Phanerozoic and to within ±4% (or 40 Ma, whichever is smaller) for the Precambrian. These age limits were based on comparing average rates of apparent polar wander with uncertainties surrounding mean poles of Phanerozoic and Paleoproterozoic age.

The second criterion established a statistical norm for the precision of paleomagnetic data based on the number of samples required ($N \geq 25$), the clustering parameter k for directional data means (Dec, Inc) or K for the of virtual geomagnetic poles (VGP's), where $k(K) \geq 10$ and the cone of 95% confidence about the mean direction α_{95} (or A_{95} for paleomagnetic poles) is $\leq 16°$ (Fisher, 1953).

Adequate demagnetization techniques used to isolate mean vectors forms the basis for the third criterion. This requires stepwise alternating field, thermal or chemical demagnetization techniques that can separate multicomponent magnetizations through the use of principal component or great-circle analyses (Zijderveld, 1967; Halls, 1976, 1978; Kirschvink, 1980).

Criterion number four is met when the study can constrain the age of magnetization via a field test. One of the commonly used field tests is the fold test (McElhinny, 1964), wherein the age of magnetization is confirmed to be older/younger (or coeval with) the deformational event that resulted in tilting/folding of the rocks. The fold test (Graham, 1949; Figure 1) is most useful when the age of folding is only slightly younger than the rocks. Statistical complications of the fold test are discussed at length in McFadden and Jones (1981), McFadden (1990), McFadden (1998), Watson and Enkin (1983), Tauxe and Watson (1994) and Enkin (2003).

Fig. 1 Here

The baked contact test (Everitt and Clegg, 1962) is relatively straightforward in concept, though often problematic in the field. Figure 2a shows a theoretical field setting of a dyke intrusion and the expected thermal imprint on the host rocks. A positive baked contact test should ideally include all of the following (a) a stable high-unblocking temperature (T_{ub}) magnetization in the intrusive body; (b) a stable high T_{ub} magnetization in the baked zone; (c) a stable, but lower T_{ub} magnetization in the 'hybrid' (or partially baked) zone that matches the direction in the intrusion and a stable high T_{ub} that matches the stable host rock direction. Ideally, the T_{ub} of the dyke component should decrease with increasing distance away from the contact and; (d) a stable high T_{ub} magnetization in the host rock that is distinct from the intrusive body (figure 3b). Schwarz (1977) proposed a baked contact profile test which requires a more detailed sampling profile through the intrusive body, contact, and host rocks in order to demonstrate the acquisition of a partial thermal remanent magnetization (pTRM) that decreases with distance from the contact (Mclelland-Brown, 1981; Hyodo and Dunlop; 1993;Buchan et al. (1993).

Fig. 2 here

Graham (1949) introduced the conglomerate test (Figure 3), positing that clasts of parental rocks should have their directions randomized during subsequent transport. A test for randomness was suggested by Bruckshaw and Vincenz (1954) and later formalized and quantified by Watson (1956a,b; see also Irving, 1964; Stephens, 1964; Gine, 1975; Diggle et al., 1985; Shipunov et al., 1998; Heslop et al., 2018). A positive test requires that the clasts have randomly oriented directions as compared to the underlying or adjacent lithology from which the clasts were derived. The age of the conglomerate (and its clasts) along with its relation to bounding units is a critical consideration for evaluating the significance of the test. The conglomerate test is best defined when the conglomerate is interbedded with the unit being investigated (intraformational conglomerate test; MacNiocaill, 2000; Meert et al. 2009; Levashova et al., 2009). Ideally, the demagnetization behavior (e.g. unblocking temperature and/or coercivity) and rock magnetic characteristics of the conglomeratic clasts should be identical to their parent material (Buchan and Hodych, 1989; Meert et al., 1994).

Fig. 3 Here

The fifth Van der Voo (1990) quality criterion was developed to address the reality that paleomagnetic results from orogenic belts or from non-stratified (e.g. plutonic and metamorphic) rocks can be problematic. Carey (1958) realized that fold belts can experience simple rotations about a vertical axis. In the absence of a stable reference frame (craton), vertical axis rotations can still provide critical information regarding paleolatitude (Van der Voo and Channell, 1980). Without additional information, most plutonic and metamorphic rocks lack a suitable reference for paleohorizontal and therefore are less likely to provide useful information regarding the paleoposition of that block. Dyke swarms that preserve widespread verticality of the intrusions, especially among intersecting swarms of variable orientations, are a notable exception to this rule. Layered intrusions might also preserve useful paleohorizontal datums, although significant tilting may occur between establishment of the igneous layering (ca. 1000°C) and the acquisition of magnetic remanence (≤ 580°C for $Fe_{3-x}Ti_xO_4$).

For his sixth criterion, Van der Voo (1990) made the observation that paleomagnetic studies that carry a dual-polarity magnetization provide evidence that (a) secular variation is likely to be time-averaged and (b) is more commonly observed in rocks that are otherwise known to carry a primary magnetization, although remagnetized rocks do sometimes carry a dual-polarity magnetization (see Johnson et al., 1984; Johnson and Van der Voo, 1989). The presence of polarity changes in sequential stratigraphic order provides the most powerful evidence for a primary magnetization. Van der Voo (1990, 1993) acknowledged that his use of reversals as a reliability criterion did not require a positive statistical test since the tests available at the time were known to be flawed (e.g. Cox and Doell, 1960; McElhinny, 1973) or had not yet been sufficiently tested (McFadden and McElhinny, 1990). In addition, the statistical tests merely demonstrate the presence or absence of an incompletely removed secondary component of single polarity, which might bias the characteristic remanence component such that its means significantly differ from the 180° ideal case; in some situations, magnetostratigraphy may retain its utility and robustness even if the statistical test fails (e.g. Evans et al., 2000).

The final, seventh Van der Voo (1990) criterion suggests the rejection of any paleomagnetic pole that resembles a younger pole (>period) from the same craton or block. The logic is simple in that resemblance to a younger paleopole from the same tectonic block raises suspicion of a remagnetization. Van der Voo (1990) understood the significance of research showing that remagnetization was common and not necessarily restricted to the tectonically active margins of cratonic regions (McCabe and Elmore, 1989). Van der Voo (1990) argued that field tests are required to ameliorate any concerns about remagnetization when an older pole resembled a much younger pole from the same block.

Table 1. Here

3. The "R" Reliability Index: A Modest Proposal

We propose a modest revision to the Van der Voo (1990) "Quality" Index. Colloquially known as the "Q" factor, the paper significantly impacted the paleomagnetic community. Paleomagnetic studies and proposals were framed in such a way as to meet as many of the Q-criteria as necessary. Publications touted results as "our data earn a Q-value of X". This represented a major step forward in our science, but also created a number of debates amongst the scientists responsible for evaluating the paleomagnetic database as well as interpreting the original intent of Van der Voo (1990). Our goal is to review/revise these criteria in light of modern methods, equipment and understanding of the science. We choose the letter "R" for this scheme as it sequentially follows "Q" and also because "Reliability" is an accurate descriptor.

Reliability Criterion #1-Age of the Rocks constrained to within +/- 15 Ma and magnetization is presumed to be the same age as the rocks.

We propose stricter age constraints for meeting the requirements of R1. Geochronological studies have advanced in the past 28 years, particularly with respect to dating of mafic igneous bodies using baddeleyite and zircon (e.g., Kamo et al., 1989). Geochronologists are also more skilled at recognizing interbedded ash flows in sedimentary rocks (see, for example, Compston et al., 1992; Grotzinger et al., 1995; Rasmussen et al., 2002). New techniques for direct dating of sedimentary rocks are still in their nascent stages but show promise of providing robust age control (McNaugton et al., 1999; Rasmussen et al., 2004; Selby and Creaser, 2005; Zhang et al., 2015; Aleinikoff et al., 2015).

The original Q-scheme required that the age of a Phanerozoic paleomagnetic pole should be constrained to within half a period (or ± 4% *whichever is larger*) and that Precambrian poles should be dated to within either 4% or ± 40 Ma (*whichever is smaller*). The Phanerozoic age limits were based on apparent polar wander rates for Wrangellia and North America in the Phanerozoic. The calculated average APW rate of ~ 0.32°/Ma degrees (3.5 cm/yr) resulted in overlapping mean poles in 25-Ma windows. Van der Voo (1993) concluded that higher precision ages would not result in better APWP resolution. The Precambrian threshold was similarly determined on the basis of observed angular uncertainties of +/-16° per 80 Ma (Van der Voo and Meert, 1991). This seemingly simple scheme nevertheless produces some rather odd results. The Cretaceous Period spans about 80 Ma. Therefore, a Cretaceous-age pole with an error of ± 40 Ma would be acceptable (and equivalent to the acceptable maximum error of a Precambrian-age pole). In contrast, a pole from the Silurian (which spans ~25 Ma) would demand an error of less than ± 13 Ma in order to meet Q1. Because of the irregular spacing for the Phanerozoic time scale, this criterion is unequally applied compared to the simpler Precambrian age limits set forth in Van der Voo (1990, 1993).

Given the many advances in geochronological methods/techniques, we propose a more rigid (and simpler) age constraint on paleomagnetic poles. Our proposal is that the age of the rock (and presumed age of the magnetization) should be known to within ± 15 Ma. Although the blanket ± 15 Ma limit on Phanerozoic rocks allows for a larger percentage error on the younger studies, it is more stringent than the original Q-criterion and allows for reasonable definitions of APWP's.

In cases of well-defined remagnetizations, the age criterion should apply to the age of remagnetization rather than that of the rock. For example, a demonstrably synfolding magnetization might be sufficiently well dated if there are independent age constraints on that deformation within the limits of precision set above.

Considerable discussion with regard to the age constraints took place amongst the authors with some advocating for more stringent limits. It is important to remember that both the Q and R criteria are not disqualifying. For example, someone investigating rapid true polar wander may want tighter age constraints on relevant paleomagnetic poles and may freely apply their own filter during that analysis.

Reliability Criterion #2- Techniques and Statistical Analyses

The original Van der Voo (1990) criterion #Q2 establishes requirements for measurement precision using Fisher (1953) statistics, whereas criterion #Q3 focused on measurement accuracy. Because imprecise and inaccurate measurements can result from user error or from inadequate sampling of paleosecular variation, we advocate for the following to satisfy R2:

a) Attempt at least two methods of stepwise demagnetization (e.g. alternating field and thermal, Meert et al., 1995; or thermal/chemical, Billardello and Kodama, 2011) on at least pilot suite of samples to demonstrate that individual vector components are being separated effectively (figure 4).

b) Analyze the directional data using Zijderveld diagrams and principal component analysis (Zijderveld, 1967; Kirschvink, 1980) or great circle intersections to separate overlapping unblocking temperature/coercivity components (Halls, 1976,1978; McFadden and McElhinny, 1988).

c) Achieve a VGP scatter that adequately averages paleosecular variation. Methods by which secular variation is assessed may include using a field-based model (McFadden et al., 1991) or a statistical based model (Deenan et al., 2011, 2014), and guided by these approaches we advocate a simple set of statistical tests of the mean result.

Fig. 4 here

We presuppose that some may view this tripartite list of requirements as being too bulky for one criterion. Whereas sub-criteria (a-b) are now intuitive and routinely performed, the quality of the end result depends on satisfying subcriterion (c). Though not required to satisfy R2, we advocate that authors report several examples of non-ideal behavior when identified.

The original sample size, precision parameter and α_{95} requirements for Q2 criteria were somewhat arbitrary. For example, the original α_{95} threshold was chosen empirically as an overlap in error within time constraints set by Q1. Fisher (1953) statistics demonstrate that the number of samples (sites), precision parameter (k) and cone of confidence (α_{95}) are co-dependent. Using the original Q2-criteria of N = 25 and k = 10 yields an α_{95} of ~9° rather than the 16° advocated by Van der Voo (1990). Modern paleomagnetic studies routinely exceed the N=25 sample limit proposed by Van der Voo (1990) whereas older studies may not. Therefore, the statistical limits required to satisfy R2 use a different approach (Deenan et al., 2011). By definition, a paleomagnetic pole represents the time-averaged position of the geomagnetic pole that is presumed to be symmetric about the center of the Earth and coaligned with the Earth's spin axis (the Geocentric Axial Dipole, or GAD; Meert, 2009). Debates about the nature of this assumption are beyond the scope of this paper; however, we feel that a quantitative assessment of secular variation should be addressed in any paleomagnetic study (McFadden et al., 1988; Deenan et al., 2011; Tauxe and Kodama, 2009; Lund, 2018).

In general, averaging of secular variation is thought to occur over an interval of ~3,000-10,000 years. Sedimentary units should adequately average secular variation over a few meters of sampling (Kodama, 2012), and therefore more easily satisfy this R criterion. On the other hand, quickly cooled igneous rocks provide only a spot reading of the field (McFadden et al., 1988). Secular variation of intrusive rocks is difficult to evaluate as the size of the intrusive body, chemistry of the remanence carriers and temperature of the surrounding country rock affect the timing of remanence acquisition. We prefer the application of a statistical method for evaluating secular variation as part of the R-criteria.

A popular method for evaluating PSV in paleomagnetic studies follows the analysis by McFadden et al. (1988, 1991) wherein the “Model-G” field (Figure 5; McFadden et al., 1991; McElhinny and McFadden, 1997) is compared with the observed paleosecular variation (S_T) using the formula of Cox (1970):

$$(2)\quad S_T = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} \Delta i^2}; \quad (i=1,\ldots,n)$$

where n=number of sites (>5) and Δ*i*= angle between the *i*th VGP and the mean VGP. S_T represents the sum of geomagnetic secular variation effects S_B and random errors due to sampling S_W. Nevertheless, in most cases S_T provides a close approximation to S_B.

Fig. 5 here

The quantitative assessment of secular variation noted above applies to studies where individual sites/samples likely represent a spot reading of the Earth’s magnetic field (basalt flows, dykes, sills and small intrusions etc. The S_T parameter estimation is still commonly used to evaluate averaging of secular variation in spite of the fact that there are known mathematical issues with the model (Tauxe and Kodama, 2009; Deenan et al., 2011; Linder and Gilder, 2012).

Deenen et al. (2011, 2014) described in detail the problems in assigning specific k, N and α_{95} values for the Q2 criterion due to their dependence on one another. For example, 25 *samples* from 3 basalt flows or dykes (cooling units) would meet all the Q2 criterion quite easily but may be unlikely to provide averaging of secular variation (see also Deenen et al., 2011). They make the argument that an N-dependent A95 (*averaging of virtual geomagnetic poles*) should be applied to a dataset to satisfy the Q2 criterion. According to their assessment, a paleomagnetic study where the A95 value lies between the following confidence bounds should provide adequate averaging of secular variation:

$$12 \times N^{-0.40} \leq A95_{obs} \leq 82 \times N^{-0.63}$$

These bounds were established by Deenen et al. (ibid.) to conform to various models of a time-varying GAD field, but they also serve to demand a minimum expectation of precision for a valuable paleomagnetic pole. However, the maximum allowable bound on imprecision (A95) may be too lax. For example, using typical values for N among published high-quality paleomagnetic poles (10-20 sites), the formula yields acceptable limits on Fisher’s K of 1.5–2.6.

Such datasets might be marginally acceptable according to some time-varying GAD models, but they are at odds with our experience of reliable poles, which lean more toward what Van der Voo (1990) suggested as having a minimum empirical bound of data clustering (K≥10). In the other direction, the hallmark signature of a dataset that doesn't adequately average secular variation is *too much* precision on the pole, which would correspond to an anomalously low value of A95 and high value of K. When the number of sites is as large as some of the most intensively sampled units (N ~ 40-50 sites), the Deenen et al. (2011) lower bound on A95 corresponds to values of K ~ 65-70. Although smaller sample sets could have ranges of K >70 that conform to statistical GAD models, we suggest that any value of K >70 warrants some suspicion of inadequate averaging of secular variation.

In addition to the requisite bounds on K between 10 and 70, we also suggest a minimum number of independent spot readings of the ancient magnetic field. Van der Voo (1990) cited personal experience in assigning n ≥ 25 samples for a pole's reliability, and we broadly accept that order of value. Multiple samples should be collected from each site in order to average within-site or between sample errors (McElhinny and McFadden, 2000). Opdyke and Channell (1996) suggest that three or more samples are required for unambiguous determination of polarity at each site. Therefore, we suggest that the 'test' for PSV should be applied to a study with N ≥ 25 (samples), 10 ≤ K ≤ 70 and B ≥ 8 sites (a site represents a spot reading of the magnetic field; *minimum of 3 samples per site*).

In summary, meeting the R2 criterion requires both adequate demagnetization and sampling to achieve the goal of averaging secular variation. As a final note, the authors of this proposal, as both users and developers of paleomagnetic databases, appeal to the community at-large to consider including, at a minimum, a specific set of information in each publication that includes new results, listed by example in Table 2. Inclusion of this information in each publication facilitates entry into global databases and evaluation of R-criteria. Authors may feel free to add more entries into their data tables, but the data shown in example Table 2 are essential for database compilations and other calculations.

Table 2 Here

Reliability Criterion #3- Characterization of Magnetic mineralogy/rock magnetism

Modern studies should include an investigation into the magnetic carriers via rock magnetic tests and/or petrographic examination. Characterization of the magnetic carriers aids in determining the primary/secondary nature of a particular remanence direction (Halls and Zhang, 1995; Halls et al., 2001; Jackson and Swanson-Hysell, 2012; Auborg et al., 2012; Zechmeister et al., 2012; Kodama and Dekkers, 2004).

A general description of magnetic carriers includes an evaluation of any of the following: unblocking/coercivity spectra, isothermal remanent acqusition (IRM) tests, temperature-susceptibility analyses, 3-axis IRM (Lowrie, 1990), low-temperature treatment of IRM (Nagata et al., 1964; Ozdemir et al., 1993; Dekkers et al., 1989). Hysteresis properties are useful in evaluating the domain size of remanence carriers. Hysteresis studies may include Day plots (Day et al., 1977; Roberts et al., 2018) and first order reversal curves (FORC diagrams; Pike et al., 1999; Roberts et al., 2000). In addition, magnetic fabric studies have proven useful in evaluating remanence carriers and/or deformation. These include anisotropy of magnetic susceptibility (AMS; Graham, 1954, 1957), anisotropy of isothermal remanence (AIR; McCabe et al., 1985) and anisotropy of anhysteretic remanence (AAR).

Microscopic investigations of magnetic carriers using polished thin sections under reflected light; scanning electron or transmission electron microscopes help identify possible magnetic carriers and their relationship to the original petrology (Poldervaart and Gilkey, 1954; Pichamuthu, 1959; Halls and Zhang, 1995; Halls et al., 2007; Sun and Jackson, 1994). In the case of fine-grained sediments, mineral separation techniques may be applied to identify the size and composition (Opdyke and Channell, 1996).

The identification of magnetic carriers is particularly important in clastic sedimentary rocks (redbeds) where inclination shallowing during detrital remanence acquisition (DRM) can adversely affect tectonic interpretations (King, 1955; Gilder et al., 2001; Tan and Kodama, 2003; Tauxe and Kent, 2004; Li and Kodama, 2016). Chemical remanent magnetization (CRM) can post-date, and overprint, depositional remanence (DRM) through a significant time interval, complicating paleomagnetic interpretations (Kodama and Sun, 1992; Kodama and Dekkers, 2004; Jiang et al., 2015).

R3 criterion will be met if there is a reasonable attempt to identify and comment on the significance of the magnetic carriers in the study, either through petrographic or rock-magnetic investigation.

Reliability Criterion #4- Field Tests that constrain the age of magnetization

a. Baked Contact/Inverse Baked Contact Test

A study can receive the R4 criterion provided that the baked contact test exhibits most of the features outlined in Figure 2a ($R4_{C+}$). The baked contact test often departs from the ideal models described above. A positive baked contact ($R4_{C+}$) test is also confirmed when the dyke and baked zone exhibit stable and similar paleomagnetic directions and the unbaked region yields a stable and different direction even if there is no hybrid zone. It is not uncommon for the unbaked host rock to exhibit unstable behavior regardless of whether or not regional remagnetization has occurred. In the case where the intrusive body and baked host show the same direction and the country rock exhibits unstable behavior, the baked contact test should be noted as $R4_{Co}$. Salminen et al. (2009) note a special case where heating associated with meteorite impact may provide evidence of a primary magnetization in the melt zone and adjacent regions. Inverse baked contact tests, as long as they satisfy the characteristics noted above, may also provide useful age constraints on magnetization directions in the host rocks and would also qualify for R4.

b. Fold/Tilt/Slump Tests

The strongest fold tests are those that (a) pass rigorous statistical analyses and (b) have an age of folding that is 'close' to the age of the rocks in question. The fold test should be applied in a stepwise manner and we require that the magnetization direction have optimal grouping within error of 90-110% unfolding in order to meet R4 standards. Although the fold test provides more clarity on the age of magnetization when the age of folding is close to the age of the rocks (Van der Voo, 1969), the R4 positive fold test would be satisfied regardless of the age of folding. Regarding the question of whether a pole is reliable for a given purpose, we prefer to leave this decision in the hands of each individual in the context of their particular analysis. In similar fashion, we recognize several statistical variations of the fold test, catered to a variety of fold geometries and sampling strategies; any statistically robust test can be used to satisfy R4.

The intention of R4 is to identify evidence in favor of the possibility of a primary magnetization in the rock. Thus, syn-folding magnetizations do not meet the R4 criterion unless they are demonstrably syn-sedimentary slump folds (Smith et al., 1983; Schmidt et al., 1991). We do not devalue the significance of a syn-folding (re)magnetization, but since the result neither 'passes' nor 'fails' the fold test, we prefer a simplistic approach in the grading scheme.

Individual researchers may pass judgement on the validity of a syn-folding magnetization as needed

c. Conglomerate Test

A paleomagnetic pole will receive the R4 criterion for the conglomerate test if it (a) fulfills the statistical requirements set forth in Watson (1956b), Shipunov et al. (1998) or Heslop and Roberts (2018a) and (b) N is sufficiently large to test the null hypothesis H_0 of Watson (1956b) which assumes a uniform ("random") distribution of vectors or the Bayesian assumptions set forth in Heslop and Roberts (2018a). Heslop and Roberts (2018a) tested sample sizes ranging from n=5 to n=35. While not specifically assigning an optimal N-value, they note that a strong level of support for the conglomerate test is difficult for sample sizes where $n < 19$. We attempt to balance statistical vagaries with practicality in field sampling and argue that $n \geq 10$ in order to be a useful conglomerate test. Providing that the statistical analysis indicates a positive conglomerate test, the age of the conglomerate should, in principle, be reasonably close to the age of the rocks being studied; however, as with the fold test described above, we do not place a specific restriction on the age of a conglomerate (other than devaluing any misuse of the reliability scale by applying the test to trivially young conglomerates or breccias). The ideal case requires that the conglomerate clasts are taken from an intraformational conglomerate wherein the clasts are derived from the underlying units and exhibit the same magnetic characteristics as the parent materials (see for example Buchan and Hodych, 1989; Levashova et al., 2009; Meert et al., 1994; Meert et al., 2009).

Fig 6 Here

d. Unconformity Test

The unconformity test (Kirschvink, 1978) was proposed for the special case in which a stratigraphically ordered polarity sequence is truncated by an unconformity. Figure 6a illustrates a positive unconformity test wherein the polarity sequence below the unconformity is discontinuous across the unconformable surface. In this case, the magnetization in the lower sequence is older than the unconformity. Figure 6b illustrates a negative unconformity test because the polarity zonation is continuous across the unconformity.

Reliability Criterion #5- Structural control

We accept the original rationale employed by Van der Voo (1990) and argue that paleomagnetic poles derived from allochthonous or parautochthonous terranes, non-stratified rocks and regions that have undergone internal vertical axis rotations will not meet the R5 criterion. Results from intrusive rocks younger than the last deformational event may meet this criterion. We also note that we apply the R5 criteria in a stricter fashion than Van der Voo (1993). As an example, in the VdV (1993) compilation of paleomagnetic poles from Laurentia, results from the Colorado Plateau and northern limb of the Pennsylvania salient were 'corrected' for vertical-axis clockwise rotations of 5 and 23 degrees respectively and each pole from those regions received a Q=5 checkmark. The tacit assumption was that the amount of rotation for each region was well-known; however, the magnitude of the CP rotation and 'corrections' turn out to be far more complicated (see McCall and Kodama, 2014). Therefore, a pole will meet R5 if there is a presumption that the region was a rigid part of the craton since the time the magnetization was acquired.

The definition of autochthonous in the Precambrian is complicated by the fact that Phanerozoic 'continents' are themselves amalgams of smaller nuclei with a complex assembly history (Kilian et al., 2017; Hoffman, 1998; Meert and Pandit, 2015; Bogdanova et al., 2008; Gladkochub et al., 2006; Cawood and Korsch, 2008; Boger, 2011; de Waele et al., 2008; Tassiniari and Macambira, 1999). Most modern paleomagnetic studies recognize this obstacle and use poles that represent only the region to which they are rigidly attached (our stipulation). The situation is sometimes further complicated by "post-assembly" rotation or rifting. For example, Cawood and Korsch (2008) argue that three key elements of Australia (Northern Australia, Western Australia and the Mawson continent) were assembled during the Mesoproterozoic. Li and Evans (2011) provide a convincing argument for a large 40º degree intraplate rotation between a coupled western Australia/southern Australia and northern Australia during the late Neoproterozoic. In this example, Mesoproterozoic poles calculated from the blocks that have undergone rotation can receive the R5 criterion when applied to their respective regions. Authors assigning R5 to poles referred by their studies should specify their definition of each "craton" along with its present and paleogeographic bounds.

Clastic sedimentary rocks often carry a detrital remanent magnetization (DRM) that can experience inclination flattening during deposition and compaction (King, 1955; Figure 7). The relationship between flattening factor (*f*) and inclination is given as:

$$f\tan(I_f) = \tan(I_0)$$

Where:

f= flattening factor (0 $\leq f \leq 1$*)*

I_f= expected GAD inclination for latitude of deposition

I_0= observed inclination

Fig 7 here

There are two main strategies employed for detecting and correcting inclination shallowed directions (Jackson et al., 1991; Kodama and Sun, 1992; Kodama and Dekkers, 2003; Kodama, 1997; Li and Kodama, 2016; Tauxe and Kent, 2004; Tauxe et al., 2008). The first technique is based on detailed measurements of anisotropy (Li and Kodama, 2016) that are labor intensive but may provide a more direct measure of inclination shallowing than the 'easier' statistical analysis (Tauxe and Kent, 2004). As noted by Li and Kodama (2016), both techniques have underlying assumptions and limitations that require a cautious approach in drawing paleogeographic conclusions from inclination-shallowed rocks. We therefore argue that any poles based on flattening corrections will not meet the R5 criterion unless the inclinations are corroborated by paleomagnetic data from either coeval volcanic rocks that have a similar R-value or other sedimentary rocks that do not require flattening corrections.

Reliability Criterion #6- Presence of Reversals- Statistically valid reversal test (McFadden and McElhinny, 1990; Heslop and Roberts, 2018b)

The power of the reversal test in paleomagnetism is based on the assumption that a positive result indicates sufficient passage of time required to average secular variation. Furthermore, antipodal directions suggest that there were no systematic overprints on the primary magnetization.

Unfortunately, the reversal test has sometimes led to the false conclusion that the rocks record a primary magnetization. This is neither the intended purpose of a reversal test nor always an accurate assumption. Dual-polarity remagnetization is possible (see Johnson et al., 1984; Johnson and Van der Voo, 1989) and single polarity results can be demonstrably primary. Furthermore, data collected from 'spot' readings of the geomagnetic field (smaller dykes or flow units) may exhibit dual polarity magnetization without adequately averaging secular variation. A positive reversal test is therefore supportive, but not conclusive, of a PSV-averaged primary magnetization in the sampled sequence (see R2).

In the original Q-criteria compilation (Van der Voo, 1990) there was no robust statistical test required for meeting this criterion other than the presence of both polarities with overlapping α_{95} confidence limits. In part, this was because the statistical test proposed by McFadden and McElhinny (1990; hereafter M&M) had not been sufficiently applied to the extant database. The reversal test of M&M (1990) grades significance by comparing the means of the normal and reverse directions assuming that they are drawn from the same population. The assumption of a common population depends on the number of observations of each polarity and the precision parameter kappa (k). If there is no common precision parameter, or isolated observations from one of the polarity groups, then the test is not necessarily invalid, but requires additional analysis (see M&M, 1990). We note that the sample size and common kappa assumption for the M&M (1990) test have a key effect on the test results. If the common population assumption is statistically valid (i.e. $\gamma_o < \gamma_c$) then the reversal test is evaluated according to the critical angle (γ_c). A positive reversal test is graded "R_A" when $\gamma_c < 5°$; "R_B" when $\gamma_c < 10°$; "R_C" when $\gamma_c <$ 20° and "Indeterminate", or "R_0", when $\gamma_c \geq 20°$. A negative reversal test occurs when $\gamma_o > \gamma_c$. If the test is based on isolated observations from one of the polarity groupings, we propose following the suggestion of M&M (1990) of assigning grades R_{AI}, R_{BI} and R_{CI} for the reversals test.

A second reversal test was recently proposed by Heslop and Roberts (2018b; hereafter H&R) that is more nuanced in grading the reversals test. The H&R (2018b) test is particularly useful when the M&M (1990) result is indeterminate (R_0). H&R (2018b) show that ~40% of "R_0" reversal tests under the M&M (1990) scheme yield positive support for a common mean, ~59% are ambiguous and <1% yield positive support for a different mean. To meet the R5 criterion, a positive reversal test must rise above the M&M (1990) "indeterminate" or the H&R (2018b) "ambiguous" label. As a cautionary note, we note that the SIAPD program (Torsvik et al., 1999) reversal test assumes the user has evaluated the common kappa and sample size requirements for the M&M (1990) test. These assumptions must be met in order to avoid incorrect calculation of reversal test results (Nagaraju et al., 2018; Kumar et al., 2017).

Reliability Criterion #7: No Resemblance to younger poles by more than a period unless there is field evidence for an older magnetization

One of the more contentious discussions in Precambrian paleomagnetism is whether or not Q7 "resemblance to a younger paleopole by more than a period" should be considered in the revised "R" reliability criteria. Veikkolainen et al. (2014), during their compilation of the global Precambrian database, argued that Q7 should be disregarded because it could lead to erroneous conclusions about remagnetization. They argued that the presence of several self-closing APWP loops in the Precambrian were merely coincidental and not indicative of remagnetization.

Using an argument nearly antithetical to that of Veikkolainen et al. (2014), Bazhenov et al. (2016) took a pessimistic approach towards the Precambrian database from Baltica. Bazhenov et al. (2016) calculated the statistical probabilities for a 95% confidence deviation from the true mean (see McFadden, 1980; *p*=.05, N=number of observations; R=length of the resultant mean vector):

$$cos\psi_{(1-p)} = 1 - (N - R)\left[\left(\frac{1}{p}\right)^{\frac{1}{N-1}} - 1\right]$$

The approximation for the 95% deviation angle is given by:

$$\psi_{95} = \frac{140}{\sqrt{k}}$$

ψ_{95} was then used to create a double-width 'alarm band' around the Phanerozoic APWP for Baltica (Figure 8; using an average k of 100 from published studies). They observed that ~50% of Precambrian poles; (a) fell within the 'alarm band'; (b) were not randomly distributed and; (c) formed distinct clusters which they concluded should be viewed with a suspicion of remagnetization.

Fig. 8 here

Pivarunas et al. (2018) approached the issue by generating hundreds of synthetic APWP's in an effort to evaluate the statistical probability of self-intersection (Figure 9). Pivarunas et al. (2018) show that the likelihood of APWP self-intersection is 69.1 ± 9% in 500 million years and 97.1 ± 2% in 1000 million years with a 'plate-reorganization' every 70 Ma. In other words, resemblance to younger paleopoles noted by Bazhenov et al. (2016) and Veikkolainen et al. (2014) are the expected outcome of continental motion over geological time.

Fig 9 Here

There are disagreements regarding inclusion of this criterion in our revision amongst the authors of this paper. Some side with the more conservative approach of Bazhenov et al. (2016) whilst others favor the abolition of this criterion. Arguments for abandoning this criterion were summarized by one of us (D.A.D. Evans) as follows:

(1) The definition of 'resemblance' is not clearly defined in the Van der Voo (1990) criterion.

(2) What level of reliability is required of the younger pole?

(3) How far do we draw our geographic boundaries when attempting to assess 'resemblance' for a particular region? This is particularly relevant when assesssing Precambrian poles.

These are legitimate and confounding issues. In some cases, the solution is simple. Any paleomagnetic pole with field tests that constrain the age of magnetization to be older than the younger pole(s) it resembles will meet this criterion.

Dealing with the other concerns raised above is more problematic. Van der Voo (1990) stated that any pole that fell on a younger part of the APWP should be viewed with suspicion. The implication is that a cratonic block must have a well-defined path for comparison, but few cratons have well-defined Precambrian APWP's and in some cases the age of cratonic coherence is not well-established (Meert and Pandit, 2015). Furthermore, no specific guidance was offered by Van der Voo (1990, 1993) regarding points (1) and (2).

We offer the following instructions for evaluating R7.

(1) Comparison to younger poles: Heslop and Roberts (2019) discuss the difficulty in assessing what constitutes 'resemblance to a younger pole'. They argue that a binary "yes' or 'no' decision is difficult and propose a series of information metrics that can aid in this decision. In spite of known limitations outlined in that study, we propose that paleomagnetic poles with overlapping A95 envelopes with younger poles (of R $\geq$ 3) will not meet this criterion. Individual investigations may wish to apply the metrics described in Heslop and Roberts (2019), but we choose to apply the more conservative approach of overlapping A95 confidence intervals for our criterion. This approach may be justified at least qualitatively by the recognition that A95 values indicate statistical precision but do not always represent all possible sources of error in paleomagnetic data (e.g., Rowley, 2019).

(2) Geographic boundaries: The comparison to younger poles should only be made with poles from stable regions within the connected craton(s). Poles from orogenic belts should not be used for this comparison as they do not provide a unique pole position.

This requires knowledge of the assembly history the continent/craton being evaluated and is best considered by the authors at the time of publication.

There is no perfect solution to the issue of remagnetization, but we feel that Van der Voo's (1993) cautionary statement "guilty (i.e. remagnetized) until proven innocent" is still valid.

4. Conclusions & Recommendations

The Van der Voo (1990) Q-criteria served the paleomagnetic community for nearly 30 years and resulted in more careful and detailed paleomagnetic studies. Modern paleomagnetic methods, automation, advanced statistical tools along with better precision in geochronological methods necessitated a re-evaluation of the reliability criteria and our proposal for the new "R" system. Similar to its predecessor, the R-factor is based on seven criteria used to assess the reliability of a paleomagnetic pole. These seven criteria are presented in Tabular form (Table 3). We emphasize that the R-criteria merely form a checklist that provides a numerical reliability score. The R-score value does not imply rejection or endorsement of any individual paleomagnetic study. Decisions as to how to apply the R-score to a particular study is up to the individual researcher or research group.

Table 3 here

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Figure Legends

Figure 1. Conceptual diagram of (a) positive fold test correction, where rotating inclination and declination data back to pre-folded values results in agreement between data within the folded bed and; (b) post-folding magnetization, where rotating inclination and declination back to pre-folded values results in scattering of data from within the folded unit.

Figure 2. (a) expected unblocking temperature spectra (T_{ub}) along a baked profile showing completely baked host, hybrid host and unbaked host; (b) Stereonet showing an idealized positive baked contact test (C+); (c) Stereonet of vector components in an inconclusive baked contact test (Co). Although the baked host matches the dyke direction, results away from the bake zone do not exhibit stable hybrid or stable host directions. (d) Negative baked contact test where all directions are similar suggesting a more widespread remagnetization.

Figure 3. (a) positive intraformational conglomerate test (from Meert et al., 2009). Bounding layers show a stable magnetization above and below the conglomeratic layer. Clasts from the intervening layer exhibit the same demagnetization behavior as their parent materials with statistically random directions (b) negative intraformational conglomerate test where layers above and below the conglomerate show identical directions and clasts from the conglomerate are clustered in the same location.

Figure 4. (a) Stereoplot of alternating field (AF-top) versus thermal demagnetization (bottom) directional changes from a Paleoproterozoic dyke in India. (b) Plot of thermal (to 560 C) followed by AF-demagnetization of a Paleoproterozoic dyke in India. In both (a) and (b) thermal demagnetization is ineffective in isolating the characteristic NW-shallow up magnetization (Pivarunas et al., in prep). (c) Alternating field demagnetization of Mbozi Complex and (d) Thermal demagnetization of Mbozi Complex. In this case, AF-demagnetization was unable to resolve the characteristic direction (Meert et al., 1995).

Figure 5. Model G (McElhinny and McFadden, 1997) based expected VGP scatter at different latitudes using equation (1). For example, a mean VGP scatter of 20 degrees would be expected at a latitude of 60 degrees.

Figure 6. (a) Positive unconformity test (after Kirschvink, 1978). Reversal pattern is truncated across the unconformity surface; (b) Negative unconformity test. Reversal pattern is continuous across the unconformity surface.

Figure 7. Effect of inclination shallowing versus geocentric axial dipole inclination for a range of flattening factors (f=0.3 orange; f=0.6 grey; f=0.8 yellow; GAD field blue).

Figure 8. From Bazhenov et al. (2016). Alarm band (light green) surrounding the Phanerozoic apparent polar wander path for Baltica along with Precambrian poles from Fennoscandia, Ukraine and the Urals.

Figure 9. From Pivarunas et al. (2018) (a) example of self-intersecting APWP and (b) a 500 Myr long non-intersecting APWP. Both (a) and (b) use randomly generated velocities between 2-10 cm/yr with a plate re-organization interval of 70 Ma.

Table1

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Table 1. Van der Voo (1990) Criteria Summary

Q	Brief Description	Limits
1	Well-determined rock age and a presumption that magnetization is the same age	Within ½ period or ± 4% (whichever is larger) in the Phanerozoic. +/-4% or 40 Ma (whichever is smaller) in the Precambrian
2	Sufficient number of samples and statistical limits	k(K) $\geq$ 10, $\alpha_{95}(A_{95}) \leq 16°$, N $\geq$ 25 samples
3	Adequate demagnetization that demonstrably includes vector subtraction.	Zijderveld (1967), PCA (Kirschvink, 1980) or great circle analyses (Halls, 1976, 1978)
4	Field Tests that constrain age of magnetization	Positive fold, baked contact or conglomerate tests that are statistically valid.
5	Structural control, and tectonic coherence with craton or block involved	Results from thrust sheets or intrusives older than the last tectonic phase not valid.
6	The presence of reversals	Presence of dual-polarity magnetization. No test required
7	No resemblance to paleopoles of younger age (by more than a Period)	No suspicion of remagnetization.

Table2
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Table 2. Sample Data Table for Paleomagnetic Results

Site	Slat	Slong	N/n	Dec	Inc	α_{95}	k	VGP Lat	VGP Long
I915	25.1232° N	87.3456° E	7/7	45°	+55°	8°	56	47.7° N	151.3° E
I916	25.1342° N	86.9984° E	8/6	53°	+47°	7°	112	42.9° N	160.9° E
I917*	24.9765° N	87.0034° E	7/3	123°	+14°	27°	11	26.0° S	154.8° E
I918	24.9965° N	87.1254° E	9/8	48°	+52°	5°	78	47.6° N	155.3° E
Mean Result	Specify mean of VGP's or mean D,I and reference locality		Specify whether mean is based on unit samples (n) or unit sites (B). Specify any data NOT used in calculating mean.	49°	+51.4°	7.3°	288	46.1° N A95=6.6°	156.0° E K=348

Slat=Site latitude; Slong=Site Longitude; N=samples; n=samples used; Dec=Mean Declination; Inc=Mean Inclination; α_{95}=cone of 95% confidence about the mean result; k=Fisher precision parameter; VGP Lat=virtual geomagnetic pole latitude; VGP long=virtual geomagnetic pole longitude; A95= cone of confidence about the mean paleomagnetic pole; K= Fisher's precision parameter in pole space; *Site not used to calculate mean result (Please make sure rejected sites are properly annotated).

Table3
Click here to download Table: Table 3.docx

Table 3. Brief Description of the R-Score

R	Brief Description	Limits
1	Well-determined rock age and a presumption that magnetization is the same age	Radiometric age constrained to within +/-15 Ma
2	Techniques and Statistical analysis	Stepwise demagnetization effectiveness confirmed by multiple demagnetization methods. Test for averaging of PSV. $N \geq 25$, $10 \leq K \leq 70$, $B \geq 8$ sites (minimum 3 samples/site)
3	Evaluation of remanence carriers	Rock magnetic and/or microscopic examination and identification of magnetic carriers.
4	Field Tests that constrain age of magnetization	Fold/tilt test. Baked contact tests; conglomerate test or other field tests that constrain age of magnetization.
5	Structural control, and tectonic coherence with craton or block involved. Inclination shallowing assessed in clastic sedimentary rocks	Data from thrust sheets or intrusive rocks must be younger than the last tectonic deformation in the area. Detrital sedimentary rocks that do not require inclination corrections will meet this criteria.
6	The presence of magnetic reversals	Statistically significant antipodal normal and reverse directions R_a, R_b or R_c rated (McFadden and McElhinny, 1990) or show support for a common mean (Heslop and Roberts, 2018b).
7	No resemblance to younger poles by more than a period based on overlapping A95	Field tests that constrain the magnetization to be older than the younger pole(s) it resembles.

Figure 1

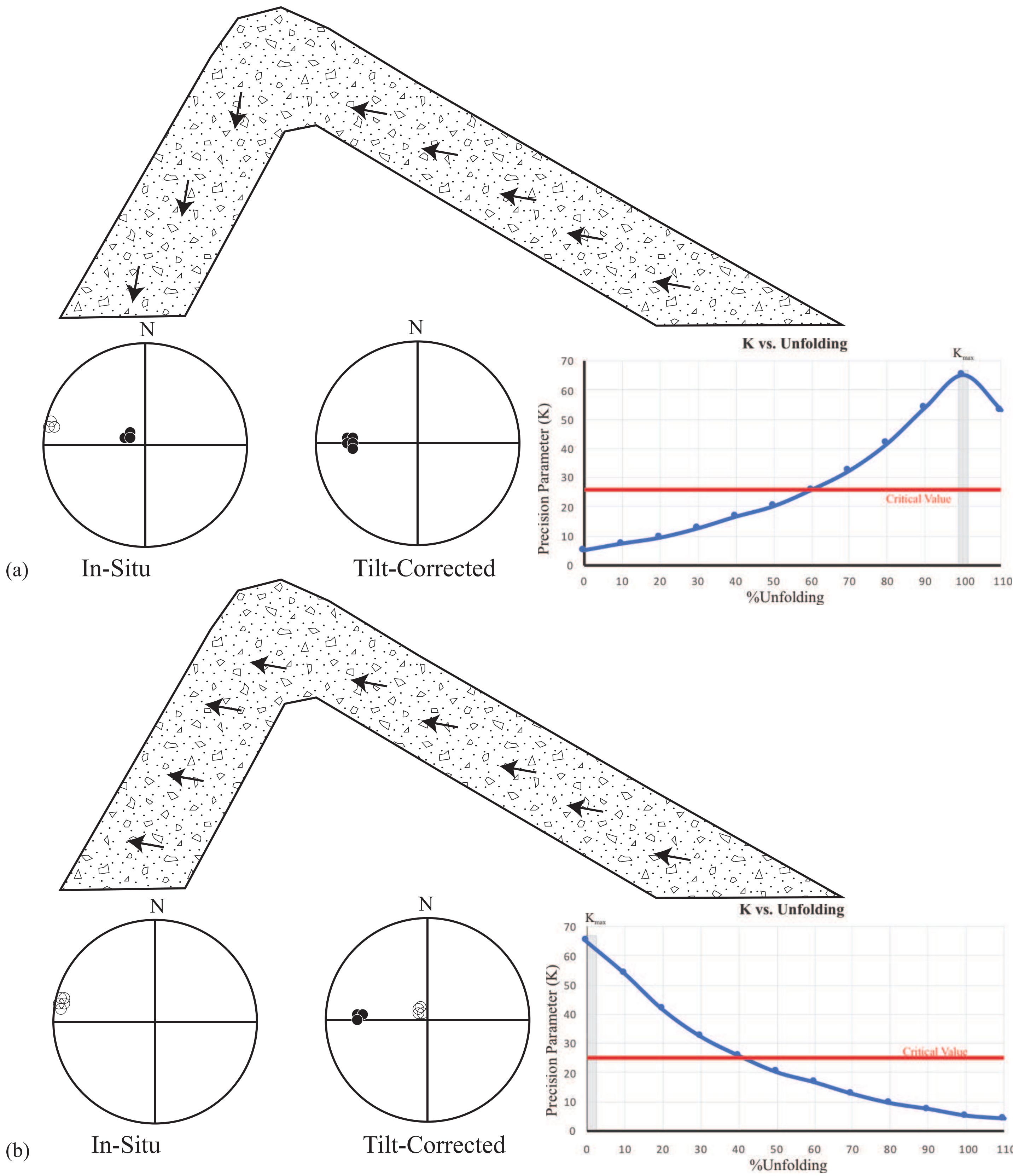
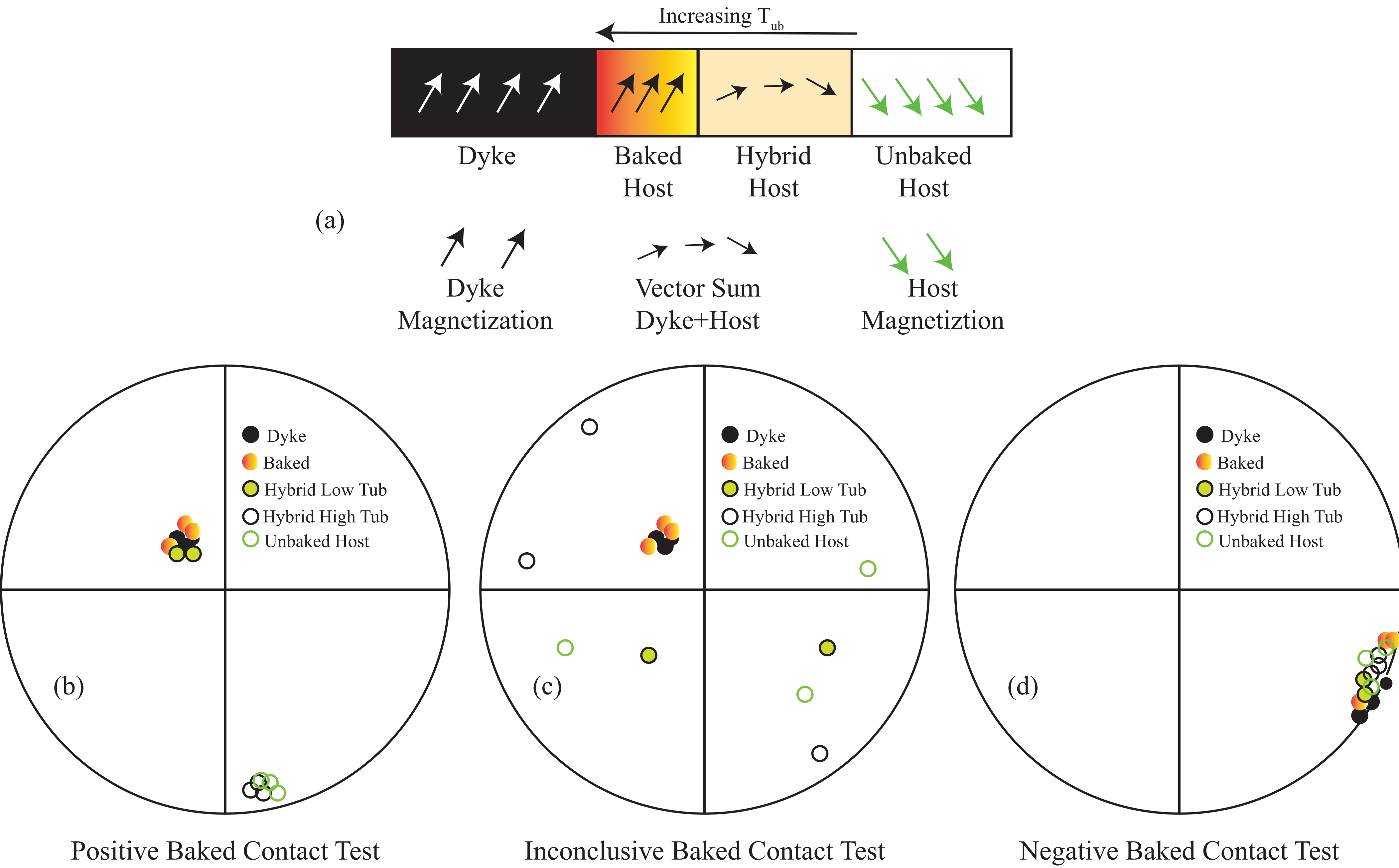

N
N
(a)
In-Situ
Tilt-Corrected
K vs. Unfolding
K$_{max}$
Precision Parameter (K)
Critical Value
%Unfolding
N
N
(b)
In-Situ
Tilt-Corrected
K vs. Unfolding
K$_{max}$
Precision Parameter (K)
Critical Value
%Unfolding

Figure2



Increasing T_{ub}
Dyke
Baked Host
Hybrid Host
Unbaked Host
(a)
Dyke Magnetization
Vector Sum Dyke+Host
Host Magnetiztion
Dyke
Baked
Hybrid Low Tub
Hybrid High Tub
Unbaked Host
(b)
(c)
(d)
Positive Baked Contact Test
Inconclusive Baked Contact Test
Negative Baked Contact Test

Figure3

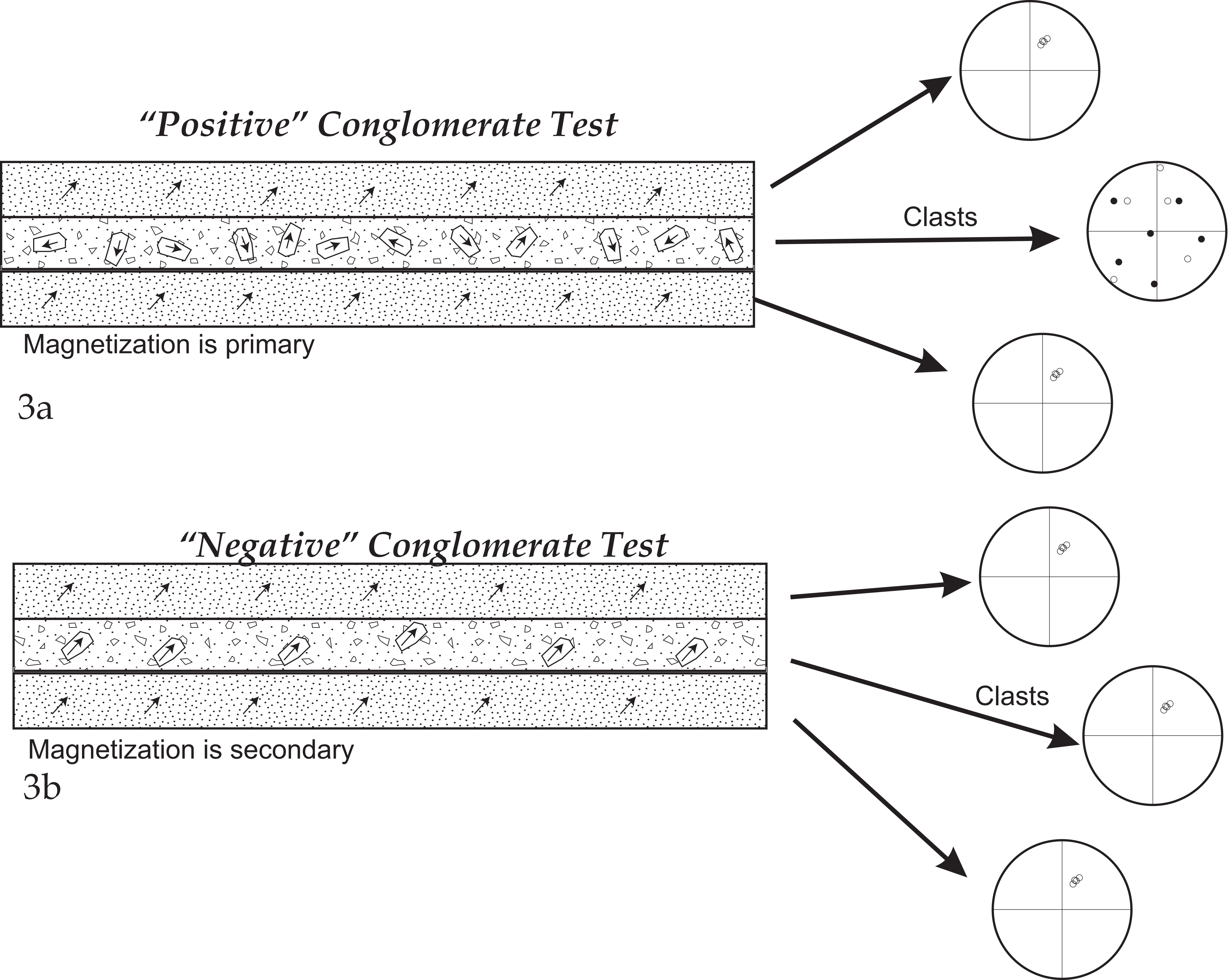

"Positive" Conglomerate Test
Clasts
Magnetization is primary
3a
"Negative" Conglomerate Test
Clasts
Magnetization is secondary
3b

Figure4

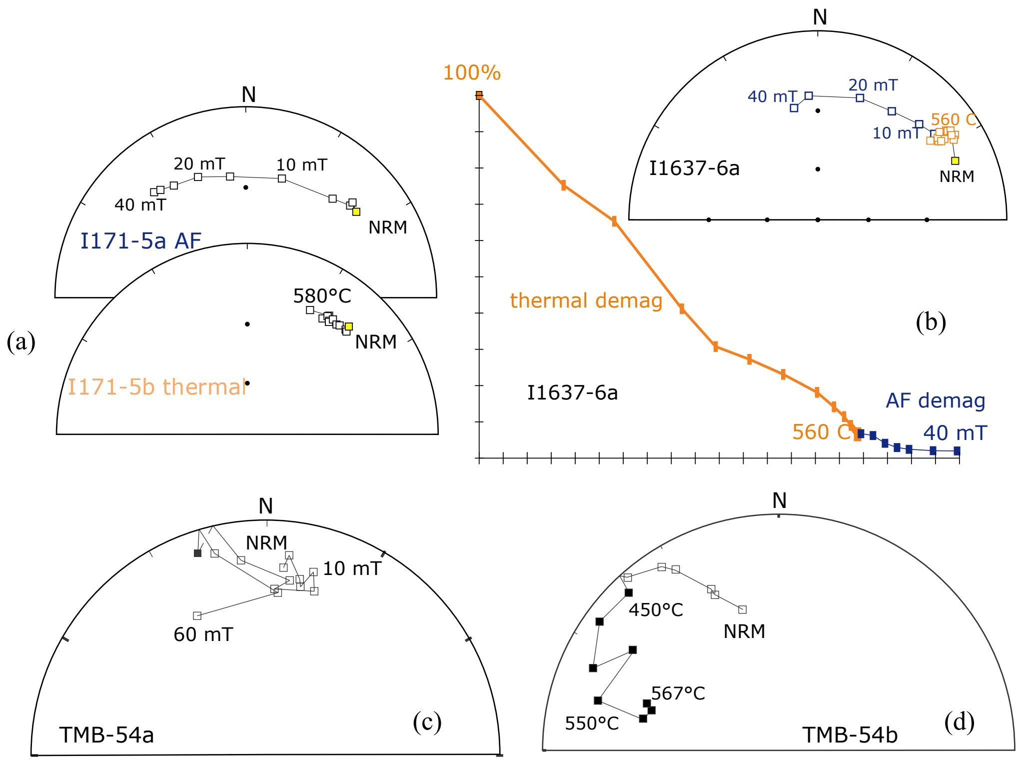

N
20 mT
10 mT
40 mT
NRM
I171-5a AF
580°C
NRM
(a)
I171-5b thermal
100%
thermal demag
I1637-6a
560 C
AF demag
40 mT
N
40 mT
20 mT
10 mT
560 C
I1637-6a
NRM
(b)
N
NRM
10 mT
60 mT
TMB-54a
(c)
N
450°C
NRM
567°C
550°C
TMB-54b
(d)

Figure5

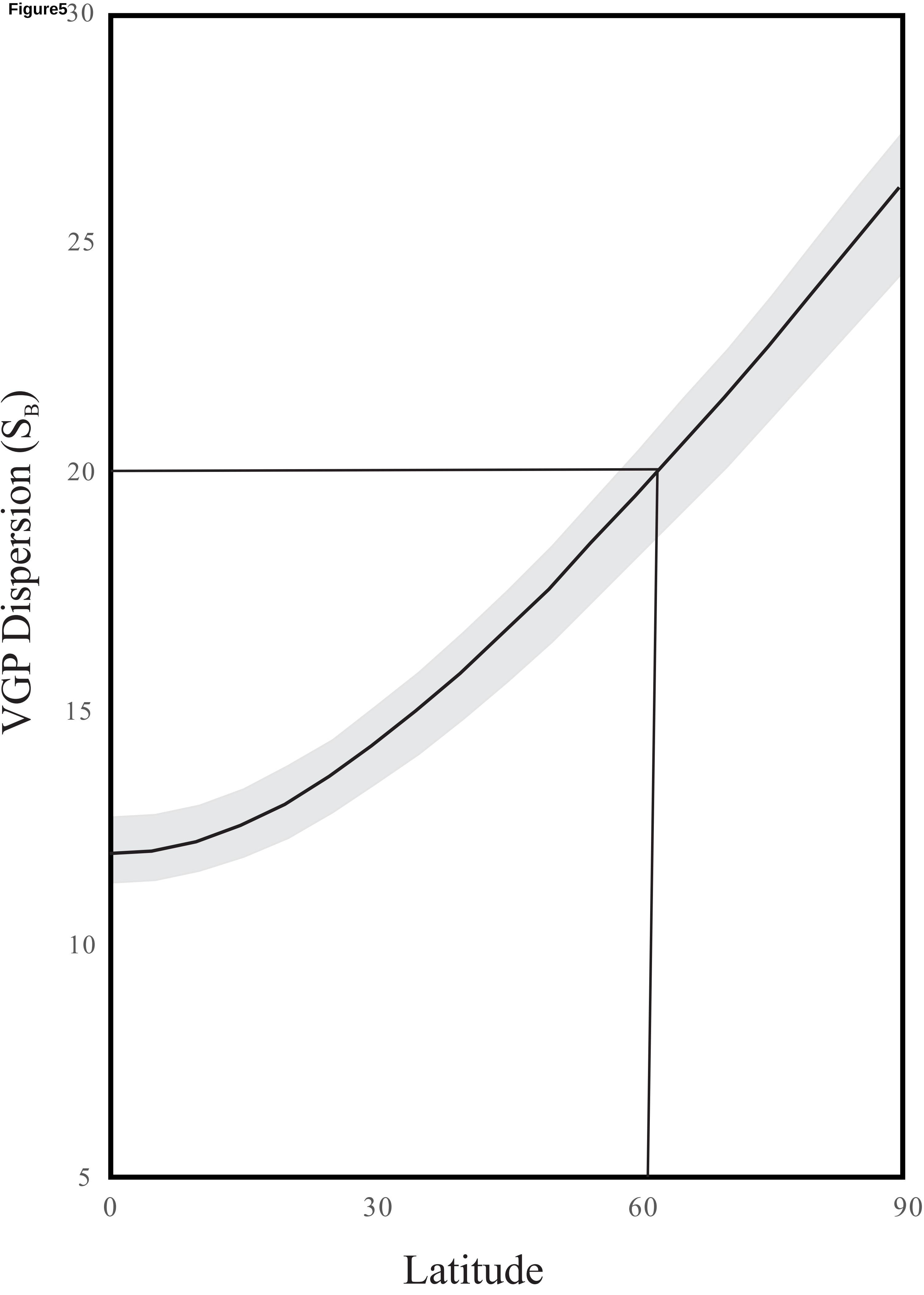


Figure6

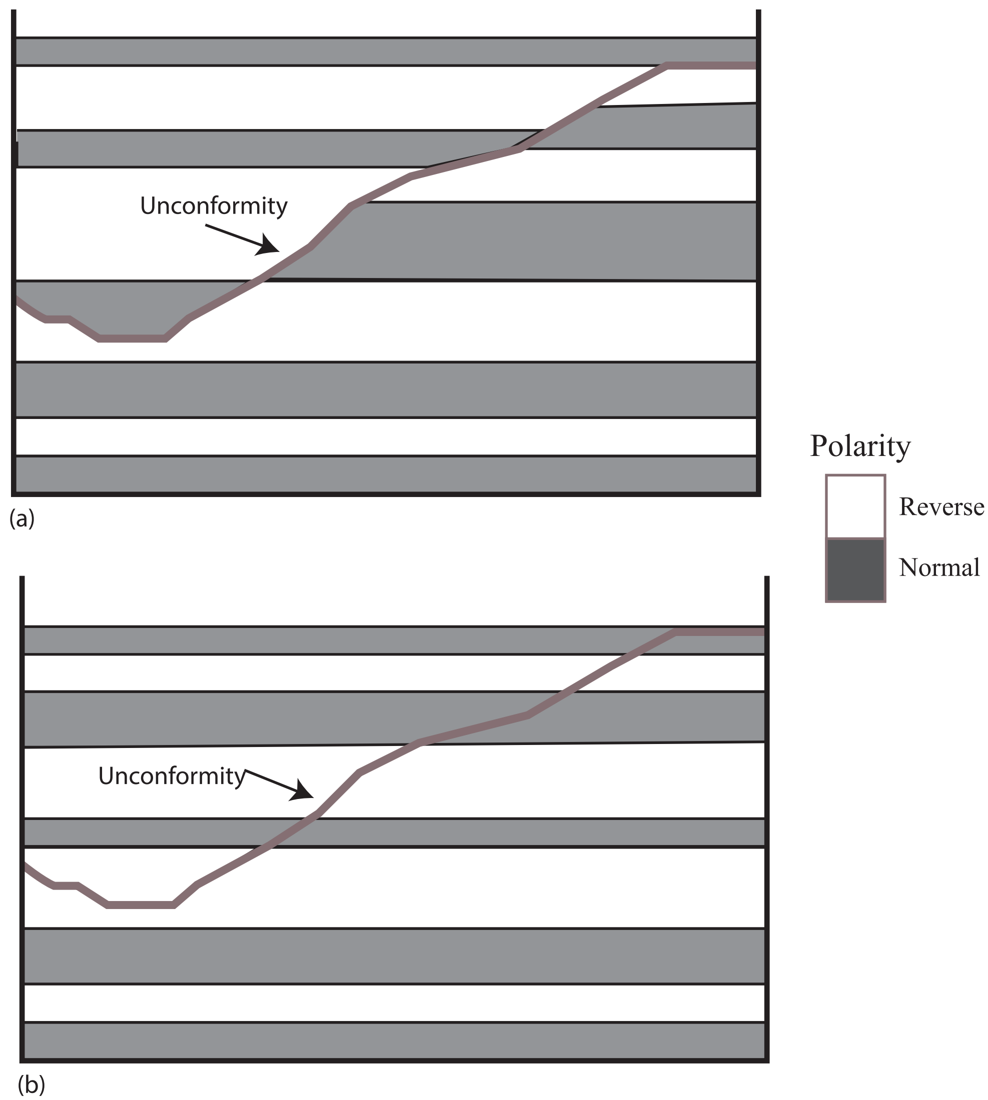


Figure7

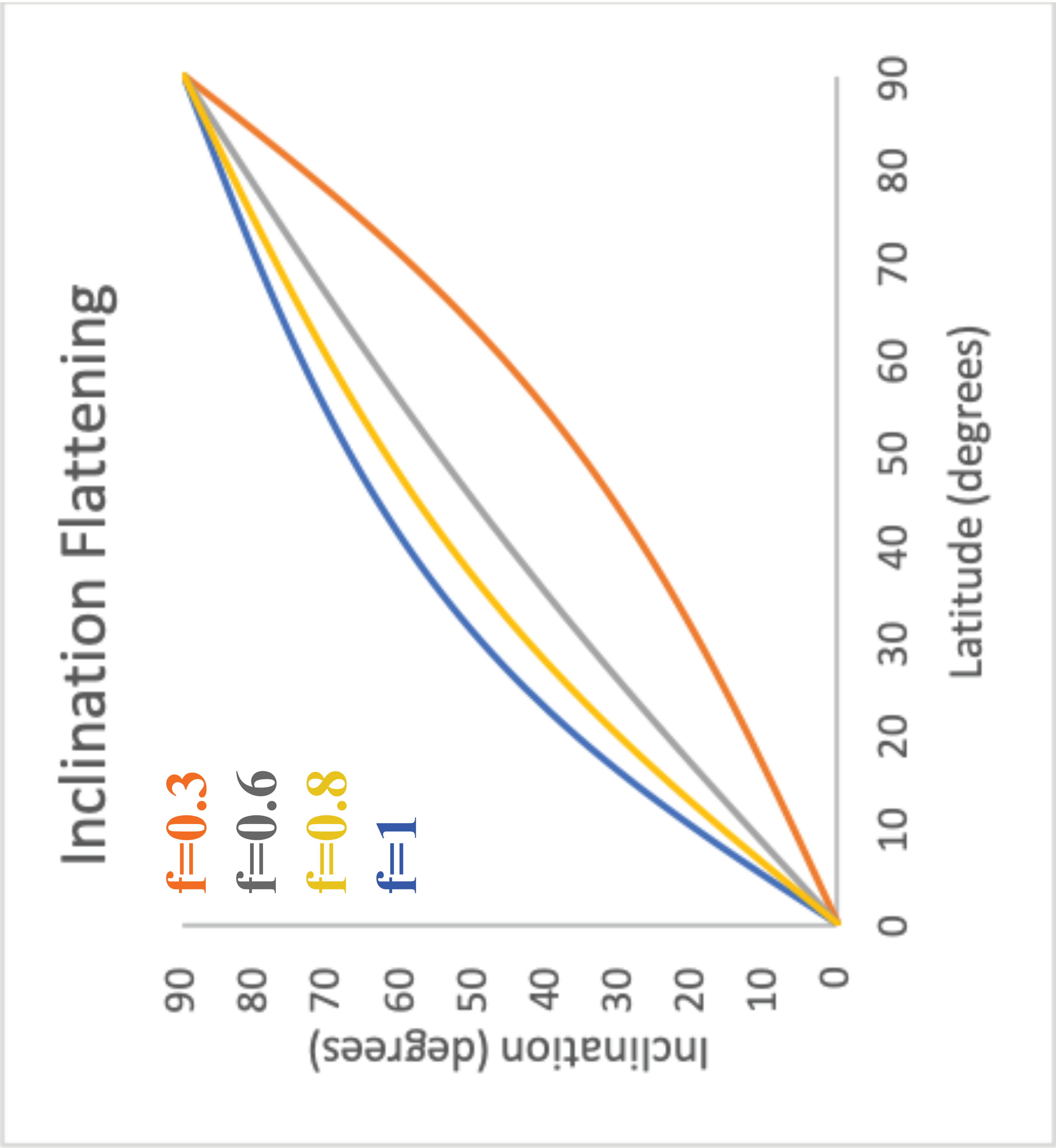

Inclination Flattening
f=0.3
f=0.6
f=0.8
f=1
Inclination (degrees)
Latitude (degrees)
0
10
20
30
40
50
60
70
80
90

Figure8

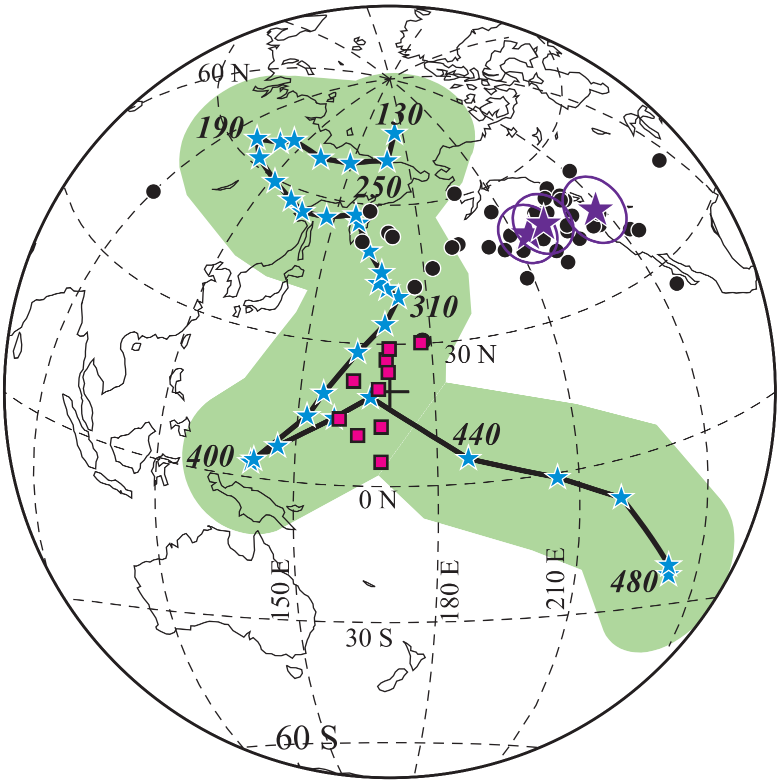
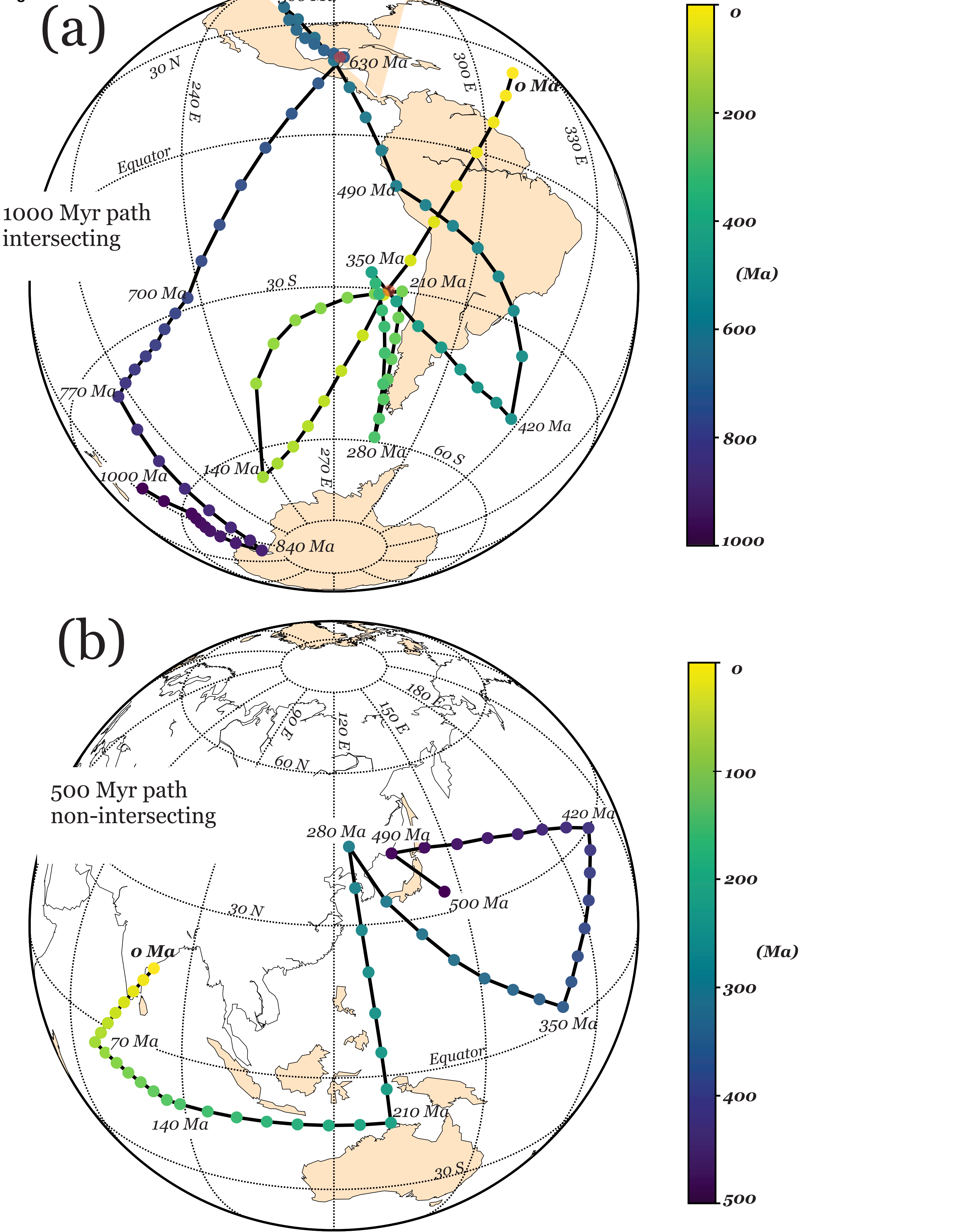


Figure9



(a)
1000 Myr path
intersecting
560 Ma
630 Ma
0 Ma
490 Ma
350 Ma
210 Ma
700 Ma
770 Ma
420 Ma
280 Ma
140 Ma
1000 Ma
840 Ma
30 N
Equator
30 S
60 S
240 E
270 E
300 E
330 E
0
200
400
600
800
1000
(Ma)
(b)
500 Myr path
non-intersecting
420 Ma
280 Ma
490 Ma
500 Ma
350 Ma
0 Ma
70 Ma
140 Ma
210 Ma
60 N
30 N
Equator
30 S
90 E
120 E
150 E
180 E
0
100
200
300
400
500
(Ma)

***Declaration of Interest Statement**

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: