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Reliability of palaeomagnetic poles from sedimentary rocks

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SUMMARY

Palaeomagnetic poles form the building blocks of apparent polar wander paths and are used as primary input for quantitative palaeogeographic reconstructions. The calculation of such poles requires that the short-term, palaeosecular variation (PSV) of the geomagnetic field is adequately sampled and averaged by a palaeomagnetic data set. Assessing to what extent PSV is recorded is relatively straightforward for rocks that are known to provide spot readings of the geomagnetic field, such as lavas. But it is unknown whether and when palaeomagnetic directions derived from sedimentary rocks represent spot readings of the geomagnetic field and sediments are moreover suffering from inclination shallowing, making it challenging to assess the reliability of poles derived from these rocks. Here, we explore whether a widely used technique to correct for inclination shallowing, known as the elongation–inclination (E/I) method, allows us to formulate a set of quality criteria for (inclination shallowing-corrected) palaeomagnetic poles from sedimentary rocks. The E/I method explicitly assumes that a sediment-derived data set provides, besides flattening, an accurate representation of PSV. We evaluate the effect of perceived pitfalls for this assumption using a recently published data set of 1275 individual palaeomagnetic directions of a >3-km-thick succession of ∼69–41.5 Ma red beds from the Gonjo Basin (eastern Tibet), as well as synthetic data generated with the TK03.GAD field model. The inclinations derived from the uncorrected data set are significantly lower than previous estimates for the basin, obtained using coeval lavas, by correcting inclination shallowing using anisotropy-based techniques, and by predictions from tectonic reconstructions. We find that the E/I correction successfully restores the inclination to values predicted by these independent data sets if the following conditions are met: the number of directions N is at least 100, the A95 cone of confidence falls within a previously defined $A95_{\text{min-max}}$ reliability envelope, no negative reversal test is obtained and vertical-axis rotation differences within the data set do not exceed 15°. We propose a classification of three levels (A, B and C) that should be applied after commonly applied quality criteria for palaeomagnetic poles are met. For poles with classification ‘A’, we find no reasons to assume insufficient quality for tectonic interpretation. Poles with classification ‘B’ could be useful, but have to be carefully assessed, and poles with classification ‘C’ provide unreliable palaeolatitudes. We show that application of these criteria for data sets of other sedimentary rock types classifies data sets whose reliability is independently confirmed as ‘A’ or ‘B’, and that demonstrably unreliable data sets are classified as ‘C’, confirming that our criteria are useful, and conservative. The implication of our analysis is that sediment-based data sets of quality ‘A’ may be considered statistically equivalent to data sets of site-mean directions from rapidly cooled igneous rocks like lavas and provide high-quality palaeomagnetic poles.

Key words: Palaeomagnetic secular variation; Palaeomagnetism; Statistical methods; Inclination shallowing; E/I correction.

1 INTRODUCTION

Palaeomagnetic poles are extensively used as input for palaeogeographic reconstructions and models of regional tectonic deformation, and for the construction of apparent polar wander paths (APWPs, e.g. Besse & Courtillot 2002; Torsvik *et al*. 2008, 2012; Kent & Irving 2010; Kent & Muttoni 2020; Li *et al*. 2017; Wu *et al*. 2020). These APWPs describe the motion of plates and continents relative to the Earth's spin axis and thereby provide the reference frame for palaeogeography, -palaeoclimate, palaeobiology and palaeoceanography studies (e.g. van Hinsbergen *et al.* 2015). Each palaeomagnetic pole is assumed to provide an accurate representation of the time-averaged geomagnetic field that existed during the formation of the rock, and that this field is approximately a geocentric axial dipole (GAD) field (e.g. Creer *et al.* 1954; Tauxe & Kent 2004). To evaluate the reliability of a pole, the palaeomagnetic community widely uses a set of seven criteria, originally formulated by van der Voo (1990) and recently updated by Meert *et al.* (2020). A fundamental requirement for a reliable pole is that the short-term, palaeosecular variation (PSV) of the geomagnetic field is adequately sampled, such that it can be averaged 'out' to obtain an accurate estimate of the GAD field (e.g. Butler 1992; Deenen *et al.* 2011; Meert *et al.* 2020).

To assess to what extent PSV is recorded by a data set, the observed dispersion of virtual geomagnetic poles (VGPs) is commonly evaluated against statistics-based criteria that are derived from reference models of the geomagnetic field (e.g. Butler 1992; Deenen *et al*. 2011, 2014; Meert *et al.* 2020). These models are calibrated against palaeomagnetic measurements obtained from fast-cooled, young (<5 Ma) igneous rocks, whose within-site directional reproducibility is checked against quantitative criteria (typically sites with $k > 50$ are considered reliable spot readings, e.g. Biggin *et al.* 2008; Johnson *et al.* 2008), and whereby the thermal remanent magnetization acquired during rapid cooling provides, in principle, an 'instantaneous' record of the ambient field (e.g. McElhinny & McFadden 1997; Tauxe & Kent 2004; Johnson *et al.* 2008; Cromwell *et al.* 2018; Doubrovine *et al.* 2019). Statistics-based quality criteria derived from these models thus apply to data sets whereby each VGP represents a spot reading of the geomagnetic field, such as those obtained from lavas and thin dykes (e.g. Meert *et al.* 2020). But, for sedimentary rocks, it is often unclear whether individual directions (or VGPs) provide spot readings of the geomagnetic field. On the one hand, sediment samples represent some geological time and partial averaging of PSV may occur in a single palaeomagnetic sample, depending on the rate of sediment accumulation and the duration of acquisition of the remanent magnetization (Kodama 2012). On the other hand, because sedimentary beds do not form geologically instantaneously, like lavas do, there are currently no objective criteria to assess whether a sediment-based palaeomagnetic direction is reproducible and whether it may be considered a spot reading. For instance, Meert *et al.* (2020) recommend taking at least three samples per horizon but provide no definition of a horizon or a statistical criterion to test the internal consistency of a sedimentary site. As a result, the chance of including erroneous directions is thus larger for sediments than for lavas. This makes it challenging to test whether the scatter of directions (and associated VGPs) in a sediment-based data set is representative for PSV, such that an accurate palaeomagnetic pole may be determined.

Despite these problems, a method that is widely used in the palaeomagnetic community to correct for the notorious problem of inclination shallowing explicitly assumes that each palaeomagnetic direction obtained from a sedimentary rock closely represents a spot reading of the geomagnetic field: the so-called elongation–inclination (E/I) method of Tauxe & Kent (2004). In sedimentary rocks that suffer from inclination shallowing, the observed inclination is shallower than the inclination of the geomagnetic field in which the rocks were initially magnetized (King 1955). Inclination shallowing is widely observed in clastic sedimentary rocks, and particularly in hematite-bearing red beds, but has also been documented for carbonate rocks (e.g. Dallanave *et al*. 2009, 2012; Meijers *et al.* 2010a,b; Muttoni *et al*. 2013, 2018). When unnoticed, inclination shallowing may lead to major underestimations of the primary palaeomagnetic inclination (and associated palaeolatitude) of up to 25–30° (e.g. Kodama 2012). Inclination shallowing may thus cause a substantial bias in palaeogeographic reconstructions or (reference) APWPs, for which palaeomagnetic poles from sedimentary rocks are widely used as input (e.g. Kent & Irving 2010; Domeier *et al.* 2011; Torsvik *et al.* 2012; Muttoni *et al.* 2013; Wu *et al*. 2017, 2020; Kent & Muttoni 2020). Therefore, this artefact must be corrected for before a sediment-based pole is included in such models, and the E/I method is widely used to this end.

Importantly, the E/I method critically relies on the assumption that the observed distribution of palaeomagnetic directions provides, besides flattening, an accurate representation of PSV (Tauxe & Kent 2004; Tauxe *et al.* 2008). The method has been shown to successfully restore inclinations to values confirmed by independent data sets that were obtained using anisotropy-based inclination shallowing corrections or from lava-based data sets (e.g. Kent & Tauxe 2005; Tauxe *et al.* 2008; Bilardello *et al.* 2011; Huang *et al.* 2013, 2015). Nevertheless, there are several perceived pitfalls that could make it difficult to distinguish the scatter related to PSV from other sources of noise, for example resulting from syn-sedimentary rotations (Kodama 2012; Li & Kodama 2016; Meng *et al.* 2017), secondary magnetic overprints (Channell *et al.* 2010; Bilardello *et al.* 2018), misorientations of particles (Jezek *et al.* 2012; Bilardello 2013; Bilardello *et al.* 2013), partial averaging of PSV in a sample (Kodama 2012; Li & Kodama 2016), tectonic strain (Dallanave & Kirscher 2020), or measuring errors. Importantly, if the observed scatter in the palaeomagnetic data set does not accurately represents PSV, the E/I correction yields erroneous inclination shallowing corrections. However, if the E/I method indeed restores the correct primary inclination, then the assumption that the data scatter represents PSV is apparently a correct approximation. In that case, a reliable, inclination shallowing-corrected palaeomagnetic pole is obtained. Despite the identification of potential pitfalls such as those listed above, there are currently no (quantitative) guidelines for the robust application of the E/I correction.

In this paper, we investigate under which circumstances the E/I method accurately corrects for inclination shallowing. As a basis for our analysis, we use an exceptionally large data set of 1275 individual palaeomagnetic directions from a >3 km-thick succession of red beds from the Gonjo Basin of eastern Tibet (Fig. 1), covering a magnetostratigraphically constrained ∼27.5 Ma time interval (∼69–41.5 Ma, Li *et al.* 2020a,b). Li *et al.* (2020a,b) showed that the sampled sedimentary sequence contains commonly quoted potential pitfalls for the E/I correction method (e.g. Kodama 2012; Li & Kodama 2016): intervals with syn-sedimentary vertical-axis rotations, large variations in sedimentation rate (of <10 to >25 cm ka^{-1}), intervals with low magnetic intensity, and intervals with stronger and weaker anisotropy of magnetic susceptibility (AMS) fabrics, amidst segments without such potential pitfalls. We assess how these parameters affect the results of the E/I correction. In addition, we test the influence of partial averaging of PSV, the application of commonly used cut-offs, and the number of directions used for the

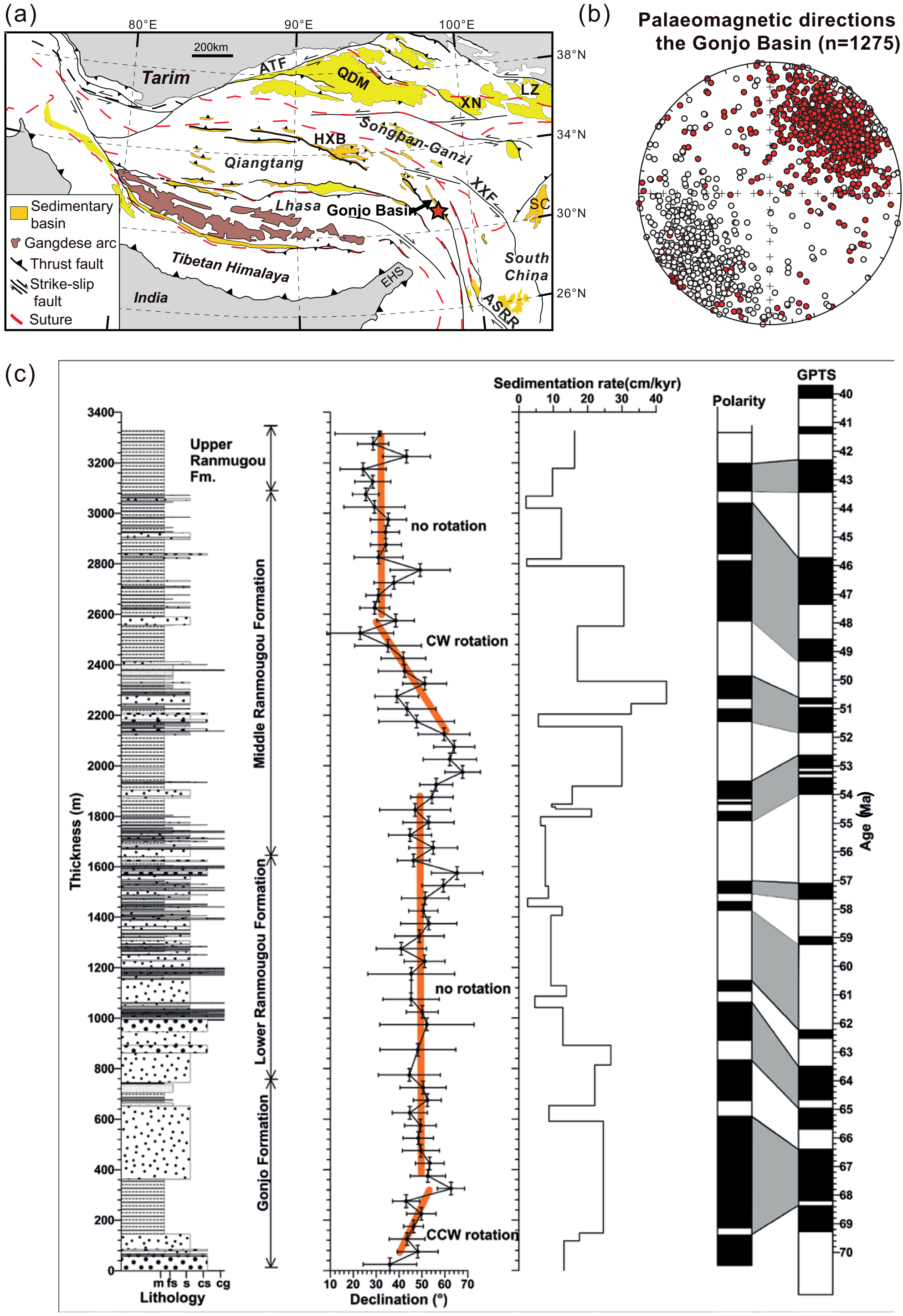

Figure 1. (a) Simplified tectonic map of the Tibetan region after Li *et al.* (2020a). The location of the sampled section (30.85°N, 98.3°E) is indicated by a red star. For more details on the basins and faults, please see Li *et al.* (2020a). (b) All 1275 palaeomagnetic directions of the Gonjo Basin from Li *et al.* (2020a,b) that are used in this study. (c) Comparison of lithology, palaeomagnetic declination and sedimentation rate against stratigraphic level in the Gonjo Basin section, modified after Li *et al.* (2020a,b). The interpreted magnetozones and their correlation with the geomagnetic polarity timescale is also shown. The orange curve shows the vertical-axis rotations identified by Li *et al.* (2020a).

E/I correction, by using both the Gonjo Basin data set as well as synthetic data sets drawn from the TK03.GAD field model of Tauxe & Kent (2004). Based on our analysis, we propose a set of reliability criteria for the successful application of the E/I correction. We then use an extensive compilation of previously published E/I corrected data sets to evaluate whether our new criteria correctly classify data sets that were independently demonstrated to be reliable or unreliable. We discuss how the new criteria, which form an extension of the widely applied criteria as formulated by Meert *et al.* (2020), may be used to evaluate the reliability of sediment-based palaeomagnetic poles. Finally, we discuss the implications of our analysis for the use and statistical treatment of palaeomagnetic data from sedimentary rocks and the poles derived from those.

2 BACKGROUND OF THE E/I METHOD

Inclination shallowing was first recognized some 65 yr ago by King (1955) and results either from depositional processes (e.g. Griffiths *et al.* 1960; Tauxe & Kent 1984; Tauxe *et al.* 2006) and/or post-depositional compaction (e.g. Anson & Kodama 1987; Kodama 1997). More recently, it was shown by both numerical and lab experiments that particle misalignment due to processes that occur in the water column may provide a significant contribution to shallow inclinations (e.g. Jezek *et al.* 2012; Bilardello 2013; Bilardello *et al.* 2013). Palaeomagnetic directions that suffer from inclination shallowing are well-documented, for instance from Cenozoic clastic sedimentary rocks in Central Asia (e.g. Gilder *et al.* 2001; Tan *et al.* 2003; Dupont-Nivet *et al.* 2010; Huang *et al*. 2013, 2015; Li *et al.* 2013). The problem of inclination shallowing is not restricted to a specific type of sedimentary rocks, and has been reported for hematite-bearing red beds (e.g. Tauxe & Kent 1984; Garcés *et al.* 1996; Gilder *et al.* 2001; Tan & Kodama 2002; Kent & Tauxe 2005; Billardello & Kodama 2010a), magnetite-bearing (marine) clastic sediments (e.g. Ali *et al.* 2003; Tamaki *et al.* 2008; van Hinsbergen *et al.* 2010; Huang *et al.* 2015) and carbonate rocks (e.g. Dallanave *et al*. 2009, 2012; Meijers *et al.* 2010a,b; Channell *et al.* 2010; Muttoni *et al*. 2013, 2018).

Presently, two different approaches are routinely used to correct for inclination shallowing: the palaeomagnetic direction-based E/I method (Tauxe & Kent 2004) and the sedimentary fabric-based methods that use magnetic anisotropy of susceptibility and remanence (e.g. Jackson *et al.* 1991; Kodama 1997, 2009; Tan & Kodama 2003). The anisotropy-based corrections focus on the assemblage of individual magnetic particles themselves, providing direct physical evidence for compaction-induced strain, and infer from this the magnitude of inclination shallowing. The E/I method, on the other hand, relies on the comparison of the observed distribution of palaeomagnetic directions with the expected ratio of elongation versus mean inclination, as predicted by the TK03.GAD giant Gaussian process (GGP) model of the geomagnetic field (Tauxe & Kent 2004). Although the two approaches have previously provided very similar results where they were both applied to the same sample collection (Tauxe *et al.* 2008; Bilardello *et al.* 2011; Huang *et al*. 2013, 2015; Tong *et al.* 2017; Westerweel *et al.* 2019), the E/I method has several important advantages: it requires no additional time-consuming (rock) magnetic experiments other than straightforward demagnetization, it is relatively easy to use, and it is routinely incorporated in palaeomagnetic software packages (e.g. Koymans *et al*. 2016, 2020; Tauxe *et al.* 2016).

The E/I method forms one of the main applications of the TK03.GAD statistical model of geomagnetic secular variation (Tauxe & Kent 2004). The TK03.GAD model parameters were configured to fit a compilation of palaeomagnetic data by McElhinny & McFadden (1997), whereby each of the >2500 palaeomagnetic directions (and associated VGPs) represented a multispecimen average of a spot reading of the geomagnetic field obtained from a single lava flow or thin dyke that erupted during the last 5 Myr. Although the compilation of McElhinny & McFadden (1997) is now outdated, the TK03.GAD model still provides an adequate fit with the more recent PSV10 database by Cromwell *et al.* (2018), at least for latitudes up to 70° (Brandt *et al.* 2020). Importantly, by using the TK03.GAD model, and therefore also the E/I method, one implicitly assumes that the past time-averaged geomagnetic field behaved similar to that of the last 5 Myr and closely resembles that of a GAD field (Tauxe & Kent 2004; Tauxe 2005). The E/I method has been shown to produce robust results when applied to data sets derived from Mesozoic and Upper Palaeozoic rocks (e.g. Kent & Tauxe 2005; Tauxe *et al.* 2008; Bilardello *et al.* 2011), suggesting that the technique may be reliably applied to rocks much older than 5 Ma.

The TK03.GAD model generates circularly symmetric distributions of VGPs, which give directional distributions that are elongated along the meridian, that is in the north–south direction. This elongation of palaeomagnetic directions was already described more than 50 yr ago and varies as a function of latitude (Creer *et al.* 1959; Creer 1962; Cox 1970; Tanaka 1999). The degree of elongation can be expressed by the elongation parameter *E*, which is defined as the ratio of the intermediate and minimum eigenvalues (τ_2/τ_3) of a tensor fit to the distribution of directions (Tauxe 1998). In the TK03.GAD model, the elongation decreases with increasing latitude (and hence increasing inclination) from about 3 at the equator to close to 1 at the poles (Tauxe & Kent 2004). The E/I method exploits this relationship between the elongation and inclination to both detect and correct for inclination shallowing.

Inclination shallowing processes like post-depositional compaction may result in a ‘flattening’ of the distribution of palaeomagnetic directions from sedimentary rocks, reducing both the (north–south) elongation (*E*) and mean inclination (*I*). In principle, the E/I method assumes that any deviations from the elongation versus inclination curve, as predicted by the TK03.GAD model, are purely the result of inclination shallowing and that this shallowing follows the equation of King (1955): $\tan I_0 = f \tan I_f$, where f is the so-called flattening factor and I_0 and I_f are the observed and applied field inclination, respectively. This relationship indicates that the effect of inclination shallowing is the greatest for rocks formed at intermediate latitudes, whereby observed inclinations may be up to 25–30° too shallow (e.g. Kodama 2012). Notably, it has been shown that there is no characteristic flattening factor for either hematite- or magnetite-bearing sediments, and the magnitude of inclination shallowing may vary significantly between different sedimentary successions or lithologies (e.g. Kent & Tauxe 2005; Bilardello & Kodama 2010b; Kodama 2012), indicating that the magnitude of flattening depends on the specific lithological and rock magnetic characteristics of the sampled rocks. We note, however, that the E/I method assumes that the palaeomagnetic directions used for the correction have the same average flattening factor (Tauxe *et al.* 2008), regardless of the lithological variations throughout the sampled stratigraphy. For hematite-bearing rocks such as (most) red beds, obtained flattening factors are often within the range of $f = 0.4$–0.7 (Kent & Tauxe 2005; Bilardello & Kodama 2010b; Kodama 2012).

The E/I method relies on the assumption that the scatter in the palaeomagnetic data set on which it is applied is representative of PSV. Based on Monte Carlo simulations, an estimated minimum number of 100 readings of the geomagnetic field are required to accurately represent secular variation and to provide a reliable inclination shallowing correction (Tauxe *et al*. 2003, 2008). The method is thus particularly well suited on large data sets, such as those derived from magnetostratigraphic studies. To correct for inclination shallowing, a stepwise unflattening of the distribution is applied by using different values for f, starting with $f = 1$ (no flattening) and decreasing toward $f = 0$ (complete flattening). The ‘original’ field inclination is then estimated by calculating the ratio of elongation versus mean inclination, until it matches the predicted E/I curve

(Fig. 2; Tauxe & Kent 2004). Confidence bounds are subsequently obtained by performing a bootstrap resampling technique on the data set, whereby the 95 per cent confidence bounds are given by the interval of inclinations in which 95 per cent of the (e.g. 1000) bootstrapped pseudosamples lie (Fig. 2).

3 DATA SET

We use the extensive palaeomagnetic data set from a high-resolution magnetostratigraphy study by Li *et al.* (2020a) from a section covering the 69–41.5 Ma time interval. Sampling was performed along a 3325-m-thick section in the Gonjo Basin (30.85°N, 98.3°E, Fig. 1a), located in the eastern part of the Qiangtang terrane, eastern Tibet. The >200-km-long NW–SE-oriented Gonjo Basin is one of many thrust-bounded basins in central and eastern Tibet and is interpreted to have formed as a syn-contractional basin in the footwall of the Yangla fold-thrust system (Studnicki-Gizbert *et al.* 2008; Tang *et al.* 2017). The sedimentary strata of the basin are now exposed in an asymmetric syncline, and mainly consist of red-coloured mudstones, sandstones and rare conglomerates, reaching a total thickness of >3500 m (Studnicki-Gizbert *et al.* 2008; Tang *et al.* 2017).

Palaeomagnetic samples were collected in the field with an average interval of ∼2 m. Rock magnetic analysis suggested that hematite is the main carrier of magnetic remanence in the Gonjo Basin rocks, with a small contribution of magnetite for the bottom part of the section (Li *et al.* 2020a,b). After progressive stepwise thermal demagnetization up to a maximum temperature of 690 °C on 1766 palaeomagnetic samples, a total of 1317 characteristic remanent magnetization (ChRM) directions were identified, of which 42 directions were determined using the great circle approach of McFadden & McElhinny (1988). Because great circle-determined directions are not direct measurements of the palaeomagnetic field, but best-fitting approximations, we exclude these from the data set. This gives a total of 1275 palaeomagnetic directions that were used for the analysis presented here (Fig. 1b; Table S1, Supplementary Materials A). A positive fold test (Tauxe & Watson 1994) and positive reversal test of the non-rotated intervals support a primary origin of the remanent magnetization for the sampled succession (see Li *et al.* 2020a), consistent with previous palaeomagnetic studies of the same basin (Tong *et al.* 2017; Zhang *et al.* 2018).

Li *et al.* (2020a) showed that the sampled sedimentary sequence of the Gonjo Basin records two syn-depositional vertical-axis rotation phases: a ∼10° counter-clockwise rotation from 69 to 67 Ma and a ∼30° clockwise rotation from 52 to ∼48 Ma (Fig. 1c). In addition, correlation of the observed magnetozones with the geomagnetic polarity timescale revealed two phases with a higher sediment accumulation rates of ∼20 cm ka^{-1}, at 69–64 Ma and 52–48 Ma, amidst rates of 7–8 cm ka^{-1} for the other time intervals (Fig. 1c). These phases with rapid sedimentation are largely coeval with the observed rotations, leading Li *et al.* (2020a) to suggest that they reflect two distinct pulses of crustal shortening. This interpretation is supported by a subsequent study on the AMS of the same sedimentary succession, which showed the presence of a ‘pencil structure’ fabric (e.g. Parés *et al.* 1999) in the ∼52–41.5 Ma interval of the section, indicating an increase in tectonic strain at ∼52 Ma (Li *et al.* 2020b). Here, we make extensive use of the detailed information on the sampled sedimentary succession of the Gonjo Basin provided by these previous studies, and we refer the reader to Li *et al.* (2020a,b) for details on demagnetization, rock magnetism, AMS and field tests.

4 METHODS

We perform a series of experiments to test under which circumstances the E/I method produces robust and reproducible results, and how the technique may be used to assess whether PSV is adequately sampled by the palaeomagnetic data set. We assess how the results may be affected by vertical-axis rotations, variations in sedimentation rate, the presence of non-PSV-induced scatter, the effect of cut-offs and the number of directions used for the correction. In each experiment described below, we apply the E/I correction for inclination shallowing (Tauxe & Kent 2004) to collections of palaeomagnetic directions selected from the total data set of 1275 directions. The size of each collection depends on the question addressed, but sample sets were drawn in consecutive stratigraphic order. In addition, we use synthetic data sets of directions generated from the TK03.GAD model of Tauxe & Kent (2004). We developed a number of Python codes to perform our calculations and to visualize our results, whereby we made extensive use of several key functions and programs from the freely available palaeomagnetic software package PmagPy (Tauxe *et al.* 2016). In particular, we used the ‘find_ei’ and ‘tk03’ programs from this package to perform the E/I correction and to generate synthetic data from the TK03.GAD model, respectively. The E/I correction uses the principal direction of the data, corresponding to the eigenvector associated with the maximum eigenvalue of a tensor fit to the distribution of palaeomagnetic directions (Tauxe & Kent 2004; Tauxe 2005). For consistency, we express the average palaeomagnetic direction of each collection of palaeomagnetic directions by the principal direction, rather than the Fisher (1953) mean direction. It has long been shown that Fisher (1953) statistics should not be applied to palaeomagnetic directions (e.g. Creer *et al.* 1959; Cox 1970; Tauxe & Kent 2004), but may be applied to VGPs instead (Deenen *et al.* 2011). In the following, we only use Fisher (1953) statistics for the calculation of two commonly used statistical parameters related to the observed distribution of VGPs: the radius of the 95 per cent confidence circle about the mean (A95) and the Fisher precision parameter (K).

As a reference to test the E/I corrected inclination values against, we use three independent estimates of the inclination (and palaeolatitude) for (the eastern part of) the Qiangtang terrane (Fig. 3). First, we use the result of the anisotropy-based inclination shallowing correction method of Hodych & Buchan (1994) performed by Tong *et al.* (2017) on Gonjo Basin sediments, revealing a corrected inclination of 41.6° ($\alpha_{95} = 3.2°$), corresponding to a palaeolatitude of 23.9 ± 1.9°. They obtained similar values by applying the E/I method to separate data sets from two limbs of a large fold, yielding corrected inclinations of 40.3° (34.0–45.3°) and 40.4° (33.5–46.7°), respectively. The age of the sampled succession was initially estimated as 43.2–56.0 Ma by Tong *et al.* (2017), but is likely younger than the end of the ∼30° clockwise rotation (∼48 Ma), based on a comparison of the observed mean declination of ∼35° with the declination curve from Li *et al.* (2020a). Secondly, Roperch *et al.* (2017) reported a mean inclination of 41.6° ($\alpha_{95} = 8.0°$), corresponding to an in situ palaeolatitude of 23.9 ± 6.5°, from 21 sites in 49–51 Ma lavas of the Xialaxiu area, located ∼250 km to the north-northwest of the Gonjo basin. Third, we use estimates of the inclination of the (eastern) Qiangtang terrane as predicted by kinematic restorations of eastern Tibet based on structural geological constraints on intra-Tibetan shortening and extrusion (van Hinsbergen *et al.* 2019) placed in the global palaeomagnetic reference frame of Torsvik *et al.* (2012) (Fig. 3). We note that the observed inclination values of Tong *et al.* (2017) and Roperch *et al.* (2017) are

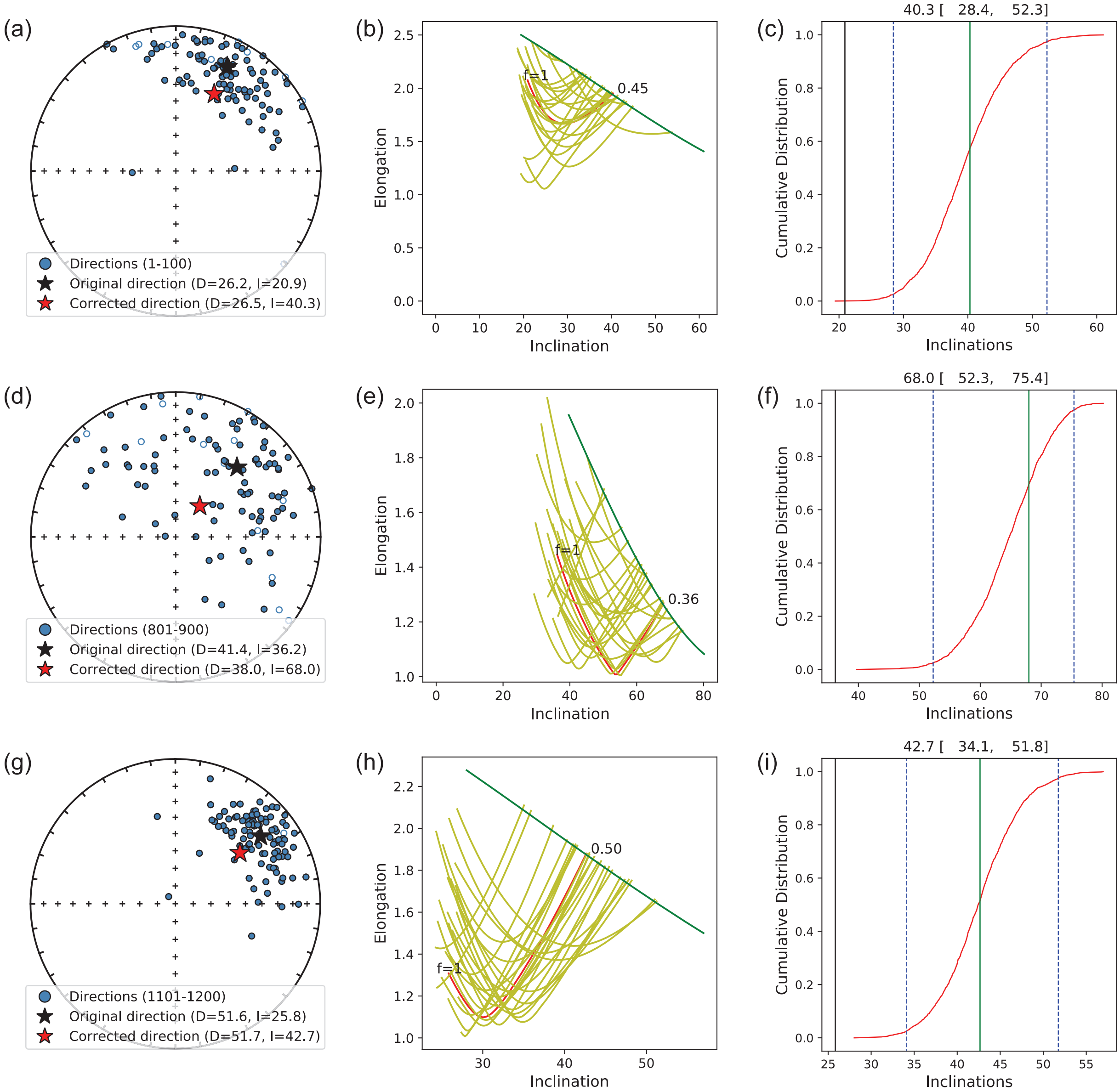

Figure 2. Examples of three groups of 100 successive palaeomagnetic directions from the Gonjo Basin data set. The stereographic plots (a, d, g) show the uncorrected palaeomagnetic directions (converted to normal polarity, blue circles), the principal direction (black star) and the E/I corrected mean direction (red star) for the three different groups. (b, e, g) Application of the E/I method to the directional data set. The red curves show the elongation versus inclination upon stepwise unflattening of the data set by gradually decreasing the flattening factor (*f*). The dark green curve is the elongation versus inclination curve predicted by the TK03.GAD model (Tauxe & Kent 2004). The intersection between these two curves gives the flattening factor used in the correction for inclination shallowing, as indicated in the plots. The light green curves show the results of stepwise unflattening of 25 bootstrap pseudosamples. (c, f, i) Plots of the cumulative distribution of the corrected inclination as calculated in 2000 bootstrap runs (red). The black and green vertical lines show the uncorrected and corrected inclination, respectively. Confidence bounds that contain 95 per cent of the bootstrap results are shown as two dashed, blue lines.

~5–8° lower than the expected values based on the global APWP of Torsvik *et al.* (2012), in line with previous reports of persistently low inclinations for East Asia for the 50–20 Ma time interval (e.g. Cogné *et al.* 1999, 2013, Hankard *et al.* 2007; Dupont-Nivet *et al.* 2010). For the ~41.5–50 Ma time interval, we therefore use the results obtained by Tong *et al.* (2017) and Roperch *et al.* (2017) as the primary reference against which we compare our corrected inclinations.

5 RESULTS

5.1 Reproducibility of the results of the E/I method

First, we test the reproducibility of the E/I method by applying the correction to groups of 100 successive palaeomagnetic directions selected from the total data set (see examples in Fig. 2). We select these directions by using a sliding window with an inter-

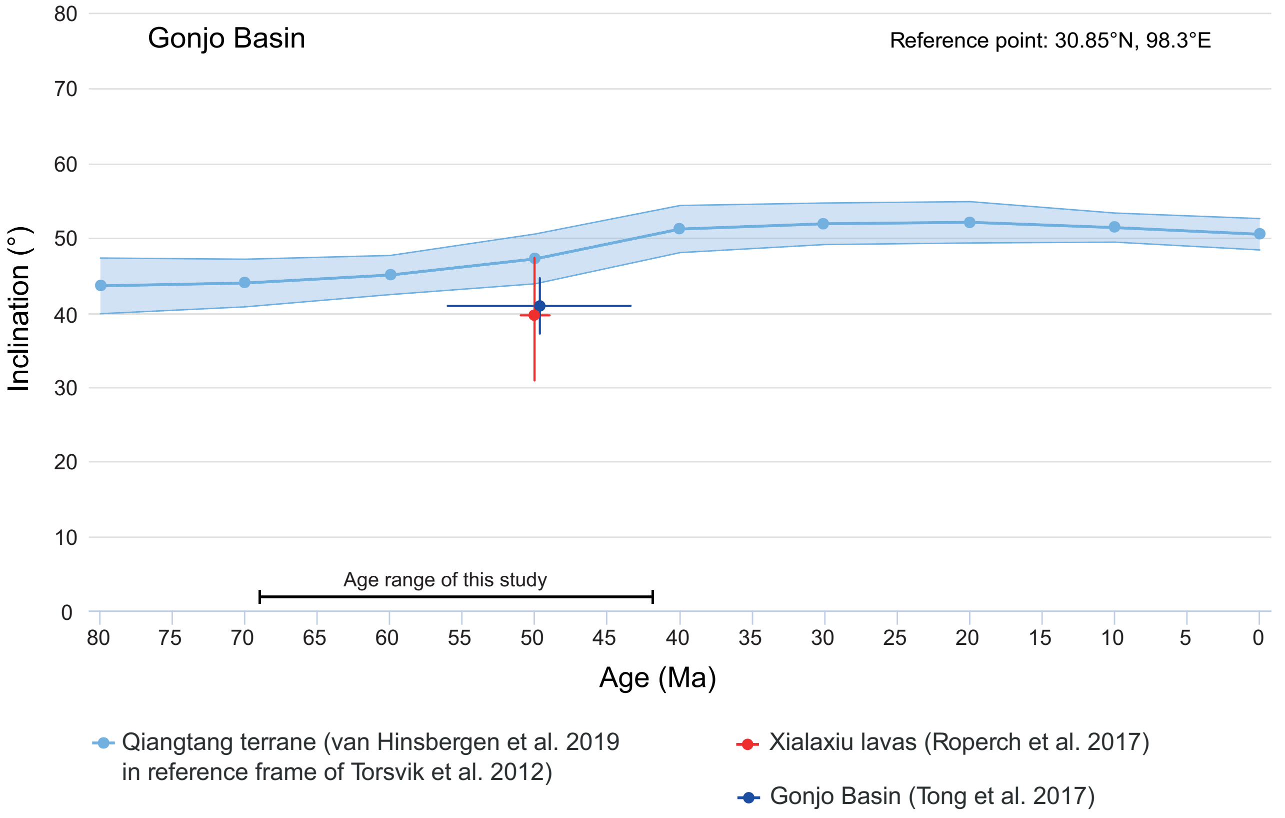

Figure 3. Estimated inclination for the eastern Qiangtang terrane at reference coordinate 30.85°N, 98.3°E based on previously published palaeomagnetic results: the 51–49 Ma lavas of the Xialaxiu area (Roperch *et al.* (2017) and the inclination shallowing-corrected result for the Gonjo Basin red beds (Tong *et al.* 2017), which are shown in red and blue, respectively. The expected inclination for the Gonjo Basin based on the kinematic reconstruction of the Tibetan region by van Hinsbergen *et al.* (2019), placed in the palaeomagnetic reference frame of Torsvik *et al.* (2012), is depicted by the light blue curve (with confidence region). This figure was created using paleomagnetism.org (Koymans *et al*. 2016, 2020).

val of 25 directions. By doing so, we obtain 48 groups of 100 directions, and compute the inclination before and after E/I correction (Fig. 4). The uncorrected group-mean inclinations mostly fall within the range of 20–30°, with some outliers of >30° (Fig. 4a). These are significantly (∼10–20°) lower than the primary inclinations estimated by Tong *et al.* (2017) and Roperch *et al.* (2017), and the predicted inclination for the eastern Qiangtang terrane (Section 4; Fig. 3).

The E/I correction yields mean inclinations that are generally ∼10–25° higher than the observed inclinations. The associated flattening factors are generally between $f = 0.40$ to $f = 0.65$ (Fig. 4b), with a mean of $f = 0.50$ and a standard deviation of 0.10, consistent with previously obtained values for hematite-bearing rocks (Kent & Tauxe 2005; Bilardello & Kodama 2010b; Kodama 2012). The median uncorrected and corrected inclination are 27.0° and 45.0°, respectively, and approximately 60 per cent of the corrected inclinations fall within 5° from this median value. The results for the youngest part of the succession, with an age of <50 Ma, are in agreement with the estimated primary inclination of 41.6° from Tong *et al.* (2017) and Roperch *et al.* (2017) and are thus somewhat lower than predicted by the reference APWP of Torsvik *et al.* (2012). However, for seven groups the E/I correction yields anomalously high inclinations of >55°, some 25–35° higher than the original group-mean inclinations, and entirely inconsistent with independent estimates or tectonic reconstructions (Fig. 4a). In the following, we evaluate to what extent selected potential pitfalls may explain these mismatches.

5.2 Syn-sedimentary rotations

Vertical-axis rotation phases that occur during sediment deposition leads to a wider spread of palaeomagnetic declinations than caused by PSV alone, and thus affects the elongation of the distribution of directions (e.g. Kodama 2012; Tong *et al.* 2015; Meng *et al.* 2017; Zhang *et al.* 2018). To quantify the effect of syn-sedimentary rotations, we created data sets of palaeomagnetic directions generated with the TK03.GAD field model. We used 200 directions to obtain more precise corrections compared to when using the required minimum of 100 directions, although we note that the latter produces very similar results. We first simulated inclination shallowing by applying a flattening factor of 0.6 to the synthetic data, after which we rotated half of the directions with a predefined rotation angle, followed by the application of the E/I method to retrieve the original inclination. Fig. 5 shows that increased elongation caused by the vertical-axis rotation leads to an overcorrection of the original inclination. Unsurprisingly, this overcorrection increases with increasing rotation angle. We note that the results are independent of the applied flattening factor, however. The simulations predict an overestimation of the original inclination of <3° for vertical-axis rotations up to 10°. Also, the magnitude of the rotation-induced overcorrection is dependent on the latitude (and thus, inclination) for which the synthetic data were generated. The largest effect of the simulated syn-sedimentary rotations is observed for the latitude range of ∼10–30° (Fig. 5). For low latitudes, overcorrections of >10° may be expected for rotations >20°. For higher latitudes (>50°), the effects of vertical-axis rotations are relatively limited.

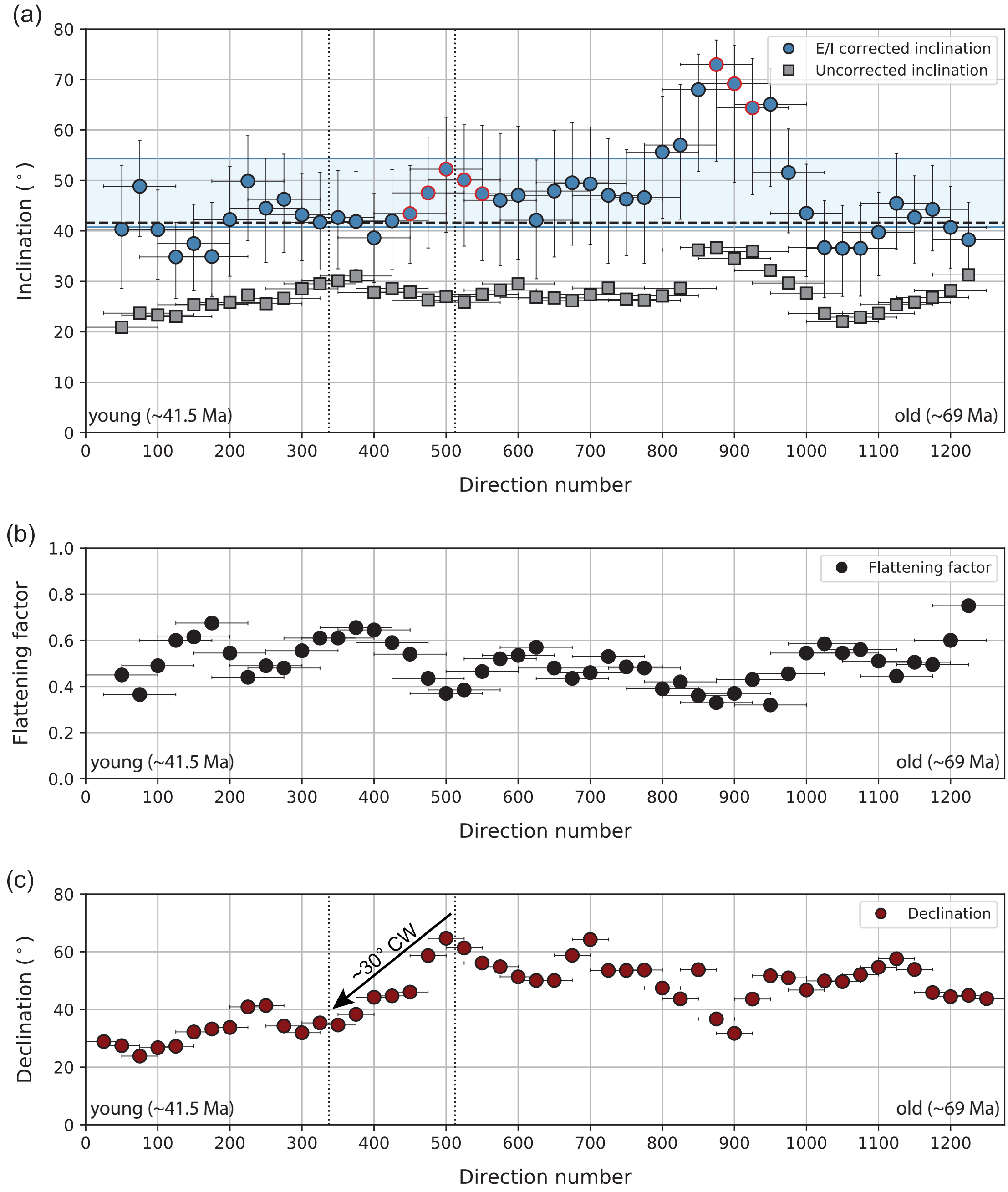

Figure 4. (a) Uncorrected (grey squares) and E/I corrected (blue circles) inclinations for groups of directions of the Gonjo Basin data set. Circles with a red border denote groups with a negative bootstrap reversal test. The E/I method of Tauxe & Kent (2004) is applied to groups of 100 successive directions, using a sliding window with a step of 25. Note that the age of the sampled rocks increases with increasing direction number. As a reference, the inclination of 41.6° obtained from an anisotropy-based inclination shallowing correction by Tong *et al.* (2017) is shown by the dashed black line. The light blue band shows the range of expected inclinations as predicted by the model of van Hinsbergen *et al.* (2019) placed in the reference frame of Torsvik *et al.* (2012). (b) Flattening factors per group of 100 directions as determined by the E/I correction. (c) Mean declination of 50 successive directions calculated using a sliding window with an interval of 25. The ~30° clockwise rotation identified by Li *et al.* (2020a) is highlighted by the black arrow.

Within our data set, most groups in the interval that recorded the ~30° clockwise rotation phase (~52–48 Ma; Figs 4a and c) do not yield a significant overestimation of the initial inclination, although it should be noted that the rotation phase covers an interval of ~160 directions: collections of 100 samples in this case thus only record part of the rotation. Only the groups that consist mostly of directions numbered 450–500, the interval of successive samples for which we observe a change in declination of ~20°, give an overcorrection of ~5–10°. A larger effect is, however, observed for data sets that cover the entire rotation phase. In Section 5.6, where we will test the effect of increasing N, we will return to this topic. We note that the ~52–48 Ma deformation phase also coincides with the development of a 'pencil structure' AMS fabric, which appears in the sediments of ~52 Ma and younger (Li *et al.* 2020b). The presence of a (strong) tectonic fabric may affect the elongation of the directional distribution, as recently shown by Dal-

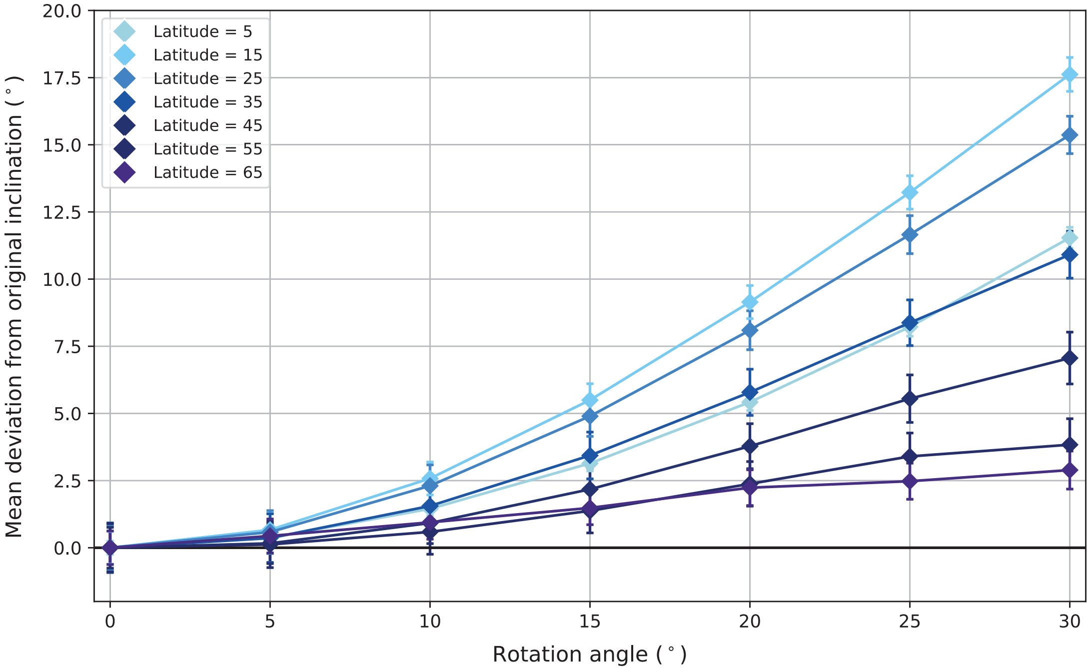

Figure 5. Effect of vertical-axis rotations on the E/I correction. The curves show the average difference between the corrected and original inclination, that is prior to flattening, versus the rotation angle. The average difference is calculated from 100 runs whereby 200 directions generated from the TK03.GAD statistical model are flattened with a flattening factor of 0.6, followed by a rotation of half of the data set with the specified angle and by the application of the E/I correction. Each curve corresponds to the specific latitude for which the directions are initially simulated with the TK03.GAD model. Error bars represent two standard error of the mean.

lanave & Kirscher (2020), and thus also contribute to the observed overestimations of the primary inclination for this interval. However, the 'pencil structure' fabric is also observed for the ∼48–41.5 Ma interval (Li *et al.* 2020b), which yielded corrected inclinations that are consistent with independent results (Fig. 4a), suggesting that the influence of the tectonic fabric on our results is limited. Finally, we find that the ∼10° counter-clockwise rotation recorded by the lowermost part of the sampled sequence (∼69–67 Ma) does not seem to significantly affect the results of the E/I method, in line with the results of the simulations described above.

As a third experiment, we tested the effect of a vertical-axis rotation by using the data set obtained by Gilder *et al.* (2001) of $N = 222$ palaeomagnetic directions from Oligo-Miocene red beds of the Subei area (western China), which was used for the original E/I correction by Tauxe & Kent (2004). Gilder *et al.* (2001) found that the upper part of the section may have rotated ∼15° relative to the lower part. Not correcting for this rotation yielded a minor overcorrection in the inclination of 1.2° (Fig. S1, Supplementary Materials B). Because the rotation of 15° is an estimate with an uncertainty, the magnitude of which depends on the number of samples averaged, and the interpretation of which data are pre- and post-rotation, the rotation correction may add more uncertainty than that it solves.

Overall, these results demonstrate that the effect of vertical-axis rotations of up to 15° on the results of the E/I correction are often limited (<3° for most latitudes, and up to 5° at latitudes of 10–30°). Also, we note that the observed outliers in the results of the E/I method applied to 100 directions of the Gonjo Basin data set (Figs 4a and c) cannot be explained by the effects of vertical-axis rotations. Instead, significant overcorrections of >5° of the primary inclination are only expected for vertical-axis rotations of >15°.

5.3 Sedimentation rate and averaging of PSV

The sedimentation rate controls, for a large part, the amount of time and thus PSV that is recorded in a single palaeomagnetic sample. Decreasing sedimentation rates could lead to an increase in the amount of averaging of PSV that occurs within each sample, reducing the scatter of palaeomagnetic directions/VGPs. Although it is not directly evident that this also affects the elongation of the distribution, it has been suggested that low sedimentation rates may cause an underestimation of the primary inclination obtained from the E/I correction (e.g. Kodama 2012; Li & Kodama 2016). The Gonjo Basin section contains an order of magnitude variations in sedimentation rate (Figs 1c and 6) from >20 cm ka^{-1} to as low as 2–10 cm ka^{-1} (Li *et al.* 2020a). We note, however, that the calculated sedimentation rates correspond to an average rate for a stratigraphic interval of tens to hundreds of metres, and the true accumulation rate for an individual bed may be highly variable (e.g. Opdyke & Channell 1996). Nevertheless, our results reveal no correlation between sedimentation rate and the E/I corrected inclination (Fig. 6). The intervals with relatively low sedimentation rates, at ∼900–1800 m and ∼2800–3325 m, do not correlate with anomalously low corrected inclinations. Instead, some of the lowest (corrected) inclination values correspond to an interval (∼400–600 m) with a high sedimentation rate of >20 cm ka^{-1}. In addition, we observe no correlation between sedimentation rate and the observed scatter of palaeomagnetic directions/VGPs, as indicated by A95 and K (Fig. 6). The intervals with low(er) sedimentation rate do not correlate with reduced scatter, suggesting that the averaging of PSV is not significantly increased compared to intervals with high(er) sedimentation rate.

To assess how the averaging of PSV may influence the observed distribution of directions (or VGPs), we applied the E/I correction

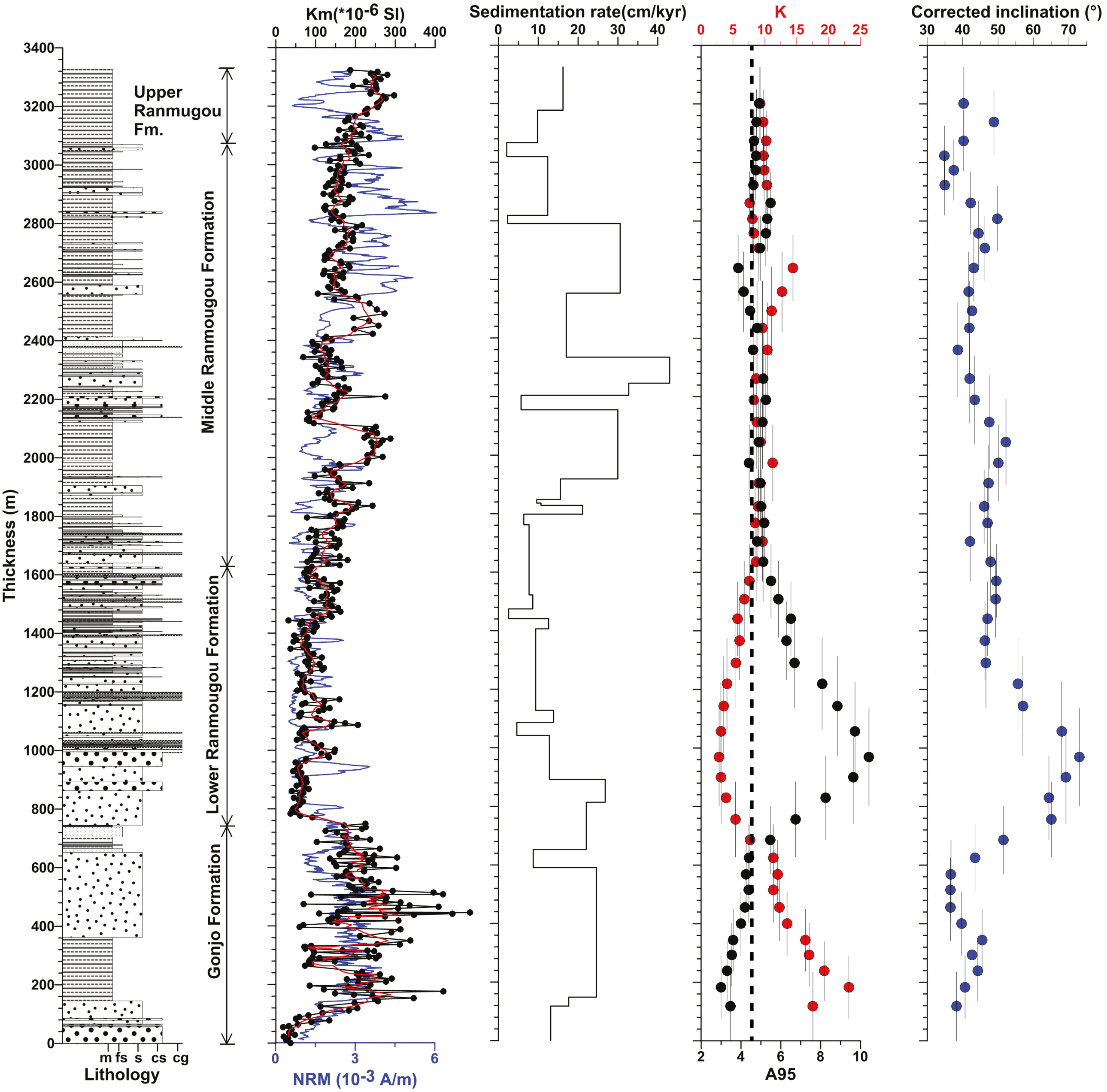

Figure 6. Comparison of (a) lithology, (b) mean magnetic susceptibility (Km, black) and intensity of the natural remanent magnetization (NRM, blue) and (c) sedimentation rate against stratigraphic level in the Gonjo Basin section, after Li *et al.* (2020a,b). (d) A95 (black circles) and *K* (red circles) calculated from the distribution of VGPs obtained from 100 successive palaeomagnetic directions of the Gonjo Basin data set. The dashed, black line shows the $A95_{max}$ calculated for $N = 100$, following the reliability criterion of Deenen *et al.* (2011). (e) E/I corrected inclinations per group of 100 successive directions, using a sliding window with a step of 25, as also plotted in Fig. 4(a).

to sets of 100 artificially created ‘sites’, whereby each site is the average of three successive palaeomagnetic directions from the Gonjo Basin data set (Figs 7a and b). The corrected inclinations for collections of 100 of such ‘sites’ are, on average, only 1.1° (median of 1.8° and standard deviation of 3.5°) lower than the corrected inclinations obtained from the 300 individual directions that were used to create the sites (Fig. 7b). In addition, we applied the E/I correction to sets of 100 ‘sites’ of $N = 3$, 5 and 10 directions generated with the TK03.GAD model, after we applied a flattening factor of $f = 0.6$ to the site-mean directions (see example in Fig. 7c). Again, the effect of averaging multiple directions is limited: the corrected inclinations calculated using the sites are, on average, ∼2° lower than those whereby the E/I correction is applied to the sets of $N = 300$, 500 and 1000 individual directions (see Figs 7c and d). The increased elongation as a result of inclination shallowing processes is thus not significantly reduced by partial averaging of PSV. This demonstrates that although partial averaging of PSV may indeed result in a slight underestimation of the primary inclination, its effect is small, and the E/I method still provides accurate estimates of the primary inclination.

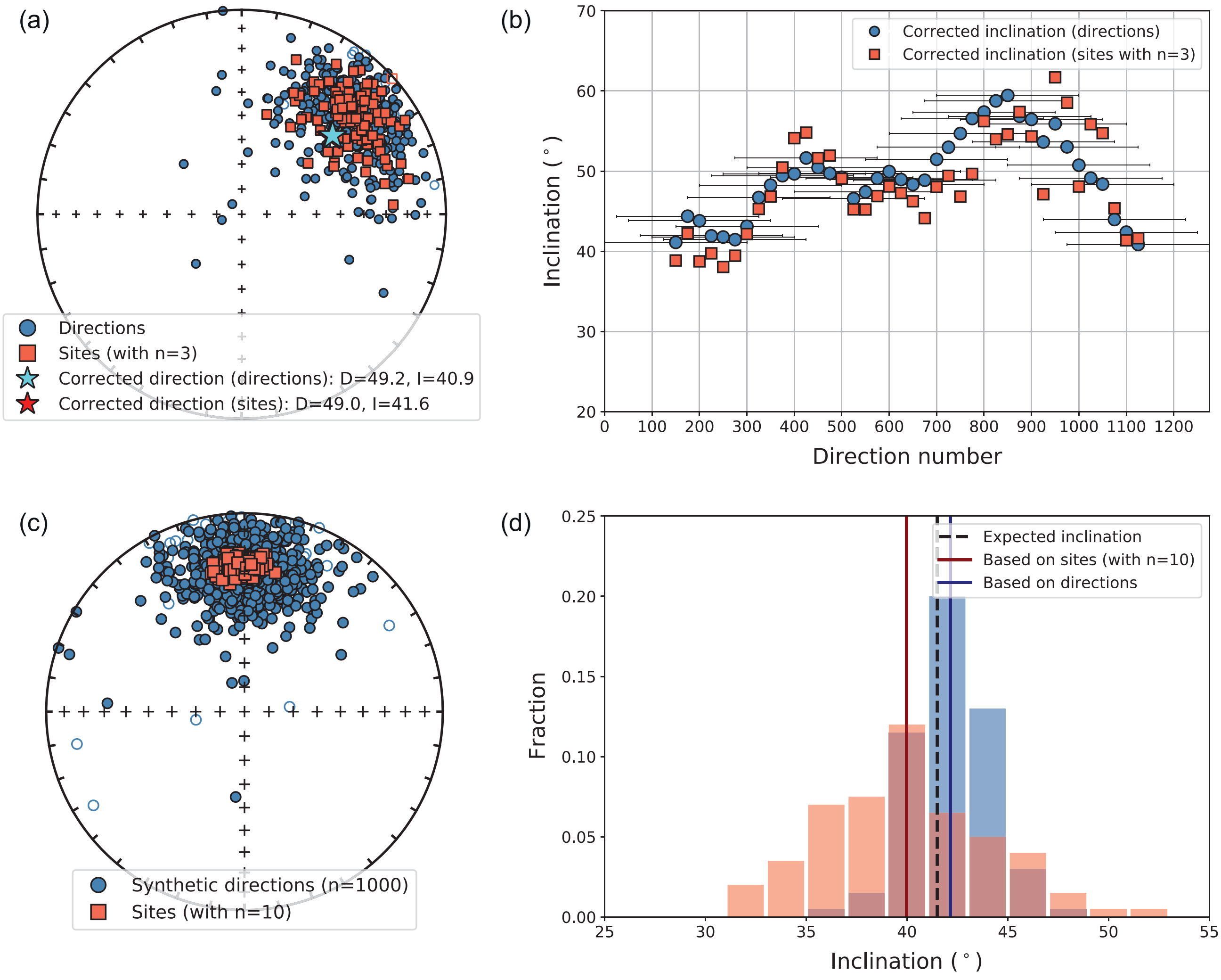

Figure 7. (a) Stereographic plot of 300 palaeomagnetic directions from the Gonjo Basin data set, converted to normal polarity (directions numbered 975–1275, blue circles). 100 'sites' calculated by averaging three successive directions are shown by orange squares. The E/I corrected direction based on the individual directions and 'sites' are indicated by the cyan and red stars, respectively. (b) E/I corrected inclinations calculated from groups of 300 individual directions of the Gonjo Basin data set (blue circles) and from 'sites' based on three successive directions (orange squares). (c) Stereographic plot of 1000 synthetic directions generated with the TK03.GAD statistical model (Tauxe & Kent 2004) for a latitude of 25° (blue circles). The directions are flattened using a flattening factor of $f = 0.6$ (blue circles). Artificial 'sites' based on 10 directions are plotted as orange squares. (d) Histogram of the E/I corrected inclinations of 100 simulated data sets of 1000 individual directions (blue) and 100 'sites' (of $N = 10$ directions). The mean inclinations are depicted by the vertical blue and red lines. The expected inclination (for a latitude of 25°) is plotted by the dashed, black line.

5.4 Scatter of directions unrelated to PSV

The E/I method assumes that the scatter of directions is exclusively due to geomagnetic field behaviour (PSV and geomagnetic excursions), whereby each direction is considered a spot reading ('site') of the past geomagnetic field (e.g. Tauxe *et al.* 2008). Also, it assumes that the distribution of directions was solely distorted by inclination shallowing, following the relation of King (1955) (Section 2). To test whether non-PSV-induced scatter affects our results of the E/I method, we first apply the bootstrap reversal test of Tauxe (2010) to the 28 (out of 48) groups of 100 directions which include at least 20 normal or reverse polarity directions. Even though a reversal test for the two non-rotated intervals was positive (Li *et al.* 2020a), we obtain a negative result for eight of the 28 groups (highlighted in Fig. 4a). Four of these groups (partly) cover the interval that recorded the ~30° clockwise rotation, and three groups yielded very high corrected inclinations of >60°. The latter groups correspond to the stratigraphic intervals from which most great circle directions were determined, suggesting that some magnetic overprints may not be entirely removed. The failed reversal tests of these groups show that the normal and reverse polarity directions are not antipodal, and thus indicate that for some intervals of the Gonjo Basin data set the directional distribution is likely affected by a significant contribution of non-PSV-induced scatter, for instance related to unremoved magnetic overprints or rotations.

To further evaluate this, we use the reliability criterion developed by Deenen *et al.* (2011) which informs whether the observed distribution of palaeomagnetic data may be explained by PSV. They defined an *N*-dependent A95 envelope, whereby an observed distribution of VGPs having an A95 that falls inside this envelope, between the $A95_{\min}$ and $A95_{\max}$, may in principle be straightforwardly explained by PSV alone. Values higher than $A95_{\max}$ likely include sources of scatter other than PSV, whereas values below $A95_{\mathrm{min}}$ indicate an underrepresentation of PSV.

We use this reliability envelope to evaluate whether the principal assumption that the scatter represents solely geomagnetic field behaviour, is met. For $N = 100$ directions, the $\mathrm{A95}_{\mathrm{min}}$ and $\mathrm{A95}_{\mathrm{max}}$ are 1.90° and 4.51°, respectively. We calculated the A95 from the VGPs that correspond to the uncorrected directions. We note that this is a rather lenient approach, as the A95 calculated before the E/I correction is, on average, 0.20° (standard deviation of 0.19°) lower than calculated after the correction (Fig. S2, Supplementary Materials B). A total of 13 out of the 48 groups has an A95 value—calculated prior to the E/I correction—that falls within the A95 envelope defined by Deenen *et al.* (2011), including the lowermost part of the sampled sequence (Fig. 6; Fig. S2, Supplementary Materials B). For these groups, there is no statistical ground to suspect a significant contribution of scatter from sources other than PSV. The majority of groups have an A95 that falls just above ($<1°$) the $\mathrm{A95}_{\mathrm{max}}$ value, suggesting a small contribution of non-PSV-induced scatter. However, the groups that include directions from the interval ∼750–1250 m have an A95 that is $>2°$ higher than the $\mathrm{A95}_{\mathrm{max}}$, with values up to ∼10°. Importantly, this is the interval for which the E/I correction yielded anomalously high inclinations of $>55°$ (section 5.1).

The high A95 values for this interval suggest that there is a large contribution of non-PSV-induced scatter affecting the distribution of directions (and associated VGPs). The large scatter is equivalent to very low K values of ∼3–5 for these groups (Fig. 6). Despite this clear evidence for a large contribution of non-PSV-induced scatter in these subsets of directions, only 3 of these 8 groups do not pass the reversal test. In other words, a reversal test alone is insufficient to determine whether the scatter in a data set is predominantly the result of PSV, and the Deenen *et al.* (2011) criterion appears to provide a better assessment (see also Meert *et al.* 2020).

The interval of large scatter correlates with an interval of relatively coarse-grained sediments (Fig. 6b), which may be more affected by random misorientation of the (large) grains (e.g. Tauxe 2006) and are more prone to weathering and subsequent remagnetization/overprinting. Notably, both a relatively low intensity of the natural remanent magnetization (NRM) and low magnetic susceptibility is observed for this interval (Fig. 6b). These factors may contribute to a less efficient acquisition of the NRM, and result in an additional source of scatter, unrelated to PSV, to the distribution of directions. In cases where the non-PSV-induced scatter is significant, as indicated by a high A95 value, the E/I correction may thus give a large overestimation of the primary inclination.

5.5 Cut-offs

It is common practice in palaeomagnetism to apply a cut-off to remove outliers that may distort the distribution of directions. Such cut-offs remove directions from the data set that do not represent PSV but result from e.g. orientation errors or lightning strikes instead. The cut-offs thus aim to make the data set more representative of PSV. However, applying cut-offs also removes transitional or excursional directions from the data set that are representative of geomagnetic field behaviour and such directions are included in most field models like TK03.GAD (Tauxe & Kent 2004; Tauxe *et al.* 2008). For this reason, Tauxe *et al.* (2008) argue that cut-offs should preferably not be used when comparing data sets with field models such as TK03.GAD. Despite this, however, cut-offs have regularly been applied prior to the E/I correction (e.g. Gong *et al.* 2008; Meijers *et al.* 2010a,b; Dupont-Nivet *et al.* 2010; Huang *et al.* 2015; Muttoni *et al.* 2018; Milanese *et al.* 2019). Here, we investigate the influence of two commonly used cut-offs on the E/I correction: a fixed 45° cut-off (e.g. Johnson *et al.* 2008) and the variable Vandamme (1994) cut-off. For the Vandamme (1994) cut-off, the cut-off angle is a function of the obtained initial scatter of the data set and increases with larger scatter.

First, we applied both cut-offs to data sets of synthetic palaeomagnetic directions generated with the TK03.GAD field model. In these synthetic data sets, all outliers removed by the cut-off are an integral part of geomagnetic field behaviour and should thus not be corrected for when applying the E/I method (Tauxe & Kent 2004). We use the cut-offs on data sets of 200 synthetic directions that were previously flattened with a flattening factor of 0.6. Subsequently, we apply the E/I correction to estimate the original inclination. Our tests show that when no cut-off is applied the original mean inclination of the synthetic data set is accurately approximated by the E/I method, particularly for the latitude range of 0–45°, whereas the original inclination for higher latitudes is somewhat underestimated, by ∼1.5–2° (Fig. 8a). However, the application of a cut-off, either the fixed 45° or the Vandamme (1994) cut-off, leads to a systematic underestimation of the inclination, particularly for mid-latitudes of 30–40°. The fixed 45° cut-off yields inclinations that are ∼1.5–3° lower than when no cut-off is applied, for latitudes of 15–60° (Fig. 8a). For this latitude range, the application of the Vandamme (1994) cut-off yields inclinations that are some 3–5° lower compared to when no cut-off is applied. This clearly argues for the application of the E/I correction without a cut-off.

Second, we applied both cut-offs to the 48 groups of 100 directions of the Gonjo Basin data set (Fig. 8b). In most cases, the E/I method gives lower inclinations when a cut-off is applied. The difference between the corrected inclination calculated with and without a cut-off vary strongly, depending on the number of directions that fall outside of the cut-off angle and are excluded. Notably, the overcorrected inclination values from the ∼750–1250 m interval that have A95 values well above $\mathrm{A95}_{\mathrm{max}}$ are corrected to much lower values of 31–43° when the fixed 45° cut-off is applied (Fig. 8b). The variable Vandamme (1994) cut-off does not lead to an improved fit because the large scatter of directions greatly increases the (variable) cut-off angle for these cases. Apart from this interval with the overcorrection, the median corrected inclination is 38.5° when the 45° cut-off is applied before the E/I correction and 36.9° for the Vandamme (1994) cut-off. This is much lower than the median value of 43.3° based on the results for which no cut-off was applied, as well as the reference inclinations, indicating that the application of either cut-off may lead to systematically and significantly lower estimates of the original inclination. Only for some, but not all groups that sample the interval showing a large dispersion of directions, likely as a result of non-PSV-induced scatter, the application of the 45° cut-off leads to an improved estimate of the primary inclination.

5.6 Number of directions

As final test, we evaluate the effect of the number of directions used on the results of the E/I correction. To this end, we applied the E/I method to collections of 150, 200 and 300 directions, drawn in consecutive stratigraphic order, again using a sliding window with an interval of 25 directions. As expected, the variation in the corrected inclinations decreases with a larger number of directions (Fig. 9). Also, using larger N results in a lower variation in the obtained flattening factors, particularly when 200 or 300 directions are used, whereby $f = 0.40–0.55$ for the large majority of groups.

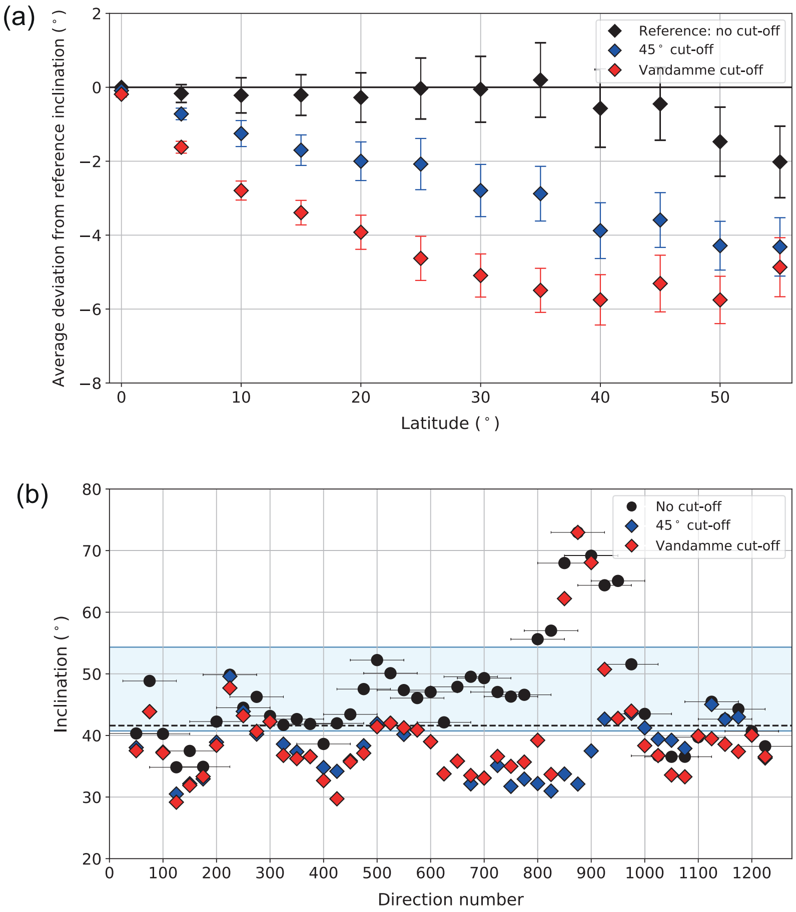

Figure 8. (a) Effect of cut-offs on the E/I correction. Each diamond represents the average deviation from the expected inclination (calculated with the dipole formula for the given latitude) of 100 E/I corrected data sets of 200 directions generated with TK03.GAD. Each data set is flattened with a flattening factor of $f = 0.6$ followed by the application of the cut-off and the correction. Results for no cut-off, the fixed 45° cut-off and Vandamme (1994) cut-off are shown by in black, blue and red, respectively. Error bars represent two standard error of the mean. (b) E/I corrected inclinations for groups of 100 directions of the Gonjo Basin data set, calculated without cut-off (black circles, same as in Fig. 4a) and with a fixed 45° cut-off (blue diamonds) or Vandamme (1994) cut-off (red diamonds) applied prior to the correction. Reference data are plotted as in Fig. 4a.

However, increasing the number of directions (N) leads to an increase in the overcorrection of the inclination for the groups that record (part of) the ∼30° clockwise rotation phase. Collections with 200 or 300 directions yield inclinations that are up to 8–10° higher than when 100 directions are used (Figs 9b and c). This is readily explained: with $N = 150$ or more, these groups contain (almost) all directions of the ∼160 sample interval that recorded the rotation, thus encompassing the full distortion of the distribution due to the ∼30° rotation. In addition, the effect of the interval with excess, non-PSV-induced scatter and the associated overcorrection relative to the expected inclination is more widely distributed and observed for a larger number of groups. The application of cut-offs to these groups with larger N yields similar results as described in Section 5.5 for groups with $N = 100$: the E/I corrected inclinations are systematically lower than the inclinations calculated without using a cut-off, and mostly fall below the range of expected values, except for those groups for which limited (<5 per cent) directions were rejected (Fig. S3, Supplementary Materials B). These results indicate that although the variation in corrected inclinations decreases with increasing N, the distribution of directions is more likely to be affected by processes unrelated to PSV and inclination flattening, and the fit with expected directions is not significantly improved with higher N.

6 DISCUSSION

6.1 Reliability criteria for the application of the E/I correction

Based on our analyses, we present a set of criteria and recommendations for the application of the E/I correction for inclination shallowing (Table 1). The reliable use of the E/I correction requires, first and foremost, that the distribution of palaeomagnetic directions provides an accurate representation of PSV, and that the observed flattening of the distribution is the result of inclination shallowing alone. Our results demonstrate that if these requirements are not fulfilled, the E/I method may provide substantial (>5–10°) under- or overestimation of the primary inclination. As a first criterion, we cite the minimum of 100 independent readings of the past geomagnetic field that were estimated by Tauxe & Kent (2004) and Tauxe *et al.* (2008) to be required to sample the full variation of the geomagnetic field and obtain a robust estimate of the elongation of the distribution.

Secondly, our analyses reveal that of all studied pitfalls, a large contribution of non-PSV-induced scatter to the distribution of palaeomagnetic directions is most important. We find that the reliability envelope of Deenen *et al.* (2011) is a successful means to

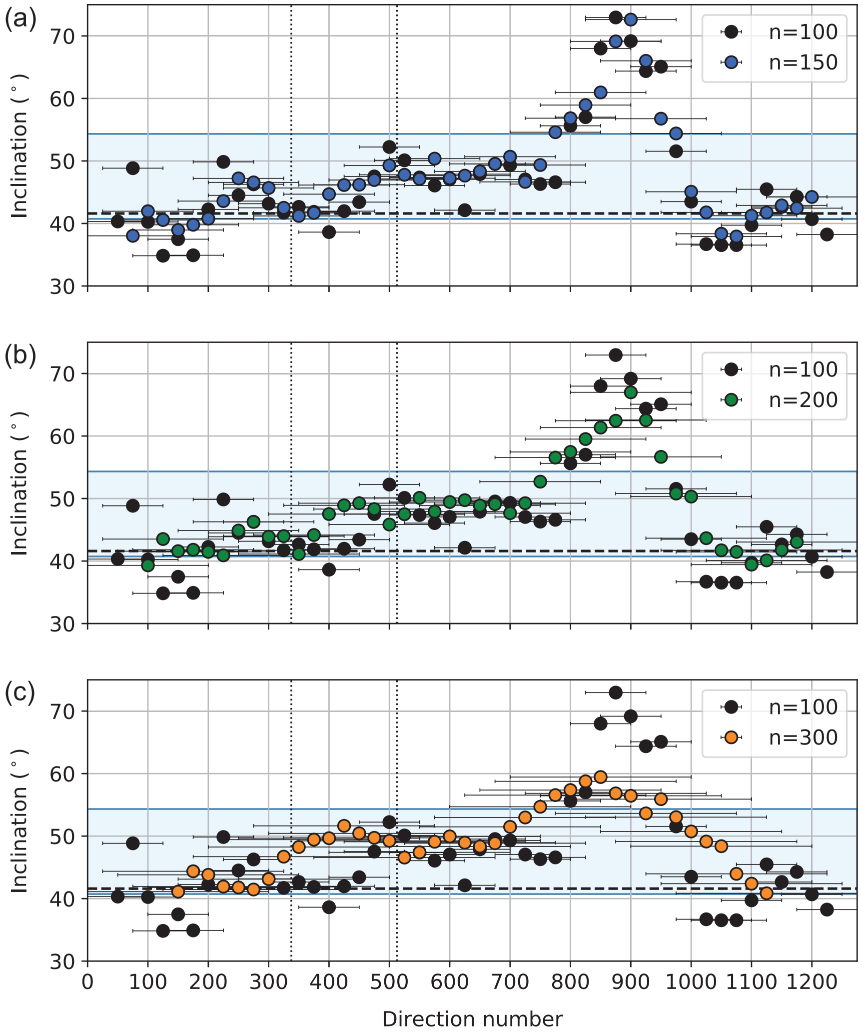

Figure 9. Effect of the number of palaeomagnetic directions used for the E/I correction. Results are shown for a sliding window with (a) 150, (b) 200 and (c) 300 successive directions from the Gonjo Basin data set. Corrected inclinations for groups of 100 directions (see also Fig. 4a) are plotted as a reference (black). Also, the corrected inclination obtained from an anisotropy-based inclination shallowing correction by Tong *et al.* (2017) of 41.6° is shown by the dashed grey line. Reference data are plotted as in Fig. 4(a).

identify data sets whereby the observed scatter cannot be straightforwardly explained by PSV alone (Section 5.4). We include this criterion to evaluate whether the principal assumption that the observed scatter of directions/VGPs is an adequate representation of PSV, is met. An A95 higher than A95$_{max}$ [see eq. 3 in Deenen *et al.* (2014)] indicates that the palaeomagnetic data set is affected by a significant contribution of non-PSV-induced sources of scatter. Nevertheless, our results indicate that for cases where the A95 is only slightly ($<1°$ for $N \geq 100$) above the A95$_{max}$, corresponding to K values of ∼8–11, the E/I method may still provide a reliable correction of the inclination (Section 5.4). But, if the A95 is well above this upper limit ($>2°$ for $N \geq 100$), indicating a large contribution of other sources of scatter, the E/I correction tends to yield a substantial ($>10°$) overestimation of the primary inclination. In cases where the A95 is below the A95$_{min}$, PSV is likely underrepresented by the palaeomagnetic data set. This may result from (re)magnetization in a short time interval, from the acquisition of a chemical remanent magnetization (CRM) after deposition, or from significant averaging of PSV in each palaeomagnetic sample, for instance for sediments with very low sedimentation rates (Deenen *et al.* 2011). Our experiments indicate that the E/I correction may still provide an accurate estimate of the primary inclination if PSV is already partially averaged, whereby A95 may be below A95$_{min}$, as long as the dispersion is predominantly the result of PSV and the excess elongation of the distribution results from flattening (Section 5.3). However, if the cause(s) of such low scatter cannot be straightforwardly determined from a set of directions/VGPs or, alternatively, from sediment properties and the NRM acquisition mechanism, we advise not to use data sets with A95 < A95$_{min}$.

Evidently, the fact that a data set satisfies the Deenen *et al.* (2011) criterion—or any other statistics-based criterion—does not preclude the presence of non-PSV-induced scatter, which may directly affect the elongation of the directional distribution. A data set with an A95 value that falls within the A95$_{min\text{-}max}$ range may represent a ‘false positive’ and be obtained, for instance, from remagnetized rocks with noisy demagnetization behaviour, and thus provide a meaningless E/I correction. Contributions of various sources of noise, for example related to measurement errors or low magnetic intensity, are inherently present in each palaeomagnetic data set and are often difficult to quantify and distinguish from PSV. This is particularly the case for data from sediments, for which no well-established quantitative criteria exist to test the reproducibility of

Table 1. Overview of our proposed criteria for the reliable application of the E/I correction, and for the calculation of E/I corrected palaeomagnetic poles derived from sedimentary rocks. N = number of individual palaeomagnetic directions; K = Fisher (1953) precision parameter of the distribution of VGPs; A95 = radius of the 95 per cent confidence circle about the mean of the VGP distribution.

Reliability criteria		
Criterion	Description	
0	General reliability criteria (based on criteria defined by Meert *et al.* 2020), which include: - Well-determined rock age - Evidence for a primary remanent magnetization (provided by field tests) - Application of modern demagnetization techniques - Analysis of directional data using Zijderveld (1967) diagrams and principal component analysis (Kirschvink 1980) - Characterization of the magnetic carriers - Application of a magnetic reversal test (if sufficient directions of both polarities are available)	
1	$\geq$100 individual palaeomagnetic directions	
2	Deenen *et al.* (2011) criterion passed: $\text{A95}_{\text{min}} < \text{A95} < \text{A95}_{\text{max}}$	
3	No vertical-axis rotations of $>15°$ within the data set	
Recommendations for the E/I correction		
1. No application of a cut-off		
2. Exclusion of poorly defined ChRM directions (e.g. directions determined using the great circle method (McFadden & McElhinny 1988))		
3. Testing the reproducibility of the results using a sliding window approach		
Quality grade	**Criteria**	**Interpretation and application**
A	All the criteria listed above are passed	Reliable, inclination shallowing-corrected pole: suitable as input for high-resolution APWPs and palaeogeographic reconstructions
B	1. Criterion 0, 2 and 3 passed and $75 \leq N < 100$	Less reliable, but provide a useful estimate of the primary inclination and palaeolatitude
	2. Criterion 0, 1 and 3 passed and $8 < K < 100$	
C	Data sets that do not satisfy the criteria defined for a quality grade 'A' or 'B'	Insufficient quality for inclusion in APWPs or as primary input for palaeogeographic reconstructions

palaeomagnetic directions. We emphasize that if the Deenen *et al.* (2011) criterion is met, there is no statistical basis to reject a data set, but it is not conclusive of PSV being adequately recorded by the data set, or of a primary magnetization. A number of careful checks for a primary magnetization, however, are included in the commonly applied quality criteria of van der Voo (1990) and Meert *et al.* (2020), and we strongly recommend the application of those prior to the use of the E/I correction (see Table 1). These criteria include the application of a reversal test, if a sufficient number of normal and reversed polarity directions are available. We note that although our analysis shows that a positive reversal test may be obtained for data sets whereby the E/I correction did not yield an accurate result (section 5.4), it provides a useful instrument to evaluate whether a data set may be contaminated by non-PSV-induced sources of noise, for example due to not entirely removed magnetic overprints.

Our criteria for the application of the E/I correction, however, replace some of the statistical requirements previously formulated for a quantitative assessment of PSV. Van der Voo (1990) argued that at least 25 spot readings are needed to test whether PSV is sufficiently recorded by the data set, whereas Meert *et al.* (2020) recommends at least eight spot readings (with a minimum of three samples per site). While those may well contain valuable information when based on rocks that are unaffected by inclination shallowing such as lavas or dykes, $N \geq 100$ is recommended to adequately correct for inclination shallowing (using the E/I method) and to assess whether the distribution of directions/VGPs represents PSV or not. In addition, we note that for such large N the Deenen *et al.* (2011) criterion is more conservative than the statistics-based criterion of $10 \leq K \leq 70$ proposed by Meert *et al.* (2020). For instance, for $N = 100$, the reliability envelope of Deenen *et al.* (2011) yields an A95_{min} and A95_{max} of 1.90 and 4.51, corresponding to K values of 56.2 and 10.8.

To reduce the effects of non-PSV-induced scatter, it is common to remove outliers from a palaeomagnetic data set by manual filtering or by using cut-offs, such as the fixed 45° and Vandamme (1994) cut-offs. However, this directly influences (the elongation of) the distribution of palaeomagnetic directions and our results indicate that the application of a cut-off leads to a systematic underestimation of the primary inclination (Section 5.5, Fig. 8), which offsets the benefit of removing non-PSV-induced outliers. We thus advise against the application of cut-offs prior to the E/I correction. Palaeomagnetic directions that are obviously not representing PSV, for example due to lightning strikes (see e.g. Strik *et al.* 2003, their fig. 7), or directions estimated through the great circle method (McFadden & McElhinny 1988), should manually be excluded from the data set. A potential source for non-PSV induced scatter is the distortion of the directional distribution resulting from vertical-axis rotations that occurred during deposition. Our experiments show that syn-sedimentary rotations of >15–20° may lead to significant overcorrections of the primary inclination of >10° (section 5.2). It may however require much larger rotations to drive A95 beyond A95_{max} and it is well possible that a rotation-induced increase of the elongation cannot be detected by using the Deenen *et al.* (2011) criterion alone. We thus recommend that prior to the application of the E/I correction, the palaeomagnetic data set is checked, for example using a moving average as in Li *et al.* (2020a), for systematic changes in declination with age/stratigraphic position that may indicate syn-sedimentary vertical-axis rotations. Previously, the effects of a rotation on the results have sometimes been corrected (see Section 5.2; Meng *et al.* 2017), but as we pointed out before, determining the exact magnitude of the rotation and propagating its associated uncertainty is not straightforward. Correcting rotations estimated from palaeomagnetic data alone (instead of e.g. bedding strike variations) may thus add more uncertainty than that it solves.

Data from intervals that record rotations smaller than 15° typically result in overcorrections of $<5°$ (Fig. 5). We recommend to not use data for the E/I correction, or for the calculation of palaeomagnetic poles, from stratigraphic intervals in which vertical-axis rotations beyond 15° are recorded or suspected. In such cases, the E/I correction is best applied to data from each of the non-rotated intervals.

Finally, we advocate testing the reproducibility of the inclination shallowing-corrected inclination for data sets with $N >\sim 150$, by applying the E/I method to multiple subsets of ∼100 directions, for example using the sliding window approach we performed in this study. Although a larger data set would ideally be used to capture the entire variability of the field to better constrain the elongation and to perform a more robust E/I correction, there is a greater chance that the distribution is contaminated by intervals that contain significant non-PSV-induced scatter or are affected by rotations. Also, for large data sets that provide a record of more than ∼5 Myr, the distribution of directions may be distorted by plate motion (Tauxe & Kodama 2009). Lastly, we note that because the E/I method applies a single average flattening factor to all palaeomagnetic directions, applying the method to subsets of directions may help to discern variations in the magnitude of flattening, for instance due to lithological variations. Evidently, if the results are shown to be internally consistent, then the E/I correction may be reliably applied to all directions, providing a robust estimate of the primary inclination.

Based on the criteria discussed above, we propose three quality grades that indicate whether a palaeomagnetic data set obtained from sedimentary rocks is appropriate to use for the E/I correction and for the calculation of an inclination shallowing-corrected palaeomagnetic pole (Table 1). We assign data sets that pass all criteria a quality grade ‘A’, indicating that the E/I method may be reliably used to correct the data set for inclination shallowing and to obtain a shallowing-corrected pole. For data sets that meet all other criteria but have $75 \leq N < 100$ or that have an A95 that falls outside the $\mathrm{A95}_{\text{min-max}}$ envelope but have $8 < K < 100$, we assign a quality grade ‘B’ (Table 1). We define this quality grade ‘B’ based on the observation that data sets with an A95 that falls just above the envelope of Deenen *et al.* (2011) still provide accurate estimates of the primary inclination (see Figs 4 and 6), suggesting that the $\mathrm{A95}_{\max}$ (corresponding to K values of ∼11–14 for $N = 100$–300) may be a bit overly strict for data sets from (clastic) sedimentary rocks. We specify a range of values for K rather than A95, for the simple reason that K is independent of N. The upper limit of $K < 100$ is chosen based on the reliable results that were obtained from data sets whereby PSV was already partially averaged and for which A95 was slightly below $\mathrm{A95}_{\min}$ (Section 5.3, Fig. 7). Also, we assign this grade to data sets that satisfy all criteria but have $75 \leq N < 100$, considering that the suggested minimum of 100 independent directions is to some extent arbitrary and that previous studies have shown that the E/I correction may provide accurate results with slightly lower N (Section 6.2). We emphasize that although data sets that are assigned a quality grade ‘B’ are in principle less reliable, they may well provide a meaningful estimate of the primary inclination and thus palaeolatitude after application of the E/I method. Finally, we assign a quality grade ‘C’ for data sets that do not satisfy the criteria for a grade ‘A’ or ‘B’, indicating that data sets do not provide a reliable E/I corrected result. In addition, we assign this quality grade to data sets whereby no fit with the TK03.GAD model is obtained upon stepwise unflattening, suggesting that the directional distribution is significantly distorted.

6.2 The applicability of the reliability criteria and its limitations

To illustrate how our criteria perform, we first applied them to groups of palaeomagnetic directions from the Gonjo Basin data set (Table 2). To this end, we selected nine sample collections of >100 directions to which we applied the E/I correction (see Figs S4, S5 and S6, Supplementary Materials B). Most of these groups include directions corresponding to several successive polarity chrons, so that the age range can be accurately determined. For groups #1–3 that cover the ∼40–50 Ma time interval, groups #1–2 are assigned quality ‘B’ and group #3 is assigned quality ‘A’. They provide corrected inclinations that are identical to those previously obtained from lavas by Roperch *et al.* (2017) and from an anisotropy-based correction by Tong *et al.* (2017) and reinforce their conclusions for the palaeolatitude of the (eastern) Qiangtang terrane in the Eocene (Fig. 10). These results suggest that our criteria for quality grade ‘A’ may be somewhat conservative and that palaeomagnetic results that are assigned grade ‘B’ may indeed provide a useful estimate of the primary inclination (and thus palaeolatitude). A quality grade ‘C’ is assigned to group #4. This interval recorded the ∼30° clockwise rotation documented by Li *et al.* (2020a) and also does not pass the bootstrap reversal test (Table 2). This group yields a corrected inclination that is ∼6–8° higher than the results of groups #1–3. It is, however, consistent with the predictions for the Qiangtang terrane placed in the palaeomagnetic reference frame of Torsvik *et al.* (2012) (Fig. 10), but as noted earlier, this may provide predicted values that are too high for East Asia for the ∼40–50 Ma time interval. Groups #6 and #7 are assigned grade ‘C’ and correspond to the interval with very large VGP scatter, whereby the A95 is >5° above $\mathrm{A95}_{\max}$. The two ‘A’ grade poles for the ∼65–69 Ma time interval yield very similar primary inclinations, which are consistent with predicted values for the Qiangtang terrane. Finally, we note that the grade ‘A’ poles come from the base of the studies section where the AMS fabric reveals a compaction-dominated fabric, and from the top of the section, which has a tectonic fabric (Li *et al.* 2020b). We find that the results of groups #1–3, corresponding to the stratigraphic interval with a ‘pencil structure’ AMS fabric, are nearly identical to those obtained from independent data sets of Roperch *et al.* (2017) and Tong *et al.* (2017) (Fig. 10). Although it has recently been shown that a strong tectonic fabric (corresponding to weak or strong cleavage state) may lead to erroneous results of the E/I correction (Dallanave & Kirscher 2020), our results illustrate that the presence of a less strong tectonic fabric, such as a ‘pencil structure’ fabric, does not necessarily lead to unreliable results of the E/I correction.

Our case study of the Gonjo Basin applies to clastic sediments with relatively high sedimentation rates, to which the E/I method has previously been mostly applied. To evaluate to what extent our criteria are successful in isolating reliable data sets from other sedimentary lithologies and rock magnetic characteristics, we compiled 78 data sets on which the E/I correction has been applied, which were published in 33 different studies (Table S2, Supplementary Materials C). This compilation includes data sets that are derived from a variety of lithologies, depositional environments, and magnetic mineralogies and were obtained from rocks with an age ranging from the Carboniferous to the Neogene. Although sampling strategies varied between studies, we note that in most studies a single sample was collected per stratigraphic level, similar to the sampling strategy used by Li *et al.* (2020a,b). For several of these data sets, the E/I corrected inclination is supported by independent

Table 2. Results for selected groups of palaeomagnetic directions from the Gonjo Basin data set. *N* = number of individual palaeomagnetic directions; Dec = declination; $\mathrm{Inc_O}$/$\mathrm{Inc_{EI}}$ = inclination before/after E/I correction; $\mathrm{Inc_{low}}$/$\mathrm{Inc_{hi}}$ = 95 per cent bootstrap confidence bounds for the E/I corrected inclination; *f* = flattening factor; *K* = Fisher (1953) precision parameter of the distribution of VGPs; A95 = radius of the 95 per cent confidence circle about the mean of the VGP distribution; $\mathrm{A95_{max}}$ = upper limit of N-dependent A95 envelope of Deenen *et al.* (2011); RT = results of bootstrap reversal test (Tauxe 2010): p is positive, n is negative, n/a indicates that no robust test could be performed due to the limited number of directions of one polarity; Rot. >15° = rotation of >15° recorded by data set; Grade = quality grade assigned to the directional group, based on the criteria listed in Table 1.

#	Interval (m)	Age (Ma)	*N*	Dec (°)	$\mathrm{Inc_O}$ (°)	$\mathrm{Inc_{EI}}$ (°)	$\mathrm{Inc_{low}}$ (°)	$\mathrm{Inc_{hi}}$ (°)	*f*	*K*	A95 (°)	$\mathrm{A95_{max}}$ (°)	RT	Rot. >15°	Grade
1	3325.4–3020.5	43.6 (41.5–45.7)	128	26.2	21.5	40.8	30.1	50.5	0.46	8.3	4.6	3.9	p		**B**
2	3018.5–2701.2	47.35 (45.7–49.0)	145	36.1	25.7	40.8	31.0	48.5	0.56	8.8	4.2	3.6	n/a		**B**
3	2699.2–2337.2	49.8 (49.0–50.6)	129	35.1	28.6	40.6	32.9	48.8	0.61	12.6	3.6	3.8	p		**A**
4	2331.2–1919.6	51.6 (50.6–52.6)	137	56.1	27.4	47.8	39.0	56.3	0.45	8.9	4.3	3.7	n	x	**C**
5	1917.6–1519.6	54.85 (52.6–57.1)	156	53.3	27.5	47.1	36.9	57.4	0.49	8.7	4.1	3.4	p		**B**
6	1514.8–1123.5	59.65 (57.1–62.2)	133	52.0	27.1	49.4	39.4	58.7	0.45	5.2	5.9	3.8	p		**C**
7	1119.5–762.0	63.75 (62.2–65.3)	113	40.1	37.0	74.8	54.9	78.4	0.29	2.9	9.7	4.2	n		**C**
8	757.0–384.2	66.25 (65.3–67.2)	167	50.7	26.0	43.0	34.9	50.1	0.51	11.9	3.3	3.3	p		**A**
9	382.2–0	68.20 (67.2–69.2)	167	48.5	29.5	41.0	34.0	48.1	0.62	16.0	2.8	3.3	p		**A**

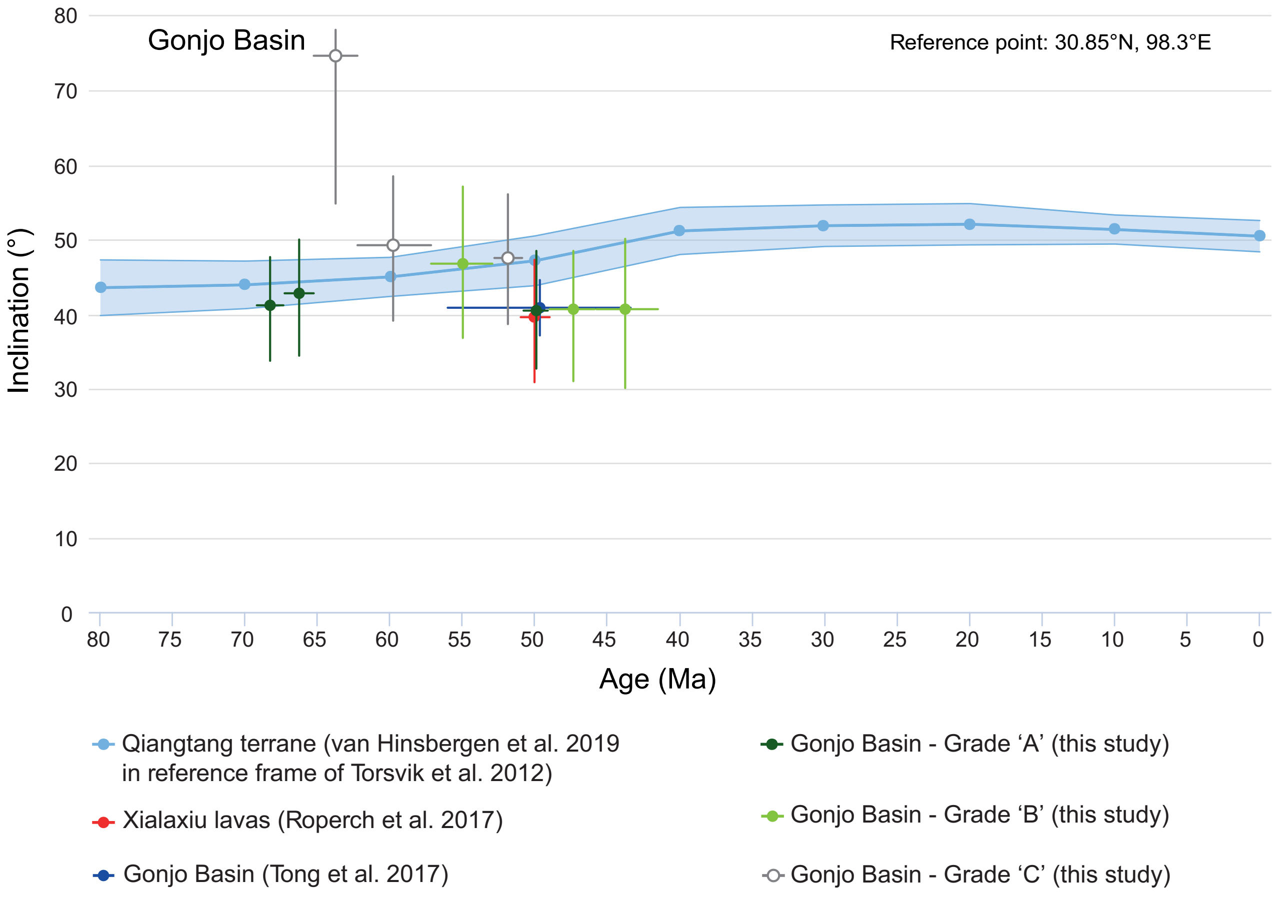

Figure 10. E/I corrected inclinations for the nine groups of palaeomagnetic directions from the Gonjo Basin data set as listed in Table 2. Horizontal error bars indicate the age range of the selected directions. Vertical error bars correspond to the 95 per cent bootstrap confidence bounds. The colour of the data points indicates the quality grade of the result based on the reliability criteria presented in Table 1. Reference data provided by previous results for the 51–49 Ma lavas of the Xialaxiu area (Roperch *et al.* (2017) and the inclination shallowing-corrected result for the Gonjo Basin red beds (Tong *et al.* 2017) are shown in red and blue, respectively. The expected inclination based on the kinematic reconstruction of the Tibetan region by van Hinsbergen *et al.* (2019), placed in the palaeomagnetic reference frame of Torsvik *et al.* (2012), is depicted by the light blue curve (with confidence region). This figure was created using paleomagnetism.org (Koymans *et al.* 2016, 2020).

estimates obtained from nearby sedimentary sections, volcanic rocks or anisotropy-based correction methods. We note that nearly all E/I corrected data sets (unless explicitly indicated) were considered in the original publication to provide a reliable estimate of the palaeolatitude or palaeomagnetic pole, which were often used as input for a palaeogeographic reconstruction or APWP.

We evaluate all data sets against our new reliability criteria, assigning each data set one of the quality grades defined in the previous section (see Table S2, Supplementary Materials C). To visualize whether the data sets meet the statistical requirements defined in Table 1, we plotted the A95 against the number of individual measurements for each data set (Fig. 11). The majority of data sets

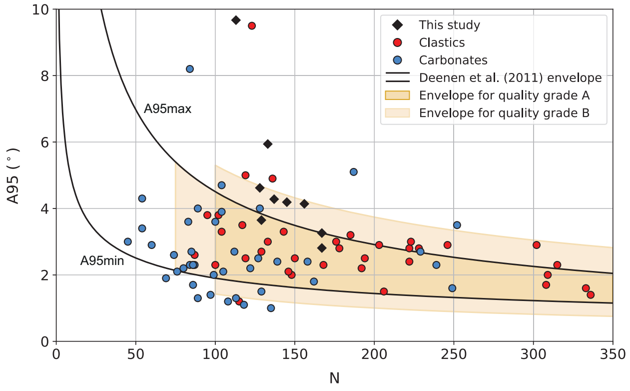

Figure 11. A95 versus *N* for a compilation of palaeomagnetic data sets on which the E/I correction has been performed. Data sets derived from clastic and carbonate rocks are shown by the red and blue circles, respectively. The A95 values for the 9 groups of this study (listed in Table 2) are plotted as black diamonds. The *N*-dependent A95 envelope is plotted by the black lines. The coloured areas indicate the criteria with respect to A95 and *N* required for a quality grade 'A' or 'B', as defined by the reliability criteria presented in Table 1. The data compilation and references are provided in Table S2 (Supplementary Materials C).

(52 from 78) have an A95 that falls within the reliability envelope of Deenen *et al.* (2011). Most of these data sets that are based on $N \geq 100$ are assigned quality grade 'A', provided that they meet all the 'general' criteria of Meert *et al.* (2020) and did not record any vertical-axis rotations of >15°. Notably, most data sets of clastic rocks that fall outside of the Deenen *et al.* (2011) envelope have an A95 $>$A95$_{max}$, whereas data sets based on carbonate rocks more often yield an A95 that is below A95$_{min}$. This suggests that palaeomagnetic records from clastic sedimentary rocks are more prone to sources of scatter unrelated to PSV, whereas data sets derived from carbonate rocks are more prone to partial averaging of PSV, possibly due to their typically lower sedimentation rates, or because of the acquisition of a chemical or post-depositional remanent magnetization after early compaction and dewatering.

The data compilation shows that the E/I correction, if the criteria are satisfied, provides reliable and reproducible results for a range of lithologies, magnetic mineralogies and rock ages, as indicated by independent data from nearby sedimentary sequences of the same age, anisotropy-based corrections and from coeval igneous rocks. We find that nearly all E/I corrected data sets that would be assigned a quality grade 'A' yield an estimate of the palaeolatitude or pole that is confirmed by independent data sets, as shown in the original publication. Importantly, the few (published) data sets for which the original authors indicated that the E/I correction did not provide a reliable result would indeed be assigned a grade 'C', either because the data set does not satisfy our statistical criteria or because it recorded vertical-axis rotations of >15° (Table S2, Supplementary Materials C). We find, however, that independently confirmed results at times are classified as grade 'B' (or even 'C'), indicating that our criteria for a grade 'A' may be overly conservative in some cases. This also indicates that data sets that are assigned a quality grade 'B' may well provide a useful estimate of the primary inclination, as previously shown by the results for the Gonjo Basin. Several data sets from carbonate rocks that are assigned a grade 'C' provided results that were shown to be reproducible, based on data sets from nearby sedimentary sequences that span the same time interval. But considering that these results are obtained from particularly small data sets ($N < 75$) or data sets whereby $K > 100$, we do not recommend such data sets to be used as primary input for palaeogeographic reconstructions or APWPs. On the other hand, data sets that do not pass the criteria for a reliable E/I corrected palaeomagnetic pole may still be used to construct a well-determined magnetostratigraphy, as this merely requires adequate identification of the magnetic polarity. Also, for studies aiming to determine the magnitude and/or timing of vertical-axis rotations, inclination shallowing is not important, and data that do not pass the criteria presented here may still be meaningful to determine such rotations.

We emphasize that our proposed criteria—like any other set of criteria—cannot unequivocally determine whether a palaeomagnetic result is reliable or not. The E/I technique itself has some inherent limitations, which may place some restrictions on the applicability of our criteria. For instance, the validity of the E/I correction relies for a large part on whether the TK03.GAD model accurately predicts the behaviour of the geomagnetic field for the time interval in which the sampled rocks acquired their remanent magnetization (see Section 2). Although the E/I correction appears successful for rocks of Early Mesozoic or Late Palaeozoic age (e.g. Kent & Tauxe 2005; Haldan *et al.* 2009; Meijers *et al.* 2010a; Bilardello *et al.* 2011), it is unclear whether the E/I curve predicted by the TK03.GAD model is accurate for time intervals for which it has not been thoroughly tested, such as the Early Palaeozoic and Precambrian. Tauxe & Kodama (2009) showed that the elongation versus inclination of a data set from ~1.1 Ga old lava flows matches those predicted by the TK03.GAD model, but future efforts are likely needed to confirm the validity of the model for ancient times. We envisage, however, that new models of the geomagnetic field, such as the GGP models recently presented by Brandt *et al.* (2020) and Bono *et al.* (2020), may potentially replace the TK03.GAD model to refine the E/I method, either to enhance the accuracy of the method in general, or for specific time intervals.

At present, some alternative strategies may be used in cases where the age of the rocks or the limited number of directions precludes a robust inclination shallowing correction by the E/I method. For instance, the magnitude of flattening may be assessed through alternative analyses of the shape of the distribution of directions (e.g. Levashova *et al.* 2013; 2015) or VGPs (Domeier *et al.* 2011). In addition, anisotropy-based methods may provide a valid alternative for the correction of inclination shallowing, as previously demonstrated (e.g. Tauxe *et al.* 2008; Bilardello *et al.* 2011; Huang *et al.* 2013, 2015). Because these methods are independent of a statistical model of the geomagnetic field, they may be particularly useful to correct data sets obtained from Precambrian sedimentary rocks (e.g. Rapalini 2006; Schmidt *et al.* 2009). But if possible, we recommend applying the E/I method in addition to an anisotropy-based correction, as was done in previous studies (e.g. Bilardello *et al.* 2011; Huang *et al.* 2013, 2015; Tong *et al.* 2017; Westerweel *et al.* 2019), to assess the robustness of the inclination shallowing correction and to evaluate—using the criteria presented here—whether PSV is adequately sampled.

6.3 Implications for palaeomagnetic poles derived from sedimentary rocks

The calculation of an accurate palaeomagnetic pole from sedimentary rocks requires that PSV is adequately sampled and averaged, and that the data set is corrected for inclination shallowing (if present). The E/I correction provides a means to not only correct for inclination shallowing, but also to assess whether the observed scatter of palaeomagnetic directions predominantly results from PSV. Our analysis implies that if a sediment-based, E/I corrected data set passes all quality criteria the observed distribution of directions (and associated VGPs) can be considered comparable—in terms of both the shape and magnitude of scatter—to a distribution of site-mean directions/VGPs from fast-cooled igneous rocks like lavas. In other words, even though the consistency of the individual palaeomagnetic directions from such a sediment-based data set cannot be independently confirmed, as is possible for lavas, the data set as a whole behaves as a collection of spot readings of the palaeomagnetic field. Such a data collection thus provides an inclination shallowing-corrected palaeomagnetic pole that averages PSV based on $\geq$100 independent measurements of the field, and can be used with equal weight as poles based on igneous rocks when used as input for palaeogeographic reconstructions and APWPs.

A large fraction of the sediment-based palaeomagnetic poles that are currently used as input for palaeogeographic reconstructions or APWPs have not been corrected for inclination shallowing in the original publication. For most of these poles, the E/I correction cannot be reliably applied because of the small ($<$100) number of palaeomagnetic directions or because the individual directions were not published or included in online appendices or in databases such as MagIC (Jarboe *et al.* 2012) or paleomagnetism.org (Koymans *et al.* 2020). In such cases, many authors apply a single 'blanket' flattening factor, typically $f = 0.6$ for clastic sediments, to correct such poles for inclination shallowing (e.g. Torsvik *et al*. 2008, 2012; Wu *et al*. 2017, 2020; Jeong & Yu 2019). However, the range of flattening factors of ~0.4–0.65 obtained in this study illustrates that the magnitude of shallowing may vary significantly even for a single sedimentary sequence. In addition, our compilation of E/I corrected data sets show that the magnitude of flattening may vary substantially for data sets derived from similar lithologies (Table S2, Supplementary Materials C). These observations support previous notions that inclination shallowing is largely dependent on the specific lithological and rock magnetic properties of the sampled rocks (e.g. Bilardello & Kodama 2010b; Kodama 2012). Notably, the application of the E/I method to carbonate rocks show that significant inclination shallowing (with estimated flattening factors ranging from 0.4 to 0.7) is not restricted to clastic sedimentary rocks, but may also affect, for example (clay-rich) limestones and marls (Table S2, Supplementary Materials C, e.g. Agnini *et al.* 2011; Dallanave *et al.* 2012; Muttoni *et al.* 2013, Muttoni & Kent 2019). This further suggests that the use of a 'blanket' flattening factor (applied to clastic sediments only) may not provide an optimal correction for all sediment-based data sets and should be treated with caution.

Importantly, poles from sedimentary rocks on which the E/I correction cannot be applied and that have previously been corrected for inclination shallowing by a 'blanket' flattening factor do not pass our proposed criteria, and our criteria thus place large restrictions on the sedimentary poles that are used as input in palaeogeographic reconstructions and APWPs. We note that the above concerns have led some authors to only use poles that were based on data sets specifically corrected using the E/I technique or anisotropy-based methods as input for their APWPs (e.g. Kent & Irving 2010; Kent & Muttoni 2020). But to what extent a 'blanket' correction affects the scatter of poles used for, or causes bias in APWPs remains to be investigated. We envisage, however, that our (conservative) quality criteria will stimulate researchers to critically evaluate (E/I corrected) palaeomagnetic poles derived from sedimentary rocks and will help unlocking sedimentary archives as a prime contributor to future, high-resolution APWPs and palaeomagnetic reference frames based on those.

7 CONCLUSIONS

Palaeomagnetic poles from sedimentary rocks are extensively used as input for APWPs and palaeogeographic reconstructions. Obtaining an accurate pole from sedimentary rocks requires that PSV is well-sampled by the palaeomagnetic data set, other sources of scatter are minimal, and that potential inclination shallowing is corrected for. However, there are currently no well-established criteria for sediment-based data sets to evaluate whether the observed scatter of palaeomagnetic directions may be representative for PSV alone, making it challenging to assess the reliability of a sediment-based pole. The E/I method by Tauxe & Kent (2004) is widely used to correct for inclination shallowing and explicitly assumes that a large, sediment-based data set provides an accurate representation of PSV. Thus, if the E/I method accurately restores the primary inclination, the assumption that PSV is adequately recorded may be a correct approximation.

In this study, we examined under which conditions the E/I method of Tauxe & Kent (2004) provides a robust correction for inclination shallowing. To this end, we analysed a large ($N = 1275$) data set from red beds of the Gonjo Basin (eastern Tibet) that contains most known artefacts that are thought to hamper the application of the E/I method and the calculation of a reliable palaeomagnetic pole, together with synthetic data sets created with the TK03.GAD field model. We proposed criteria for the reliable use of the E/I correction as an extension of already commonly used quality criteria for palaeomagnetic data. Using these criteria, we defined three quality grades that indicate whether a sediment-based data set may provide a reliable E/I corrected palaeomagnetic pole. Using an extensive compilation of previously published E/I corrected data sets, obtained from a variety of lithologies (including limestones and marls), we showed that our new criteria successfully classify data sets that were previously demonstrated to provide erroneous results as unreliable, and classify data sets whose reliability is confirmed by independent results as reliable.

An important implication of our study is that E/I corrected data sets that satisfy all reliability criteria have a distribution of directions (and associated VGPs) that can be considered comparable in scatter and shape to a data set based on site-means from rapidly cooled igneous rocks like lavas. Such data sets provide reliable inclination shallowing-corrected poles that average PSV based on a large data set of independent measurements of the field, and can be used as input for palaeogeographic reconstructions and APWPs in addition to high-quality poles based on igneous rocks. Our analysis also illustrates that the application of a 'blanket' correction factor to uncorrected data sets from (clastic) sediments may not provide an optimal correction for inclination shallowing. Palaeomagnetic poles that are corrected using a 'blanket' flattening factor do not pass our requirements for a reliable sediment-based pole and our criteria thus place restrictions on the use of palaeomagnetic records from sediments as prime input for palaeogeographic reconstructions and APWPs. We foresee, however, that our proposed criteria will provide a useful instrument for the selection and determination of sediment-based palaeomagnetic poles that can be reliably used for future, high-resolution APWPs and palaeogeographic reconstructions.

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REFERENCES

Agnini, C. *et al.*, 2011. Integrated biomagnetostratigraphy of the Alano section (NE Italy): a proposal for defining the middle-late Eocene boundary, *Bull. Geol. Soc. Am.,* **123**(5-6), 841–872.

Ali, J.R., Ward, D.J., King, C. & Abrajevitch, A., 2003. First Palaeogene sedimentary rock palaeomagnetic pole from stable western Eurasia and tectonic implications, *Geophys. J. Int.,* **154**(2), 463–470.

Anson, G.L. & Kodama, K.P., 1987. Compaction-induced inclination shallowing of the post-depositional remanent magnetization in a synthetic sediment, *Geophys J. Int.,* **88**(3), 673–692.

Besse, J. & Courtillot, V., 2002. Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr, *J. Geophys. Res.,* **107**(B11), EPM–6, doi:10.1029/2000JB000050.

Biggin, A.J., Van Hinsbergen, D.J., Langereis, C.G., Straathof, G.B. & Deenen, M.H., 2008. Geomagnetic secular variation in the Cretaceous Normal Superchron and in the Jurassic, *Phys. Earth Planet. Inter.,* **169**(1-4), 3–19.

Bilardello, D., 2013. Understanding DRM acquisition of plates and spheres: a first comparative experimental approach, *Geophys. J. Int.,* **195**(1), 148–158.

Bilardello, D., Callebert, W.C. & Davis, J.R., 2018. Evidence for widespread remagnetizations in South America, case study of the Itararé group rocks from the State of São Paulo, Brazil, *Front. Earth Sci.,* **6,** 182.

Bilardello, D., Jezek, J. & Gilder, S.A., 2013. Role of spherical particles on magnetic field recording in sediments: experimental and numerical results, *Phys. Earth Planet. Inter.,* **214,** 1–13.

Bilardello, D., Jezek, J. & Kodama, K.P., 2011. Propagating and incorporating the error in anisotropy-based inclination corrections, *Geophys. J. Int.,* **187**(1), 75–84.

Bilardello, D. & Kodama, K.P., 2010a. Palaeomagnetism and magnetic anisotropy of Carboniferous red beds from the Maritime Provinces of Canada: evidence for shallow palaeomagnetic inclinations and implications for North American apparent polar wander, *Geophys. J. Int,* **180**(3), 1013–1029.

Bilardello, D. & Kodama, K.P., 2010b. Rock magnetic evidence for inclination shallowing in the early Carboniferous Deer Lake Group red beds of western Newfoundland, *Geophys. J. Int.,* **181**(1), 275–289.

Bono, R.K., Biggin, A.J., Holme, R., Davies, C.J., Meduri, D.G. & Bestard, J., 2020. Covariant giant Gaussian process models with improved reproduction of palaeosecular variation, *Geochem. Geophys. Geosyst,* **21**(8), doi:10.1029/2020GC008960.

Brandt, D., Constable, C. & Ernesto, M., 2020. Giant Gaussian process models of geomagnetic paleosecular variation: a directional outlook, *Geophys. J. Int.,* **222**(3), 1526–1541.

Butler, R.F., 1992. *Paleomagnetism: Magnetic Domains to Geologic Terranes,* Vol. **319,** Blackwell Scientific Publications.

Channell, J.E.T., Casellato, C.E., Muttoni, G. & Erba, E., 2010. Magnetostratigraphy, nannofossil stratigraphy and apparent polar wander for Adria-Africa in the Jurassic–Cretaceous boundary interval, *Palaeogeog. Palaeoclimat. Palaeoecol.,* **293**(1-2), 51–75.

Cogné, J.P., Besse, J., Chen, Y. & Hankard, F., 2013. A new Late Cretaceous to Present APWP for Asia and its implications for paleomagnetic shallow inclinations in Central Asia and Cenozoic Eurasian plate deformation, *Geophys. J. Int.,* **192**(3), 1000–1024.

Cogné, J.P., Halim, N., Chen, Y. & Courtillot, V., 1999. Resolving the problem of shallow magnetizations of Tertiary age in Asia: insights from paleomagnetic data from the Qiangtang, Kunlun, and Qaidam blocks (Tibet, China), and a new hypothesis, *J. Geophys. Res.,* **104**(B8), 17 715–17 734.

Cox, A., 1970. Latitude dependence of the angular dispersion of the geomagnetic field, *Geophys. J. Int.,* **20**(3), 253–269.

Creer, K.M., 1962. The dispersion of the geomagnetic field due to secular variation and its determination for remote times from palaeomagnetic data, *J. Geophys. Res.,* **67**(9), 3461–3476.

Creer, K.M., Irving, E. & Nairn, A.E.M., 1959. Palaeomagnetism of the Great Whin sill, *Geophys. J. Int.,* **2**(4), 306–323.

Creer, K.M., Irving, E. & Runcorn, S.K., 1954. The direction of the geomagnetic field in remote epochs in Great Britain, *J. Geomag. Geoelec.,* **6**(4), 163–168.

Cromwell, G., Johnson, C.L., Tauxe, L., Constable, C.G. & Jarboe, N.A., 2018. PSV10: A global data set for 0–10 Ma time-averaged field and paleosecular variation studies, *Geochem. Geophys. Geosyst.,* **19**(5), 1533–1558.

Dallanave, E., Agnini, C., Muttoni, G. & Rio, D., 2009. Magneto-biostratigraphy of the Cicogna section (Italy): implications for the late Paleocene-Early Eocene time scale, *Earth Planet. Sci. Lett.,* **285,** 39–51.

Dallanave, E., Agnini, C., Muttoni, G. & Rio, D., 2012. Paleocene magneto-biostratigraphy and climate-controlled rock magnetism from the Belluno Basin, Tethys Ocean, Italy, *Palaeogeog. Palaeoclimat. Palaeoecol.,* **337,** 130–142.

Dallanave, E. & Kirscher, U., 2020. Testing the reliability of sedimentary paleomagnetic dataset for paleogeographic reconstructions, *Front. Earth Sci.,* **8,** 618.

Deenen, M.H.L., Langereis, C.G., van Hinsbergen, D.J.J. & Biggin, A.J., 2011. Geomagnetic secular variation and the statistics of palaeomagnetic directions, *Geophys. J. Int.,* **186**(2), 509–520.

Deenen, M.H.L., Langereis, C.G., van Hinsbergen, D.J.J. & Biggin, A.J., 2014. Erratum: Geomagnetic secular variation and the statistics of palaeomagnetic directions, *Geophys. J. Int.,* **197**(1), 643–643.

Domeier, M., Van der Voo, R. & Denny, F.B., 2011. Widespread inclination shallowing in Permian and Triassic palaeomagnetic data from Laurentia: support from new palaeomagnetic data from Middle Permian shallow intrusions in southern Illinois (USA) and virtual geomagnetic pole distributions, *Tectonophysics,* **511**(1-2), 38–52.

Doubrovine, P.V., Veikkolainen, T., Pesonen, L.J., Piispa, E., Ots, S., Smirnov, A.V., Kulakov, E.V. & Biggin, A.J., 2019. Latitude dependence of geomagnetic paleosecular variation and its relation to the frequency of magnetic reversals: observations from the Cretaceous and Jurassic, *Geochem. Geophys. Geosyst.,* **20,** 1240–1279.

Dupont-Nivet, G., Van Hinsbergen, D.J. & Torsvik, T.H., 2010. Persistently low Asian paleolatitudes: implications for the India-Asia collision history, *Tectonics,* **29**(5), doi:10.1029/2008TC002437.

Fisher, R.A., 1953. Dispersion on a sphere, *Proc. R. Soc. Lond., A,* **217**(1130), 295–305.

Garcés, M., Parés, J.M. & Cabrera, L., 1996. Further evidence for inclination shallowing in red beds, *Geophys. Res. Lett.,* **23**(16), 2065–2068.

Gilder, S., Chen, Y. & Sen, S., 2001. Oligo-Miocene magnetostratigraphy and rock magnetism of the Xishuigou section, Subei (Gansu Province, western China) and implications for shallow inclinations in central Asia, *J. Geophys. Res.,* **106**(B12), 30 505–30 521.

Gong, Z., Langereis, C.G. & Mullender, T.A.T., 2008. The rotation of Iberia during the Aptian and the opening of the Bay of Biscay, *Earth Planet. Sci. Lett.,* **273**(1-2), 80–93.

Griffiths, D.H., King, R.F., Rees, A.I. & Wright, A.E., 1960. The remanent magnetism of some recent varved sediments, *Proc. R. Soc. Lond., A,* **256**(1286), 359–383.

Haldan, M.M., Langereis, C.G., Biggin, A.J., Dekkers, M.J. & Evans, M.E., 2009. A comparison of detailed equatorial red bed records of secular variation during the Permo-Carboniferous Reversed Superchron, *Geophys. J. Int.,* **177**(3), 834–848.

Hankard, F., Cogné, J.P., Kravchinsky, V.A., Carporzen, L., Bayasgalan, A. & Lkhagvadorj, P., 2007. New Tertiary paleomagnetic poles from Mongolia and Siberia at 40, 30, 20, and 13 Ma: Clues on the inclination shallowing problem in central Asia, *J. Geophys. Res.,* **30**(112), doi:10.1029/2006JB004488.

Hodych, J.P. & Buchan, K.L., 1994. Early Silurian palaeolatitude of the Springdale Group redbeds of central Newfoundland: a palaeomagnetic determination with a remanence anisotropy test for inclination error, *Geophys. J. Int.,* **117**(3), 640–652.

Huang, W., Dupont-Nivet, G., Lippert, P.C., Van Hinsbergen, D.J. & Hallot, E., 2013. Inclination shallowing in Eocene Linzizong sedimentary rocks from Southern Tibet: correction, possible causes and implications for reconstructing the India–Asia collision, *Geophys. J. Int.,* **194**(3), 1390–1411.

Huang, W. *et al.*, 2015. Paleolatitudes of the Tibetan Himalaya from primary and secondary magnetizations of Jurassic to Lower Cretaceous sedimentary rocks, *Geochem. Geophys. Geosyst.,* **16**(1), 77–100.

Jackson, M.J., Banerjee, S.K., Marvin, J.A., Lu, R. & Gruber, W., 1991. Detrital remanence, inclination errors, and anhysteretic remanence anisotropy: quantitative model and experimental results, *Geophys. J. Int.,* **104**(1), 95–103.

Jarboe, N.A., Koppers, A.A., Tauxe, L., Minnett, R. & Constable, C., 2012. The online MagIC Database: data archiving, compilation, and visualization for the geomagnetic, paleomagnetic and rock magnetic communities, *AGUFM,* **2012,** GP31A–1063.

Jeong, D. & Yu, Y., 2019. Apparent polar wander path for East Asia and implications for paleomagnetic low inclination in sedimentary rocks, *Phys. Earth Planet. Inter.,* **289,** 63–72.

Jezek, J., Gilder, S. & Bilardello, D., 2012. Numerical simulation of inclination shallowing by rolling and slipping of spherical particles, *Comput Geosci*., **49,** 270–277.

Johnson, C.L. *et al.*, 2008. Recent investigations of the 0–5 Ma geomagnetic field recorded by lava flows, *Geochem. Geophys. Geosyst.,* **9**(4), doi:10.1029/2007GC001696.

Kent, D.V. & Irving, E., 2010. Influence of inclination error in sedimentary rocks on the Triassic and Jurassic apparent pole wander path for North America and implications for Cordilleran tectonics, *J. Geophys. Res.,* **115**(B10), doi:10.1029/2009JB007205.

Kent, D.V. & Muttoni, G., 2020. Pangea B and the Late Paleozoic Ice Age, *Palaeogeograph. Palaeoclimatol. Palaeoecol.,* **553,** doi:10.1016/j.palaeo.2020.109753.

Kent, D.V. & Tauxe, L., 2005. Corrected Late Triassic latitudes for continents adjacent to the North Atlantic, *Science,* **307**(5707), 240–244.

King, R.F., 1955. The remanent magnetism of artificially deposited sediments, *Geophys. Suppl. Mon. Not. R. Astron. Soc.,* **7**(3), 115–134.

Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data, *Geophys. J. Int.,* **62**(3), 699–718.

Kodama, K.P., 1997. A successful rock magnetic technique for correctng paleomagnetic inclination shallowing: case study of the Nacimiento formation, New Mexico, *J. Geophys Res.,* **102**(B3), 5193–5205.

Kodama, K.P., 2009. Simplification of the anisotropy-based inclination correction technique for magnetite-and haematite-bearing rocks: a case study for the Carboniferous Glenshaw and Mauch Chunk Formations, North America, *J. Geophys. Res.,* **176**(2), 467–477.

Kodama, K.P., 2012. *Paleomagnetism of Sedimentary Rocks: Process and Interpretation,* John Wiley & Sons.

Koymans, M.R., Langereis, C.G., Pastor-Galán, D. & van Hinsbergen, D.J., 2016. Paleomagnetism.org: an online multi-platform open source environment for paleomagnetic data analysis, *Comput. Geosci.,* **93,** 127–137.

Koymans, M.R., van Hinsbergen, D.J.J., Pastor-Galan, D., Vaes, B. & Langereis, C.G., 2020. Towards FAIR paleomagnetic data management through Paleomagnetism. org 2.0, *Geochem. Geophys. Geosyst.,* **21**(2), doi:10.1029/2019GC008838.

Levashova, N.M., Bazhenov, M.L., Meert, J.G., Danukalov, K.N., Golovanova, I.V., Kuznetsov, N.B. & Fedorova, N.M., 2015. Paleomagnetism of upper Ediacaran clastics from the South Urals: Implications to paleogeography of Baltica and the opening of the Iapetus Ocean, *Gondwana Res.,* **28**(1), 191–208.

Levashova, N.M., Bazhenov, M.L., Meert, J.G., Kuznetsov, N.B., Golovanova, I.V., Danukalov, K.N. & Fedorova, N.M., 2013. Paleogeography of Baltica in the Ediacaran: paleomagnetic and geochronological data from the clastic Zigan Formation, South Urals, *Precambrian Res.,* **236,** 16–30.

Li, S., Advokaat, E.L., van Hinsbergen, D.J., Koymans, M., Deng, C. & Zhu, R., 2017. Palaeomagnetic constraints on the Mesozoic-Cenozoic paleolatitudinal and rotational history of Indochina and South China: review and updated kinematic reconstruction, *Earth-Sci. Rev.,* **171,** 58–77.

Li, S., Deng, C., Yao, H., Huang, S., Liu, C., He, H., Pan, Y. & Zhu, R., 2013. Magnetostratigraphy of the Dali Basin in Yunnan and implications for late Neogene rotation of the southeast margin of the Tibetan Plateau, *J. Geophys. Res.,* **118**(3), 791–807.

Li, S., van Hinsbergen, D.J., Najman, Y., Liu-Zeng, J., Deng, C. & Zhu, R., 2020a. Does pulsed Tibetan deformation correlate with Indian plate motion changes? *Earth Planet. Sci. Lett.,* **536,**.

Li, S., van Hinsbergen, D.J., Shen, Z., Najman, Y., Deng, C. & Zhu, R., 2020b. Anisotropy of magnetic susceptibility (AMS) analysis of the Gonjo Basin as an independent constraint to date Tibetan shortening pulses, *Geophys. Res. Lett.,* **47**(9), doi:10.1029/2020GL087531.

Li, Y.X. & Kodama, K.P., 2016. Detecting and correcting for paleomagnetic inclination shallowing of sedimentary rocks: a review, *Front. Earth Sci.,* **4,** 7, doi:10.3389/feart.2016.00007.

McElhinny, M.W. & McFadden, P.L., 1997. Palaeosecular variation over the past 5 Myr based on a new generalized database, *Geophys. J. Int.,* **131**(2), 240–252.

McFadden, P. & McElhinny, M., 1988. The combined analysis of remagnetization circles and direct observations in palaeomagnetism, *Earth Planet. Sci. Lett.,* **87**(1-2), 161–172.

Meert, J.G. *et al.*, 2020. The magnificent seven: a proposal for modest revision of the quality index. *Tectonophysics,* **790,** doi:10.1016/j.tecto.2020.228549.

Meijers, M.J., Hamers, M.F., van Hinsbergen, D.J., van der Meer, D.G., Kitchka, A., Langereis, C.G. & Stephenson, R.A., 2010a. New late Paleozoic paleopoles from the Donbas Foldbelt (Ukraine): implications for the Pangea A vs. B controversy, *Earth Planet. Sci. Lett.,* **297**(1-2), 18–33.

Meijers, M.J., Kaymakci, N., Van Hinsbergen, D.J., Langereis, C.G., Stephenson, R.A. & Hippolyte, J.C., 2010b. Late Cretaceous to Paleocene oroclinal bending in the central Pontides (Turkey), *Tectonics,* **29**(4), 674–686.

Meng, J. *et al.*, 2017. Reduced convergence within the Tibetan Plateau by 26 Ma?, *Geophys. Res. Lett.,* **44**(13), 6624–6632.

Milanese, F., Rapalini, A., Slotznick, S.P., Tobin, T.S., Kirschvink, J. & Olivero, E., 2019. Late Cretaceous paleogeography of the Antarctic Peninsula: new palaeomagnetic pole from the James Ross Basin, *J. S. Am. Earth Sci.,* **91,** 131–143.

Muttoni, G., Dallanave, E. & Channell, J.E., 2013. The drift history of Adria and Africa from 280 Ma to Present, Jurassic true polar wander, and zonal climate control on Tethyan sedimentary facies, *Palaeogeog. Palaeoclimat. Palaeoecol.,* **386,** 415–435.

Muttoni, G. & Kent, D.V., 2019. Jurassic monster polar shift confirmed by sequential paleopoles from Adria, promontory of Africa, *J. Geophys. Res.,* **124**(4), 3288–3306.

Muttoni, G., Visconti, A., Channell, J.E., Casellato, C.E., Maron, M. & Jadoul, F., 2018. An expanded Tethyan Kimmeridgian magneto-biostratigraphy from the S'Adde section (Sardinia): Implications for the Jurassic timescale, *Palaeogeog. Palaeoclimat. Palaeoecol.,* **503,** 90–101.

Opdyke, M.D. & Channell, J.E., 1996. *Magnetic Stratigraphy,* Academic Press.

Parés, J.M., van der Pluijm, B.A. & Dinarès-Turell, J., 1999. Evolution of magnetic fabrics during incipient deformation of mudrocks (Pyrenees, northern Spain), *Tectonophysics,* **307**(1-2), 1–14.

Rapalini, A.E., 2006. New Late Proterozoic paleomagnetic pole for the Rio de la Plata craton: implications for Gondwana, *Precambrian Res.,* **147**(3-4), 223–233.

Roperch, P. *et al.*, 2017. Palaeomagnetic constraints on early collisional deformation along the eastern margin of the Qiantang terrane (Tibetan plateau) at 50 and 37 Ma, *In EGU General Assembly Conference Abstracts,* **19,** 9476.

Schmidt, P.W., Williams, G.E. & McWilliams, M.O., 2009. Palaeomagnetism and magnetic anisotropy of late Neoproterozoic strata, South Australia: implications for the palaeolatitude of late Cryogenian glaciation, cap carbonate and the Ediacaran System, *Precambrian Res.,* **174**(1-2), 35–52.

Strik, G., Blake, T.S., Zegers, T.E., White, S.H. & Langereis, C.G., 2003. Palaeomagnetism of flood basalts in the Pilbara Craton, Western Australia: Late Archaean continental drift and the oldest known reversal of the geomagnetic field, *J. Geophys. Res.,* **108**(B12), doi:10.1029/2003JB002475.

Studnicki-Gizbert, C., Burchfiel, B.C., Li, Z. & Chen, Z., 2008. Early Tertiary Gonjo basin, eastern Tibet: sedimentary and structural record of the early history of India-Asia collision, *Geosphere,* **4**(4), 713–735.

Tamaki, M., Oshimbe, S. & Itoh, Y., 2008. A large latitudinal displacement of a part of Cretaceous forearc basin in Hokkaido, Japan: paleomagnetism of the Yezo Supergroup in the Urakawa area, *J. Geol. Soc. Japan,* **114**(5), 207–217.

Tanaka, H., 1999. Circular asymmetry of the palaeomagnetic directions observed at low latitude volcanic sites, *Earth Planets Space,* **51**(12), 1279–1286.

Tang, M., Liu-Zeng, J., Hoke, G.D., Xu, Q., Wang, W., Li, Z., Zhang, J. & Wang, W., 2017. Paleoelevation reconstruction of the Paleocene-Eocene Gonjo basin, SE-central Tibet, *Tectonophysics,* **712,** 170–181.

Tan, X. & Kodama, K.P., 2002. Magnetic anisotropy and paleomagnetic inclination shallowing in red beds: evidence from the Mississippian Mauch Chunk Formation, Pennsylvania, *J. Geophys. Res.,* **107**(B11), EPM–9.

Tan, X. & Kodama, K.P., 2003. An analytical solution for correcting palaeomagnetic inclination error, *Geophys. J. Int.,* **152**(1), 228–236.

Tan, X., Kodama, K.P., Chen, H., Fang, D., Sun, D. & Li, Y., 2003. Paleomagnetism and magnetic anisotropy of Cretaceous red beds from the Tarim basin, northwest China: evidence for a rock magnetic cause of anomalously shallow paleomagnetic inclinations from central Asia, *J. Geophys. Res.,* **108**(B2), doi:10.1029/2001JB001608.

Tauxe, L., 1998. *Paleomagnetic Principles and Practice,* Kluwer Academic Publishers.

Tauxe, L., 2005. Inclination flattening and the geocentric axial dipole hypothesis, *Earth Planet. Sci. Lett.,* **233**(3-4), 247–261.

Tauxe, L., 2006. *Paleomagnetic Principles and Practice,* Vol. **17,** Springer Science & Business Media.

Tauxe, L., 2010. *Essentials of Paleomagnetism,* Univ. of California Press.

Tauxe, L., Constable, C., Johnson, C.L., Koppers, A.A., Miller, W.R. & Staudigel, H., 2003. Paleomagnetism of the southwestern USA recorded by 0–5 Ma igneous rocks, *Geochem. Geophys. Geosyst.,* **4**(4), doi:10.1029/2002GC000343.

Tauxe, L. & Kent, D.V., 1984. Properties of a detrital remanence carried by haematite from study of modern river deposits and laboratory redeposition experiments, *Geophys. J. Int.,* **76**(3), 543–561.

Tauxe, L. & Kent, D.V., 2004. A simplified statistical model for the geomagnetic field and the detection of shallow bias in palaeomagnetic inclinations: was the ancient magnetic field dipolar? *Geophys. Monogr. Ser.,* **145,** 101–115.

Tauxe, L. & Kodama, K.P., 2009. Paleosecular variation models for ancient times: clues from Keweenawan lava flows, *Phys. Earth Planet. Inter.,* **177**(1-2), 31–45.

Tauxe, L., Kodama, K.P. & Kent, D.V., 2008. Testing corrections for palaeomagnetic inclination error in sedimentary rocks: a comparative approach, *Phys. Earth Planet. Inter.,* **169**(1-4), 152–165.

Tauxe, L., Steindorf, J.L. & Harris, A., 2006. Depositional remanent magnetization: toward an improved theoretical and experimental foundation, *Earth Planet. Sci. Lett.,* **244**(3-4), 515–529.

Tauxe, L. & Watson, G.S., 1994. The fold test: an eigen analysis approach, *Earth Planet. Sci. Lett.,* **122**(3-4), 331–341.

Tauxe, L. *et al.*, 2016. PmagPy: software package for paleomagnetic data analysis and a bridge to the Magnetics Information Consortium (MagIC) Database, *Geochem. Geophys. Geosyst.,* **17**(6), 2450–2463.

Tong, Y., Yang, Z., Mao, C., Pei, J., Pu, Z. & Xu, Y., 2017. Paleomagnetism of Eocene red-beds in the eastern part of the Qiangtang Terrane and its implications for uplift and southward crustal extrusion in the southeastern edge of the Tibetan Plateau, *Earth Planet. Sci. Lett.,* **475,** 1–14.

Tong, Y.B., Yang, Z., Gao, L., Wang, H., Zhang, X.D., An, C.Z., Xu, Y.C. & Han, Z.R., 2015. Paleomagnetism of Upper Cretaceous red-beds from the eastern Qiangtang Block: Clockwise rotations and latitudinal translation during the India–Asia collision, *J. Asian Earth Sci.,* **114,** 732–749.

Torsvik, T.H., Müller, R.D., Van der Voo, R., Steinberger, B. & Gaina, C., 2008. Global plate motion frames: toward a unified model, *Rev. Geophys.,* **46**(3), doi:10.1029/2007RG000227.

Torsvik, T.H. *et al.*, 2012. Phanerozoic polar wander, palaeogeography and dynamics, *Earth-Sci. Rev.,* **114**(3-4), 325–368.

Vandamme, D., 1994. A new method to determine paleosecular variation, *Phys. Earth Planet. Inter.,* **85,** 131–142.

Van der Voo, R., 1990. The reliability of paleomagnetic data, *Tectonophysics,* **184**(1), 1–9.

Van Hinsbergen, D.J., de Groot, L.V., van Schaik, S.J., Spakman, W., Bijl, P.K., Sluijs, A., Langereis, C.G. & Brinkhuis, H. 2015. A paleolatitude calculator for paleoclimate studies, *PLoS One,* **10**(6), doi:10.1371/journal.pone.0126946.

Van Hinsbergen, D.J., Dekkers, M.J. & Koc, A., 2010. Testing Miocene remagnetization of Bey Dağları: timing and amount of Neogene rotations in SW Turkey, *Turk. J. Earth Sci.,* **19**(2), 123–156.

Van Hinsbergen, D.J., Lippert, P.C., Li, S., Huang, W., Advokaat, E.L. & Spakman, W., 2019. Reconstructing Greater India: Paleogeographic, kinematic, and geodynamic perspectives, *Tectonophysics,* **760,** 69–94.

Westerweel, J. *et al.*, 2019. Burma Terrane part of the Trans-Tethyan arc during collision with India according to palaeomagnetic data, *Nat. Geosci.,* **12**(10), 863–868.

Wu, L., Kravchinsky, V.A. & Potter, D.K., 2017. Apparent polar wander paths of the major Chinese blocks since the Late Paleozoic: toward restoring the amalgamation history of east Eurasia, *Earth-Sci. Rev.,* **171,** 492–519.

Wu, L., Murphy, J.B., Quesada, C., Li, Z.X., Waldron, J.W., Williams, S., Pisarevsky, S. & Collins, W.J., 2020. The amalgamation of Pangea: Paleomagnetic and geological observations revisited, *Bull. Geol. Soc. Am.,* doi:10.1130/b35633.1.

Zhang, Y., Huang, W., Huang, B., Van Hinsbergen, D.J., Yang, T., Dupont-Nivet, G. & Guo, Z., 2018. 53–43 Ma deformation of eastern Tibet revealed by three stages of tectonic rotation in the Gongjue basin, *J. Geophys. Res.,* **123**(5), 3320–3338.

Zijderveld, J.D.A., 1967. A.C. demagnetization of rocks, in *Methods in Palaeomagnetism,* pp. 256–286, eds Collinson, D.W., Creer, K.M. & Runcorn, S.K., Elsevier.

SUPPORTING INFORMATION

Supplementary data are available at *GJI* online.

Figure S1. Application of the E/I correction to the data set of 222 directions from the Subei region by Gilder *et al.* (2001). In (a), the data set is corrected for a bedding-parallel rotation of 15° along a fault that cuts through the sampled section. The results of the E/I correction are shown in (b, c). In (d), the same data set is shown but now without correction for the internal rotation. (e, f) Results of the E/I correction applied to the uncorrected data set. See Fig. 2 for more details.

Figure S2. The A95 of groups of 100 VGPs of the Gonjo Basin data set calculated before (black) and after (red) application of the E/I correction. The Deenen *et al.* (2011) reliability envelope calculated for $N = 100$ is indicated by the black lines.

Figure S3. E/I corrected inclinations as calculated without a cut-off (black circles), with a fixed 45° cut-off (blue diamonds) and with a Vandamme (1994) cut-off (red diamonds). (a), (b) and (c) show the results for 150, 200 and 300 directions, respectively. The vertical, dotted lines indicate the interval that records the ∼30° clockwise rotation phase identified by Li *et al.* (2020a). As a reference, the inclination of 41.6° obtained from an anisotropy-based inclination shallowing correction by Tong *et al.* (2017) is shown by the dashed black line. The light blue band shows the range of expected inclinations as predicted by the model of van Hinsbergen *et al.* (2019) placed in the reference frame of Torsvik *et al.* (2012).

Figure S4. Results of the E/I correction applied to groups #1–3 of the Gonjo Basin data set. The stereographic plots (a, d, g) show the uncorrected palaeomagnetic directions (converted to normal polarity, blue circles), the principal direction (black star) and the E/I corrected mean direction (red star). (b, e, g) Elongation versus inclination curves upon stepwise unflattening of the palaeomagnetic data set by gradually decreasing the flattening factor (f). (c, f, i) Plots of the cumulative distribution of the corrected inclination and 95 per cent confidence bounds as calculated in 2000 bootstrap runs. See Fig. 2 for more details.

Figure S5. Same as Fig. S4, but now for groups #4–6.

Figure S6. Same as Fig. S4, but now for groups #7–9.

Table S1. ChRM directions from the Gonjo Basin section (location: 30.85°N,98.3°E) from Li *et al.* (2020a). # = sample number; depth = stratigraphic level (m); *D*g/*I*g = declination/inclination in geographic coordinates; *D*s/*I*s = declination/inclination in stratigraphic coordinates; Lat/Lon = Latitude and longitude of VGP calculated from ChRM direction.

Table S2. Compilation of palaeomagnetic data sets from sedimentary rocks on which the E/I correction has been applied, and for which all key parameters were available. We have listed information on the lithology, sediment accumulation rate and sampling strategy if described by the authors in the original publication. All data sets are evaluated and graded using our proposed reliability criteria (see Table 1 and text box). NB: data sets with a red-coloured quality grade are considered unreliable by the authors of the original publication.