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# Apparent polar wander paths of the major Chinese blocks since the Late Paleozoic: Toward restoring the amalgamation history of east Eurasia

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## ABSTRACT

High quality paleomagnetic poles (a.k.a. paleopoles) are essential for quantitative lithospheric plate reconstruction. However, the current paleomagnetic database of the major Chinese blocks, including the North China Block (NCB), the South China Block (SCB), and the Tarim Block (TB), since the Late Paleozoic Era contain outdated and low quality data. Here, we update the database by adding recently published high quality paleopoles and rejecting low quality outdated ones. The database includes 288 paleopoles published 1980–2014, 90 of them published after 2000. Following the Van der Voo selection criteria, 75 paleopoles, each with a quality factor Q smaller than 4, were rejected in the first round of selection. We then removed another 59 paleopoles that have been locally rotated or shallowed since the acquisition of stable remanence. Eventually, 154 paleopoles were selected and adopted to calculate the new apparent polar wander paths (APWPs) for the major Chinese blocks. We found comparable clastic and igneous paleopoles at intervals when a quantitative comparison was available. As such comparison was not possible during most periods/epochs, our conclusions reflect an unclear extent of inclination errors in Chinese clastic paleopoles. New models of the Chinese APWPs, with and without inclination error corrections, were computed from carefully selected paleopoles: version 1 running mean (V1RM) paths were calculated at the period/epoch level; version 2 running mean (V2RM) paths were computed in a set sliding time window of 20 or 30 Myr; spline paths were calculated with the same time windows along with a smoothing parameter of 50.

Using a recent global reconstruction model and up-to-date geological observations, new models of the Chinese APWPs allowed us to re-evaluate the coalescence history of East Eurasia since the Late Paleozoic Era. Four major tectonic events were confirmed: (1) the TB accreted with the Kazakhstan orocline during amalgamation of the West Altaids during the Middle–Late Permian Period (ca. 265–250 Ma); (2) the suturing of the NCB and the SCB likely occurred in a scissor-like pattern and had been accomplished no later than the Middle Jurassic Period (ca. 180–160 Ma); (3) the amalgamation between the NCB and the TB along with the microblocks between the two might have been achieved during the Late Jurassic–Early Cretaceous Periods (ca. 160–140 Ma); (4) the Mongol-Okhotsk Ocean should have been closed no later than the Early Cretaceous Period (ca. 140–120 Ma).

## 1. Introduction

The amalgamation of east Eurasia since the Middle–Late Permian Period is a prime concern in paleogeographic studies due to its significance in understanding regional and global tectonic evolution. The North China, South China, and Tarim Blocks are stable cratons in the region and therefore hold the key to understanding this history. An apparent polar wander path (APWP) is a trajectory of consecutive paleomagnetic poles (a.k.a. paleopoles) and is one of the widely adopted approaches to paleogeographic reconstruction. Several generations of post-Paleozoic APWPs for the major continents have been produced from carefully selected paleopoles and well defined relative plate motion models (a.k.a. plate circuits) that are derived from present day seafloor isochrons (i.e., magnetic lineations and fracture zones of the same ages) to transfer paleopoles across different continents (e.g., Besse and Courtillot, 2002; Schettino and Scotese, 2005; Torsvik et al., 2008a, 2012). However, the topic is less advanced for the Chinese blocks because of (1) the outdated compilation of Chinese paleopoles, (2) the absence of plate circuits to transfer paleopoles from other major continents due to their independent motion history, and (3) the well-known tectonic complexities during the amalgamation of East Eurasia.

With the accumulation of high quality paleopoles, significant

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progress has been made in the last two decades to construct the Chinese APWPs. For instance, Lin et al. (1985) published a preliminary version of APWPs for the North China Block (NCB) and the South China Block (SCB), from which they derived the amalgamation process of the two blocks and Siberia between the Late Paleozoic and Early Mesozoic Eras. By compiling paleopoles published before 1992, Enkin et al. (1992a, 1992b) presented an updated version of post-Permian Chinese APWPs at the period/epoch level. Zhao et al. (1996) refined the Chinese APWPs by re-evaluating the quality of Phanerozoic paleopoles and then restored the amalgamation history of the Chinese blocks during the evolution of Gondwanaland. By including new paleopoles, Yang and Besse (2001) refined the Mesozoic segment of the South China APWP and then reinterpreted the suturing of the NCB and SCB. Cocks and Torsvik (2013) presented the Paleozoic APWPs of the NCB and the SCB in the form of spherical spline interpolations because of the limited number of high quality paleopoles. Van der Voo et al. (2015) recently compiled an updated database of paleopoles for the NCB, from which they calculated a new NCB APWP in the form of running means.

Nonetheless, compared to the studies of the major continents Gondwana and Laurasia (e.g., Torsvik et al., 2008a, 2012; Torsvik and Cocks, 2013), few studies have been performed in the last two decades to update and carefully evaluate the existing post-Permian paleomagnetic database of the major Chinese blocks, and to present the resulting APWPs in standard forms, i.e., sliding window (a.k.a., running mean) and spherical spline. First, none of the existing Chinese APWPs were built by applying Van der Voo paleopole selection criteria (Van der Voo, 1990) to assess the current paleomagnetic database that contains paleopoles of various levels of quality, the main reason being a lack of sufficient paleopoles in the past. As many high quality paleopoles have been published in the last decade, we believe it is the time to update the existing paleomagnetic database by including new high quality paleopoles and excluding old low quality paleopoles. Second, none of the previous Chinese APWPs are corrected for the inclination flattening error, which is a common postdepositional bias in clastic remanence directions and associated paleopoles (e.g., King, 1955; Anson and Kodama, 1987; Deamer and Kodama, 1990; Tan et al., 2003; Tauxe and Kent, 2004). In comparison, APWPs of major continents other than Asia have been corrected for such systematic error (e.g., Torsvik et al., 2012). Third, existing Chinese APWPs are presented at the period/epoch level and are inconvenient to use as an input surface kinematic condition for geodynamic and paleoclimatic modelling. With a proper age assignment method, we can apply the running mean and spherical spline approaches to smooth the Chinese paleopole datasets and to provide a better temporal coverage of the resulting APWPs. For example, the spherical spline can produce an APWP out of a limited number of paleopoles by smoothing out noise (i.e., errors in the paleopoles), assigning higher weight to more reliable data, and interpolating paleopoles in periods with no data coverage (e.g., Jupp and Kent, 1987; Schettino and Scotese, 2005; Torsvik et al., 2008a, 2012; Torsvik and Cocks, 2013).

Here, we compile updated and carefully selected post-265 Ma paleopoles for the NCB, the SCB, and the TB. New Chinese APWPs, in the forms of running means and spline interpolations, are constructed from high quality paleopoles after two rounds of selection. The APWPs are presented both with and without correcting for the inclination shallowing effect. We then reconstruct the amalgamation of East Eurasia by integrating our new Chinese APWPs into a recent global plate kinematic model (Torsvik et al., 2012) with up-to-date geologic observations.

## 2. Methods

### 2.1. Paleomagnetic pole selection

Figs. 1a and S1 illustrate the major block boundaries and geologic structures (e.g., faults and sutures) in East Eurasia that were considered when building an initial collection of Chinese paleopoles. We applied a two-round selection of the database (Tables S1–S3). During the first round of selection, we followed Van der Voo (1990) criteria to evaluate the quality of the paleopoles in terms of the quality factor Q (which ranges from 0 to 7). Van der Voo (1990) criteria are summarized as follows: (1) adequate demagnetization along with application of principle component analysis (PCA) for remanence isolation (Kirschvink, 1980); (2) implementation of field tests (fold test, conglomerate test, and baked contact test, etc.); (3) presence of (nearly) antipodal reversals; (4) solid statistics with a sufficient number ($N > 24$) of samples along with an acceptable level of errors (the confidence cone $A_{95}$ ($\alpha_{95}$) $\leq 16.0°$); (5) consistency with paleopoles from the same block (i.e., no postdepositional local rotations); (6) well determined age; and (7) no resemblance to younger paleopoles (i.e., no remagnetizations). In terms of criterion #4 (sufficient statistics), Deenen et al. (2011) suggested an alternative criterion where the value of $A_{95}$ is reduced to 5.0° if the number of samples is larger than 80; they also recommended the adoption of a precision parameter $K > 10$ rather than $A_{95} < 16°$, where K describes the dispersion of remanence directions. Due to the large number of paleopoles in our initial database, the application of such complex criteria would significantly increase the amount of work. We therefore implemented the criterion of sufficient statistics from Van der Voo (1990).

The second round of selection was carried out to paleopoles with $Q \geq 4$ by implementing several additional criteria. First, we excluded paleopoles that are presented without details of the stepwise demagnetization or PCA (both of which are critical for acquiring reliable remanence directions), even if their quality factors were no smaller than 4. Second, we rejected paleopoles reported in PhD theses and/or non-English journals because detailed paleopole quality descriptions are not easily accessible in these publications. Third, we removed paleopoles that are biased by postdepositional processes, according to suggestions from source publications or our inspection during paleopole selection.

To identify paleopoles that might have been locally rotated, we plotted a small circle around each sampling site, the radius of which is the angular distance between sampling site and paleopole (i.e., the paleocolatitude, see Figs. S2–11). There are some bewildering cases when paleopoles during some period/epoch are distributed along circular arcs on a stereonet (e.g., Early Cretaceous paleopoles in the NCB and Early–Middle Jurassic paleopoles in the SCB, Figs. S3c and S7a, respectively). It is difficult to determine the main clusters and Fisherian means in such cases, and we introduced two rules to address this issue. Rule 1 involves the "minimal" distance between consecutive paleopole clusters (i.e., means). If paleopoles of a given age exhibit reasonably good clustering (i.e., their Fisherian mean is readily and reliably determined), the resulting Fisherian mean is likely to be close to the Fisherian means of paleopole clusters in neighboring ages (e.g., Early–Middle Jurassic paleopoles in the SCB, Fig. S7a). Note that $A_{95}$ is not a good measure of the level of difficulty in identifying the main cluster of paleopoles. For example, a large number of paleopoles that exhibit a girdle distribution (in such a distribution it may not be easy to identify the mean cluster) may have a small $A_{95}$ but a large dispersion parameter (i.e., a small clustering parameter). Rule 2 to determine the main paleopole clusters posits that the Fisherian mean is more likely to be determined from the largest cluster of paleopoles in an interval (e.g., Early–Middle Jurassic paleopoles in the SCB, Fig. S7a). Rules 1 and 2 allowed us to reject paleopoles that have been locally rotated, unless there are strong reasons against such manipulation. For instance, Early–Middle Jurassic SCB paleopoles acquired in the future could raise doubts concerning our suggested main paleopole cluster established under the rule of "minimal distance" between two consecutive Fisherian means (Rule 1). Readers are referred to Supplementary Text for a detailed discussion.

The statistics for our compilation of the Chinese paleopoles are addressed for completeness. The database initially included 288 paleopoles published during 1980–2014, comprising 104 paleopoles from