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A combined methodology for reconstructing source-to-sink basin evolution, exemplified by the Triassic Songpan-Ganzi basin, central China

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Abstract: Source-to-sink evolution of basin is a key to understand sedimentary processes, especially in a complex regional orogenic setting. Detrital zircon populations can be traced from their primary sources to their depositional settings. The resulting interpretations are enhanced by calculation of the adjacent orogen's paleoaltimetry, which provide additional insights into paleogeography. In this study, we present a combined methodology which aims to reconstruct source-to-sink evolution by the analysis of detrital zircon age distribution in sandstones, together with the calculation of paleo-elevation of surrounding orogens based on the chemical compositions of coeval magmatic rocks. We test the method using detrital zircon U-Pb geochronology datasets from the Triassic Songpan-Ganzi basin in central China, combined with whole-rock geochemical data from intermediate-composition magmatic rocks in adjacent crustal blocks. Application of the combined methodology supports a syn-collisional basin model for the formation of the Triassic Songpan-Ganzi basin (in preference to a continental back-arc basin). The clastic sediments, mainly deep-marine turbidites, accumulated in a remnant Paleotethyan Ocean that was surrounded by the converging North China Block, South China Block, East Kunlun Orogenic Belt and the Qiangtang Block. The North China Block and the North Qaidam Block were major proto-sources of detrital zircons to the basin, contributing on average 12% and 15%, respectively. Triassic magmatic rocks in the East Kunlun and the Qiangtang regions were major sources of igneous zircons, up to 68% for the former and up to 56% for the latter. Despite being located at a calculated elevation of ca. 4000 m, the Qinling Orogenic Belt contributed only ca. $<10\%$ of the zircons, mostly restricted to the eastern depocenter of the basin. In contrast, supply from the North Qiangtang Block, despite its calculated lower elevation (1000-3000 m), accounts for 2-10% of the detrital zircons in the basin, suggesting high erosion rates of this block. The minimal supply of zircons from the South China Block, restricted to 3-6% in the central and western depocenters, is inconsistent with the zircon abundances predicted in the alternative back-arc basin model of the Songpan-Ganzi basin.

Keywords: detrital zircon geochronology, paleo-elevation, proto-source contribution, provenance, Songpan-Ganzi basin

1. Introduction

Sedimentary provenance provides important clues concerning processes of sedimentary deposition, basin sedimentation, hinterland tectonics and exhumation (e.g., Dickinson and Gehrels, 2003, 2008; Smyth et al., 2014). Detrital minerals has received considerable attention in clastic rock studies as they represent valuable petrogenetic and provenance indicators (e.g., Grigsby, 1990; Mange and Maurer, 1991; Morton, 1991; von Eynatten and Gaupp, 1999; Garzanti and Andò, 2019). Variations in the geochemical composition of detrital minerals relate to the host rocks and so allow the mineralogical signature of the source rocks to be characterized (e.g., Mange and Maurer, 1991; Morton and Hallsworth, 1994; Rubatto, 2002; Belousova et al., 2002; Meinhold, 2010; Andò et al., 2014).

During the last decade, attention has focused on zircon geochronology, which is widely used to unravel sedimentary provenance, the linkages between different sedimentary units, and the ages of deposition (Fedo et al., 2003; Andersen, 2005; Gehrels, 2011; Vermeesch, 2012; He et al., 2020). The combined use of a Concordia diagram with Isoplot (Ludwig, 2008) and an age-distribution diagram (or relative age probability plot) represent well-established techniques to illustrate and interpret detrital zircon ages (Sircombe, 2004; Sircombe and Hazelton, 2004). Visual methods alone are becoming increasingly difficult to compare large detrital geochronology data sets (e.g., Gehrels, 2000; DeGraaff-Surpless et al., 2003; Fedo et al., 2003; Vermeesch, 2013), mainly because of the large sample sizes and the number of samples (e.g., Saylor and Sundell, 2016). Although provenance can be interpreted by using whole-rock methods such as sediment petrography and chemical analysis, several recently developed methods aid quantification of the proto-source contributions of detrital age distribution. Specifically, the detrital age population unmixing method (Sundell and Saylor, 2017; Clift et al., 2020) helps to identify unknown sources and sedimentary recycling. In addition, paleo-elevations can be derived from intermediate-composition magmatic rocks that are well-dated radiometrically and analyzed chemically and can be used to help interpret tectonic settings and landscape evolution (Airy, 1855; Lee et al., 2015; Hu et al., 2017, 2020a; Zhu et al., 2017). Specifically, empirical relationships have recently been established between the geochemical indices of magmatic rocks and crustal thickness/elevation of mountain belts (Chapman et al., 2015; Profeta et al., 2015; Hu et al., 2017, 2020a; Tang et al., 2021; Luffi and Ducea, 2022). This approach can facilitates the interpretation of paleo-elevation and topographic relief in a potential source area, allowing a better interpretation on source-to-sink relationships.

In this paper, we provide a general guide to assist readers in interpreting sediment provenance by re-evaluating detrital-zircon age distributions and source correlations, combined with paleo-elevation estimates of surrounding orogens. In order to evaluate the efficiency and applicability of the proposed combined method, we utilize a case study involving detrital zircon geochronological datasets from Triassic sandstones of the Songpan-Ganzi basin. We combine this with whole-rock geochemical data from Permian-Upper Triassic magmatic rocks of both the Songpan-Ganzi basin and the surrounding orogens (e.g., Zhan et al., 2018; Dong et al., 2018; Hu et al., 2020b). The overall results illustrate the value of combining detrital geochronological age distributions and calculated paleo-elevations to help decipher the geological development of Paleotethys within and adjacent to the Songpan-Ganzi basin.

2. User's guide to unmixing detrital zircon age distribution

To allow a thorough comparison of detrital data sets, we propose the series of steps shown in Fig. 1a. The weighting of proto-sources (i.e., primary sources) contribution needed to take account of several precautionary aspects, complementary information and available geological interpretation, as explained below.

2.1 Step 1: Screening: sample size and age selection

The first step in detrital zircon provenance studies concerns how many detrital zircon grains should be analyzed. The statistics of individual sample indicate that at least 60 grains need to be analyzed to have a 95% probability of identifying individual component that make up at least 5% of the detrital age spectrum (Dodson et al., 1988). By comparison, Vermeesch (2004) calculated that in order to maintain a population proportion exceeding 0.05 of the total population at 95% confidence, a minimal of 117 grains should be analyzed, in accordance with the well-known binomial probability formula. Monte Carlo simulation of detrital zircon age populations suggest that the threshold values of sample size are likely to be underestimated if the complexity of zircon populations is fully considered (Andersen, 2005; Gehrels, 2011). Some quantitative statistical methods; e.g., the Kolmogorov-Smirnov (K-S) and Kuiper tests, are closely related to sample size and age distributions, such that very large data sets ($n > 300$) are usually required for quantitative comparisons (Saylor and Sundell, 2016). In order to improve statistical robustness and analytical accuracy, it is therefore advantageous, where possible, to group samples from basins and formations, thereby increasing the sample size for each specific depositional region and time period (e.g., Clift et al., 2020).

Uncertainties in the ages derived from the laboratory analysis of zircons vary as a function of age (e.g., Ludwig, 2008). In general, interpretations of zircon ages can be selected by $^{206}Pb/^{238}U$ ages for zircon grains < 1000 Ma, and on $^{207}Pb/^{206}Pb$ ages for grains > 1000 Ma (e.g., Gehrels, 2000; Gehrels et al., 2008). The ages were filtered using a ±20% discordance cutoff for zircon <200 Ma, and a ±10% discordance cutoff for zircon >200 Ma. The degree of discordance = a percentage of the $^{206}Pb/^{238}U$ age divided by the $^{207}Pb/^{235}U$ age (or $^{206}Pb/^{207}Pb$ age if zircon >1000 Ma).

2.2 Step 2: Display detrital zircon age distribution

A simple histogram can be used to illustrate the abundance of grain ages in any particular sample (Machado et al., 1996). This can be illustrated by vertical bars on finite mixture distributions; e.g., in probability density plots (PDPs), or as kernel density estimates (KDEs) (Dodson et al., 1988; Sircombe, 2004; Sircombe and Hazelton, 2004; Ludwig, 2008; Vermeesch and Garzanti, 2015). Detrital age spectra can also be illustrated on cumulative distribution functions (CDFs), with step segments shown in the distribution. CDFs can also be used for statistical comparisons of multiple samples that have different curve slopes and steps. Detailed comparisons, merits and deficiencies of these methods are discussed in Vermeesch (2012), Saylor and Sundell (2016) and Vermeesch and Garzanti (2015).

2.3 Step 3: Differences and similarities between samples

It is possible to perform quantitative comparisons of geochronological data using the K-S Test/Kuiper Test (Saylor and Sundell, 2016; Vermeesch et al., 2016). The related statistics, the D factor for the K-S Test and the V factor for the Kuiper Test, respectively, are be calculated from the two CDFs (Saylor and Sundell, 2016). In addition, metrics of Similarity, Likeness and Cross-correlation coefficients are based on either the age distribution of PDPs or the KDEs. Two- or three- dimensional nonmetric multidimensional scaling (MDS) of age distributions provides greater resolution for visual comparison, in which the distance between the sample points represents the degree of divergence between them (Vermeesch, 2013).

2.4 Step 4: Identify potential sources

Potential sources can be used as end-members to help determine the mixing proportions and to interpret the general trends in sediment derivation. It is possible to identify a range of source candidates by observing the characteristics of multidimensional scaling plots, in the light of the regional geology (e.g., Clift et al., 2020). Sediment samples and their potential sources tend to group; e.g., plot between the source end-members in the multidimensional scaling plots. Differences between samples suggest that the region was being supplied from more than one source.

Recycling is a common sedimentation processes, which can complicate sample unmixing and is known to affect provenance interpretation (Gehrels, 2011; Garzanti et al., 2013). In order to quantify provenance changes, systematic major changes in the zircon age population need to be identified, bearing in mind that even apparently unique peaks in the zircon distribution can be recycled from older sediments.

2.5 Step 5: Source unmixing and relative contributions (Monte Carlo Mixture modelling)

Mixing proportions for source samples can be determined by using the inverse Monte Carlo and forward optimization methods that compare the samples to possible source end-members (e.g., Sundell and Saylor, 2017). The computational model can be easily accessed via a MATLAB-based file (e.g., Sundell and Saylor, 2017). This software tests uncertainty by randomly generating different source contributions. For quantitative comparison, various statistics can be used; e.g., the K-S test D and Kuiper test V values of CDFs, and the Cross-correlation coefficient of PDPs or KDEs (Sundell and Saylor, 2017).

The modelled output patterns are similar to the input age patterns, allowing the relative contributions from different sources to be calculated (Sundell and Saylor, 2017). Where the analyzed zircon distributions fall close to the model range, the source proportion estimates may be considered well found. On a statistical basis, large detrital geochronological data sets, preferably from numerous samples, provide robust confidence levels and also aid quantitative inter-sample comparisons (Saylor and Sundell, 2016; Sundell and Saylor, 2017). In addition, a larger sample size allows for effective and precise rejection of the null hypothesis; i.e., that the two data sets have the same distribution, due in part to the perturbation of the random sampling of 'big data' (Saylor and Sundell, 2016).

Although source unmixing can quantitatively represent the geochronological features of samples, precautions should be taken when interpreting e.g., zircon fertility, zircon recycling, and sorting behavior (e.g., Malusà and Garzanti, 2019; Clift et al., 2020). Notably, samples can be modelled better if they have a larger sample size (Saylor and Sundell, 2016; Sundell and Saylor, 2017), which can be achieved by grouping samples that have similar depositional ages or geographic localities.

3. User's guide to paleo-elevation estimates

3.1 Step 1: Synthesis of regional magmatic rock data

Variations in paleo-elevation can help to understand the relationship between tectonic processes and landscape evolution. The recently developed paleoaltimetry technique (Chapman et al., 2015; Profeta et al., 2017; Hu et al., 2017, 2020a) that is applied here uses the whole-rock geochemistry of intermediate-composition magmatic rocks from subduction and/or collision zones to estimate quantitatively the early-growth of topography at convergent margins. The calculation of paleo-crustal thicknesses and paleo-elevation assume Airy isostatic equilibrium (Airy, 1855; Lee et al., 2015; Hu et al., 2017; Zhu et al., 2017). When magma is formed by melting and fractionation within thick crust (>1.0 GPa), Y and Yb are incorporated into garnet and amphibole, whereas Sr and La remain in the liquid leading to increased Sr/Y and $(La/Yb)_N$ in the magma (i.e., chondrite-normalized values) (after McDonough and Sun, 1995). In contrast, for magma derived from melting and fractionation of normal-thickness or thinned crust (<1.0 GPa), Sr is incorporated into plagioclase, whereas Y and Yb remain in the liquid, resulting in magma with low Sr/Y and $(La/Yb)_N$ ratios. Therefore, the trace element ratios [Sr/Y and $(La/Yb)_N$] of the intermediate magmatic rocks represent related proxies that can be used to indicate the crustal thickness, and by extension, the paleo-elevation of collisional belts and magmatic arcs. This method has been successfully applied in Iran (Chaharlang et al., 2020; Moghadam et al., 2022), the Tibetan Plateau (Zhan et al., 2018; Hu et al., 2020a; Sundell et al., 2021), the Colombian Andes (León et al., 2021), the Rocky Mountains (Lipman, 2021), and the Appalachian orogen (Hillenbrand and Williams, 2021).

The regional geological information and available analyzed data of suitable magmatic rocks of the relevant basin, its surrounding cratons and orogenic belts should next be compiled, followed by further screening (Fig. 1b).

3.2 Step 2: Screening, data filtered and paleo-elevation reconstruction

Samples that were formed by partial melting, assimilation, or fractional crystallization processes at shallow crustal levels (<1.0 GPa) are generally unsuitable for true crustal thickness/paleo-elevation estimates (Chapman et al., 2015; Hu et al., 2017) and should be excluded from the data compilation. Accordingly, for magmatic rocks formed during oceanic subduction, the samples should be filtered with SiO_2 = 55-70 wt%, MgO = 1.0-6.0 wt%, and Rb/Sr < 0.20, according to the protocols of Chapman et al. (2015). By comparison, filtered samples of magmatic rocks that were emplaced during the transition from oceanic subduction to continental-collision or in continental-collision setting are characterized by SiO_2 = 55-72 wt%, MgO = 0.5-6.0 wt%, and average Rb/Sr < 0.35 (Hu et al., 2020a), eliminating the effects of highly fractionated rocks (Chapman et al., 2015). In addition, the high La (>70 ppm) samples from collisional settings are also excluded from the compilation because La content can strongly increase during potential high-temperature melting (Hu et al., 2020a). This increase could cause the relatively high La/Yb ratios and as a result lead to inaccurate paleo-elevation calculations (Hu et al., 2020a). Sr/Y and $(La/Yb)_N$ ratios were processed and filtered by following a modified Thompson Tau method (Hu et al., 2020a). The outliers mentioned above were then excluded from the paleo-elevation calculations and the resulting contour graphs. Explanations and limitations of the method are noted by Hu et al. (2020a).

The paleo-elevations of surrounding orogens/mountain belts were calculated here according to the empirical equations of Hu et al. (2020a). The elevations of subduction zones and collisional zones tend to correlate positively with crustal thicknesses when calculated using several different empirical equations (Hu et al., 2020a). The related data were then used to plot a contour map of the study area using SURFER software. The quantitatively constrained paleo-altitude/crustal thickness of the selected region becomes more accurate according to the number of data points available.

4. Selected case history: the Triassic Songpan-Ganzi basin

Here, we take the classic geological region of the Songpan-Ganzi basin in central China as an example, to test the applicability and effectiveness of our approach to quantify detrital zircon age spectra and paleo-elevation estimates. Sandstones of Early to Late Triassic age are exposed in the Songpan-Ganzi basin, which relate to the Late Paleozoic-Early Mesozoic geological evolution of the eastern Paleotethys (Fig. 2) (Yin and Nie, 1993; Nie et al., 1994). The Triassic sandstones of this region have already been extensively studied in terms of sedimentology, petrography and geochemistry (e.g., Gu, 1994; Zhou and Graham, 1996; She et al., 2006; Zhang et al., 2008, 2012; Ding et al., 2013). Numerous efforts have been made to understand the spatial and temporal provenance characteristics of these Triassic deposits using detrital zircon geochronology (Bruguier et al., 1997; Weislogel et al., 2006; Enkelmann, et al., 2007; Weislogel, 2008; Ding et al., 2013, Jian et al., 2019; Tang et al., 2023; Pan and Hu, 2023).

Two main tectonic hypotheses have been proposed for the geological setting of the Songpan-Ganzi basin (Fig. 3). In the first hypothesis (syn-collisional basin model) (Fig. 3a), the Songpan-Ganzi basin is interpreted as part of the north-easternmost branch of Paleotethys (e.g., Stampfli and Borel, 2002), which evolved from a remnant-ocean basin into a collisional orogenic belt (e.g., Sengör, 1987; Yin and Nie, 1993; Ingersoll et al., 1995; Zhou and Graham, 1996; Chang, 2000; Tang et al., 2022). In this interpretation, the sedimentary provenance was intimately related to the collision of the South China Block and the North China Block. In the second hypothesis, a back-arc rifting setting is proposed (Fig. 3b), in which the western part of the Songpan-Ganzi basin (Hoh-Xil area) was supplied from both the North and the South China blocks (Ding et al., 2013). In this interpretation, detritus was transported along the western margin of the South China Block, mixed, and then accumulated within the westernmost part of the Songpan-Ganzi Basin (Ding et al., 2013).

To support, our case study of the Songpan-Ganzi basin, numerous geochemical data exist for the magmatic rocks in the surrounding orogens, which represent potential source rocks for the Songpan-Ganzi basin (e.g., Dong et al., 2018; Lu et al., 2019; Hu et al., 2020b).

Our case study of the Songpan-Ganzi basin sandstones aims to achieve the following: (1) to compare multiple detrital zircon data sets of sandstones throughout the Songpan-Ganzi basin; (2) to quantitatively determine the relative provenance contribution of their crustal proto-sources; (3) to shed light on the paleo-elevation and topographic evolution of the source area; and (4) to determine the potential for alternative controls on the age spectrum of detrital zircons associated with the tectonic evolution of the Songpan-Ganzi basin and the eastern Paleotethys.

4.1 Summary geology of the Songpan-Ganzi basin

The Songpan-Ganzi basin is distinguished by extremely thick Triassic sediments (c. 8 km) (Enkelmann et al., 2007), which relate to the closure of Paleotethys (Ding et al., 2013; Jian et al., 2019; Wu et al., 2020). The Songpan-Ganzi basin is separated from the East Kunlun and Qinling Orogenic Belts by an ophiolitic mélange belt, termed the A'nyemaqen-Mianlue suture zone (e.g., Dong et al., 2018; Hu et al., 2020b) (Fig. 2). During the Late Paleozoic to Early Mesozoic, Paleotethyan oceanic lithosphere was being subducted northward along the E-W-trending active margin now represented by the East Kunlun and Qinling Orogenic Belts (Fig. 2). Paleotethys in this region closed during Middle to Late Triassic times (Dong et al., 2018; Kapp and DeCelles, 2019; Wu et al., 2019; Hu et al., 2020b). In addition, the Songpan-Ganzi basin is separated from the Qiangtang Block by a wide belt of Permian-Triassic sedimentary mélange belonging to the Jinshajiang suture zone (Fig. 2), which is interpreted as a Paleotethyan subduction complex (Kapp et al., 2000, 2003; Pan et al., 2004; Pullen et al., 2008; Kapp and DeCelles, 2019).

The basement of the Songpan-Ganzi basin consists of continental crust which is generally correlated with the South China Block (e.g., Wang et al., 2016; Wu et al., 2019; Hu et al., 2022). Following earlier subduction, remnant Paleotethyan oceanic crust was emplaced onto the crust of the South China Block/Qiangtang Block as a consequence of late-stage oceanic subduction and subsequent continental collision, specifically the convergence between the Qiangtang Block and South China Block with Eurasia (Dong et al., 2018) (Fig. 3). Thick Triassic turbidites that had accumulated within the Songpan-Ganzi basin were progressively deformed as a result of the collision of the adjacent blocks (e.g., Faure et al., 2001; Kirby et al., 2002; Roger et al., 2003, 2011; Meng et al., 2019). The basin uplifted during the Late Triassic (Norian), as indicated by a switch from deep-sea turbidites to deltaic deposits (Bureau of Geology and Mineral Resources Sichuan Province [BGMRSP], 1991; Chang, 2000). During the Late Triassic, southeastward thrusting occurred along the western margin of the South China Block, forming the Longmen-Shan thrust belt and causing deformation of the Sichuan Basin to the east (Burchfiel et al., 1995) (Fig. 2).

The Lower to Upper Triassic sandstones of the Songpan-Ganzi basin discussed here accumulated during the closure of Paleotethys from oceanic subduction to continental collision. In addition, widespread magmatism during the Late Triassic inferred post-collisional stage generated widespread granitic intrusions within the Upper Triassic strata of the Songpan-Ganzi basin.

4.2 Sampling and data analysis

Published detrital-zircon populations of 63 sandstone samples were selected for inverse Monte Carlo modeling, namely from the northeastern (19), southeastern (9), central (19), and western (16) depocenters (Figs. 4-5). In order to increase sampling density and more fully evaluate the relationship between the Songpan-Ganzi basin and the potential proto-sources, a newly analyzed data subset (n=7) from the southeast of the basin was compiled in the data analysis.

The newly collected sandstone samples (n=7) from the southeast of the basin (Fig. 4) were crushed and sieved. Zircons were separated using standard elutriation and magnetic separation techniques (e.g., McLennan et al., 2001). The zircons were picked by hand using a binocular microscope, embedded in epoxy resin, and polished. U-Pb dating of zircons was conducted in situ using an Agilent 7500a Quadrupole-Inductively Coupled Plasma Mass Spectrometry (ICP-MS), coupled with a GeoLasHD 193 nm ArF excimer laser ablation system at the Institute of Geology and Geophysics, Chinese Academy of Sciences. The analytical procedure is explained in Xie et al. (2008). In this study, a laser beam diameter = 32 μm, energy density = 4 J cm^{-2}, and frequency = 5 Hz were used. Zircon standard 91500 was used for calibrating the U-Pb fractionation; its $^{207}Pb/^{206}Pb$ age is 1065.4 ± 0.3 Ma (Wiedenbeck et al., 1995). The second reference zircon SA01 with a $^{206}Pb/^{238}U$ age of 535.08 ± 0.32 Ma (Huang et al., 2020) was used to monitor accuracy. In addition, the GLITTER software (GEMOC, Macquarie University; Griffin et al., 2008) was used for calibrating the raw data. Common lead corrections were performed following the method detailed by Andersen (2002). The complete dataset is provided in the Supplementary Table S1.

Geochronological ages are summarized for the Permian to Triassic magmatic rocks in the Qinling and Qiangtang regions in Supplementary Table S2. In addition, geochemical data were compiled for Upper Permian to Upper Triassic magmatic rocks from the Songpan-Ganzi basin, the East Kunlun Orogenic Belt, the Qinling Belt, and the North Qiangtang Block (Supplementary Table S3-S4). Paleo-elevations were calculated for each of these potential source-rock domains based on these complied data by using the method presented above (Supplementary Table S3). For the margin of the Songpan-Ganzi basin, the paleo-elevation, closely related to water depth, was also estimated based on the sedimentary facies/fabrics and related fossil species (e.g., Chang, 2000).

4.3 Regional depocenters

The Triassic sedimentary rocks in the Songpan-Ganzi basin show significant spatial and temporal variations in lithology, sediment composition and facies (She et al., 2006; Weislogel, 2008; Zhang et al., 2008, 2012). Four main depocenters (Fig. 5) can be recognized based on facies variation, paleocurrent data (Weislogel et al., 2006; Ding et al., 2013; Jian et al., 2019) and restored Triassic isopachs (after Wang and Pan, 2010; Zhang et al., 2019).

The northeastern depocenter is likely to extend across the western South Qinling Belt and the south of the Mianlue-A'nyemaqen Suture (Fig. 5a). The Triassic sequence thickens westwards, reaching ca. 6 km (Wang and Pan, 2010; Zhang et al., 2019). Southwesterly paleocurrents dominate (Weislogel et al., 2006; Ding et al., 2013), whereas average grain size decrease westwards (Chang, 2000). The lithofacies change westwards from neritic/bioclastic limestone to mixed calciclastic-siliciclastic marine turbidites (Zhou and Graham, 1996; Weislogel, 2008; Weislogel et al., 2010), suggesting deepening in this direction.

The southeastern depocenter thickens westwards from the present Longmen Shan Thrust Belt to the Ganzi-Litang area (Fig. 5b), culminating in ca. 7 km of Triassic strata (Wang and Pan, 2010; Zhang et al., 2019). This depocenter is characterized by northerly paleocurrents (Ding et al., 2013; Jian et al., 2019) and an abundance of metamorphic lithic grains (Chen et al., 2006; Su et al., 2006; Zhang et al., 2012). The lithologies change northwards from dominantly calciclastics to siliciclastics (Weislogel, 2008).

The central depocenter is restricted to the Maduo-Maqin-Maqu-Ganzi-Yushu area (Fig. 5c). Paleocurrent orientations are variable, ranging from north/northwest to south/southwest (Ding et al., 2013; Jian et al., 2019).

The western depocenter, by far the largest, extends from the eastern Maduo-Yushu area to the western Hoh-Xil area (Fig. 5d). The sediments in this region display opposite paleocurrent directions (Ding et al., 2013).

5. Application of the combined method to the Songpan-Ganzi basin

We first performed the stepwise evaluation and interpretation, in line with the methodology explained above (see Section 2-3). The geochronological data pass the initial verification phase; i.e., samples with geographical proximity are pooled together to increase sample size; the ages are filtered and illustrated using the same criteria (see Section 2.1) (Fig. 1). The whole-rock geochemical data for magmatic rocks of suitable intermediate composition were then filtered (Supplementary Table S4) in order to eliminate data subsets with undefined petrogenesis (see Section 3.2), following the protocols of Chapman et al. (2015).

5.1 Geochronology age spectra

The Kernel Density Estimation (KDE) best captures the distribution of data with high quality (precision) or quantity (number of analyses) (Vermeesch, 2012) (Fig. 6).

For all of the samples considered (n=63), those from the northern depocenter (Fig. 5) contain abundant Paleoproterozoic (1700-2000 Ma) and Archean (2400-2600 Ma) zircons, together with Paleozoic populations, peaking at 270 Ma, 330 Ma, and 440 Ma (Supplementary Fig. S2) (Fig. 6). Samples from the southern depocenter (Fig. 5) yielded age populations with a notable Neoproterozoic peak and variable Triassic, Ordovician-Devonian, Paleoproterozoic and Archean clusters (Weislogel et al., 2006; Ding et al., 2013) (Supplementary Fig. S3) (Fig. 6). Samples from the central depocenter (Fig. 5) define five populations, namely 240-310 Ma (Late Carboniferous-Early Triassic), 400-480 Ma (Ordovician-Early Devonian), 750-1000 Ma (Tonian), 1700-2000 Ma (Late Paleoproterozoic) and 2300-2600 Ma (Neoarchean-Early Paleoproterozoic) (Jian et al., 2019) (Supplementary Fig. S4) (Fig. 6). Samples from the western depocenter (Fig. 5) have variable age signatures, including relatively young 480-400 Ma and 300-200 Ma populations (Supplementary Fig. S5) (Fig. 6). Neoproterozoic grains dated from 750 Ma to 1030 Ma are locally present and Paleoproterozoic and Archean zircons also occur.

5.2 Statistical comparisons of detrital zircon geochronology

To compare the potential sources of the early Mesozoic with the older components, the compiled ages were filtered to include only grains >227 Ma; i.e., ages prior to the known uplift of the Songpan-Ganzi basin, which resulted from tectonically controlled shallowing (e.g., Zhan et al., 2018; Tang et al., 2018). This filter also reduces bias in statistical analyses shat would have resulted from the inclusion of younger grains (e.g., <227 Ma arc magmatics). An existing non-metric multi-dimensional scaling (MDS) map was adapted to compare visually detrital zircon age spectra (Vermeesch, 2013). Samples with similar age spectra plot close to each other on the MDS map, whereas samples with different spectra plot far apart. A multi-dimensional scaling plot based on K-S statistical analysis of the 63 samples from the Songpan-Ganzi basin indicates two major clusters, one related to the major orogenic basement to the left of Figure 7; e.g., North China Block, South China Block and North Qiangtang Block; these are interpreted as major sources of the detrital zircons. The other cluster is related to the magmatic rocks to the right of Figure 7; this is interpreted to indicate that Qiangtang, Qinling and Kunlun magmatic rocks represent the main sources of the igneous zircons. However, individual samples from different locations vary greatly in the multi-dimensional scaling plots (Fig. 7), which could be explained by the effects of recycling. Therefore, in order to identify similar sediments within the various depocenters, we grouped similar samples within the same depocenter in order to increase sample size and improve statistical accuracy (see Section 2.1), we then used the DZStats program (Saylor and Sundell, 2016) to generate various statistical relationships between the detrital zircon U-Pb age distributions of samples and the potential source candidates (Supplementary Table S5).

Following the above statistical analysis, several groups of samples were then clearly recognized as well-separated, effective characterizing different source contributions (Fig. 8). Samples from the northeastern and southeastern depocenters identify as three groups in each area (Fig. 8a-b). On the MDS map (Fig. 7c-d), three groups of age similarities are also recognizable. The northeastern depocenter samples are quite similar to the sediments from the southeastern and western depocenters, and to a lesser extent to the central depocenter (Supplementary Table S5). Group 2 of the northeastern depocenter is particularly similar to many of the samples from the other depocenter; e.g., group 1, 3 of the central depocenter and group 3 of the western depocenter (Supplementary Table S5). The southeastern depocenter (group 3) shows the poorest commonality (Supplementary Table S5; Fig. 7) although this is insignificant because only one sample was analyzed (2003T185; n=95 grains). The Kuiper test necessitates the use of sufficiently large sample sizes (n>300) in order to effectively reject the null hypothesis (e.g., Saylor and Sundell, 2016). The zircon spectrum identified in the southeastern depocenter (group 2) exhibits distinctive characteristics, with notable zircon populations of 200-300 Ma and 360-500 Ma, which, in turn, suggest a different zircon source (Fig. 6). Also, the samples from the central depocenter show the least similarities with the other depocenters (Fig. 7), suggesting that they represent another different sedimentary provenance. The zircon spectrum of the western depocenter is closely comparable with sediments from the north/southeastern depocenter, but to a lesser extent with the central depocenter (Fig. 7). Group 1 of the western depocenter shares great similarities with that of group 2/3, group 2 and group

1 of the northeastern, southeastern and central depocenters (Supplementary Table S5).

5.3 Potential source rock identification

The scatterplot of the distances in the MDS plot also points to source correlations (Fig. 7). The zircon populations from the North China Block are closely related to those of the northeastern (e.g., sample 2004T052) and the central (e.g., samples 13SG-62, 2004T030 and 2004T013) depocenters (Supplementary Figure S2, S4). Sediments from the western depocenter; e.g., medium-grained sandstones 2007K395, 2005K117 and 2005K093 containing monocrystalline quartz, plagioclase and limestone lithics (Ding et al., 2013) are not far apart from the South China Block compositions. Sample 2003T185 from the southeastern depocenter (group 3) is a coarse-grained sandstone consisting of plagioclase, monocrystalline quartz, muscovite and limestone lithic grains (Ding et al., 2013). This sample is completely different from the other sandstones based on detrital zircon age population (Supplementary Figure S3), and, as such, was probably fed from local sources (Yidun Terrane-related) (Figs. 6-7).

There are a large number of samples with closely related zircon populations, as indicated by their clustering on the MDS map (Fig. 7); e.g., 02MTZ1, 2005K094 and 14SSG-24. Given their proximity (Fig. 7), most of these are likely to have been sourced from the North Qiangtang Block, the North Qinling Belt, the eastern/western South Qinling Belt and/or the East Kunlun Orogenic Belt. Notably, the North Qaidam Block-related source fall in the middle of the samples studied (Fig. 7), indicating a provenance relationship. In addition, the zircon populations of the Qiangtang, Kunlun and Qinling magmatic rocks plot to the right of the MDS plot (Fig. 7), indicating a potential source correlation for these samples e.g., 18BPG20, 2007K420 and 2004T286.

5.4 Source unmixing

The highly variable zircon populations of the sandstone turbidites have poorly constrained, generally Triassic depositional ages (e.g., Ding et al., 2013). For these reasons, we carried out the mixing analysis by increasing the sample size via grouping the samples with similar zircon populations (Fig. 8), as recently used by Tang et al. (2023). However, the resulting output is still a poor fit to the model age distribution (i.e., a maximum cross-correlation R^2 value =<0.6). This discrepancy can be explained by the mixed sample age distribution of the grouped samples. In order to match the observed zircon age spectrum better, 10,000 attempts were made to replicate a specific (target) detrital age spectrum by varying the contributions from different sources and then selecting the best 1%. The calculated contributions are based on several statistics; i.e., the V statistic of the Kuiper test and D statistic of the K-S test for CDFs, together with the Cross-correlation coefficient for KDEs (Table 1).

For the northeastern depocenter, the North China Block (18.3%-21.4%) and the North Qaidam (24.2%-32.8%) constitute the major source contributors for the group 1 samples (Table 1). Group 2 samples are characterized by various sources from the East Kunlun magmatic rocks (8.7%-67.9%) and the North Qaidam Block (2.4%-39.7%). In contrast, group 3 samples indicate prominent derivation from the East Kunlun and/or the Qiangtang magmatic rocks (Fig. 9) (Table 1).

For the southeastern depocenter, (1) the cratonic basements of the North China Block, the North Qaidam Block, the South China Block and the western South Qinling Belt; (2) the East Kunlun and Qiangtang magmatic rocks; and (3) the Yidun Terrane/South China Block separately represent the dominant source contributors for group 1, 2 and 3 samples (Table 1).

For the central depocenter, the East Kunlun Orogenic Belt (8.1%-11.8%) and the East Kunlun magmatic rocks (10.5%-50.1%) constitute the dominant sources for group 1 (Table 1), together with a contribution from the North Qaidam Block (5.0%-48.7%). In contrast, the zircon distributions of group 2 mainly relate to the North China Block (33.6%-39.6%) and the North Qaidam Block (17.1%-20.4%). For group 3, the North Qaidam (10.4%-26.8%), East Kunlun (15.1%-23.0%) and Qiangtang (14.6%-40.7%) magmatic rocks represent the main source contributors (Table 1).

For the western depocenter, the model result shows that group 1 samples were derived from the North China Block (20.2%-25.5%), the North Qaidam Block (12. 8%-18.1%), the western South Qinling Belt (ca. 12%) and the north Qinling Belt (9.0%-18.3%) (Table 1). The East Kunlun magmatic rocks (11.8%-19.2%) and the North China Block (32.7%-37.4%) also constitute major zircon sources for the group 2 samples. In contrast, the East Kunlun (11.2%-20.1%) and the Qiangtang (22.2%-47.8%) magmatic rocks constitute major zircon sources only for group 3 samples (Table 1).

5.5 Paleo-elevation reconstruction

The closure of the Paleotethys in western China and the formation of the East

Kunlun-Qinling orogenic belt were completed by the end of the Triassic (Dong et al., 2018; Hu et al., 2020b). However, how and when these mountain belts were uplifted and provided detritus to the surrounding region is still poorly constrained. The time when the Songpan-Ganzi basin was uplifted high enough to stopped receiving sediment from surrounding orogens is also not well known. Paleo-elevation data for the Songpan-Ganzi basin and its surrounding orogens could therefore greatly aid the regional interpretation.

According to our paleo-elevation calculation (Fig. 10), the altitude of the East Kunlun Orogenic Belt increased continuously from Permian to middle Norian (ca. 210 Ma) time. Specifically, the East Kunlun Orogenic Belt is inferred to have risen from 1000-2000 m to 4000-5000 m before the Rhaetian. Such a high elevation is supported by rapid exhumation of the East Kunlun Orogenic Belt and coarse alluvial (molasse) sedimentation during the Late Triassic (Mock et al., 1999; Jolivet et al., 2001; Liu et al., 2005; Dai et al., 2013; Liu et al., 2020). The marked increase in paleo-elevation of the East Kunlun Orogenic Belt is attributed to regional compressive stress and magmatism during continental collision (Zhu et al., 2017; Dong et al., 2018; Yu et al., 2020).

The North Qinling Belt and South Qinling Belt appear to have experienced different paleo-elevation trends. The paleo-elevation of the North Qinling Belt during the Triassic is calculated to have remained constant at ~4000 m, perhaps because the altitude was a consequence of the previous collision of the North and the South Qinling Belts during the Paleozoic (Dong and Santosh, 2016; Hu et al., 2020b). In contrast, during the Middle to Late Triassic, the South Qinling Belt apparently experienced gradually increasing paleo-elevation from ~3000 m to 6000 m, followed by a decreasing of paleo-elevation to ~3000-4000 m (Fig. 10). These paleo-elevations are consistent with the calculated paleo-Moho depths for this orogenic belt (Hu et al., 2017). The significant elevation of the South Qinling Belt is consistent with evidence of thickened continental crust (Hu et al., 2020b). The absence of coeval, Upper Triassic strata in this region (Yang et al., 2021) suggests that significant erosional process took place following surface uplift. The resulting detritus began to supply adjacent basins within the southern North China Block during the Late Triassic (Yang et al., 2021). The above-mentioned decrease in elevation could also be explained by crustal subsidence between the South and North China blocks, possibly triggered by slab break-off and regional delamination resulting from continental collision (Hu et al., 2020b).

Relevant data from the northern Qiangtang Block are relatively scarce. From Permian to Carnian times, the topographic elevation of the northern Qiangtang Block is calculated to have been between 1000m and 3000m, without an obviously increasing trend. The paleo-elevation of the northern Qiangtang Block was only about half that of the East Kunlun-Qinling orogenic belt. This relatively modest paleo-elevation is consistent with sedimentological and tectonic records from the northern Qiangtang Block, especially shallowing-upwards of the basin and evidence of terrestrial erosion (Wang et al., 2022). The northern Qiangtang Block has been interpreted as a Lower Triassic foreland basin that formed during continental collision, while a remnant Paleotethys still lay to the south (Fig. 3), followed by uplift above the sea level during Late Triassic time (Wang et al., 2022).

The magmatic rocks within the Sonpan-Ganzi Basin are mainly Late Triassic in age (e.g., Zhan et al., 2018). The reconstructed paleo-elevation based on the whole-rock geochemical data for the magmatic rocks cutting the basin (see Section 3.2) are compatible with a broad uplift trend (Fig. 10), with estimated elevations ranging from ca. 3000 m to 6000 m. Such a high elevation is consistent with geophysical and geological evidence, including a thickened crust (~55 km; Zhan et al., 2018) and contemporaneous compressional deformation (e.g., thrusting and folding) during the Late Triassic (Chang, 2000), and also the lack of Jurassic strata in the Songpan-Ganzi basin (Ding et al., 2013). The Upper Triassic magmatic rocks of the Songpan-Ganzi basin intruded these Upper Triassic strata of the basin, showing that sedimentation was completed prior to this magmatism. During the Late Triassic, the uplifted Songpan-Ganzi basin potentially acted as a source for the Upper Triassic strata of the western Sichuan Basin (Yan et al., 2019), consistent with a relatively high elevation by this time.

6. Significance for geological development

Integration of our synthesized analysis of detrital zircon contributions and our calculated paleo-elevations, allow us to quantify the proto-source contributions from different crustal basements and/or magmatic rocks; this then facilitates understanding of source-to-sink relationships. Several alternatives have been proposed for sediment provenance in and around the Triassic Songpan-Ganzi basin, in the light of two main plate tectonic hypotheses; i.e., syn-collisional basin or back-arc basin (see Section 4). (1) Multiple deposystems within the Songpan-Ganzi basin were supplied by multiple sources (Weislogel et al., 2006; Tang et al., 2023); (2) the Qinling Orogenic Belt represents the major source of the Songpan-Ganzi basin (Weislogel et al., 2006, 2010; Enkelmann et al., 2007; Gong et al., 2021), together with a possibly rare (Enkelmann et al., 2007) or more significant detrital contributions from the ultrahigh-pressure terrane of the Dabie Orogen farther east (Nie et al., 1994; Weislogel et al., 2010) (Fig. 2); (3) the South China Block source dominated only the southeastern depocenter (Ding et al., 2013; Gong et al., 2021); (4) the East Kunlun Orogenic Belt supplied the western depocenter (Enkelmann et al., 2007; Ding et al., 2013) and also the central depocenter (Jian et al., 2019); (5) Supply from the Qiangtang Block dominated the southwestern depocenter (Ding et al., 2013) and/or the more easterly parts of the basin (Gong et al., 2021); (6) whatever the sources, deposition in the basin as a whole continued until the Early Norian (Gong et al., 2021) or Late Norian (Weislogel et al., 2006, 2010; Enkelmann et al., 2007; Ding et al., 2013; Jian et al., 2019). The above very large number of alternative interpretations of the basin's provenance highlight the difficulties of using conventional methods to determine the provenance (e.g., facies, paleocurrents, petrography).

Our calculated proto-source proportions (Table 1) suggest by contrast that zircon grains were widely distributed across all of the four depocenters (Fig. 5); i.e., derived from the cratonic basement of the North China Block and the North Qaidam Block, together with magmatic zircons from East Kunlun and the Qiangtang regions (Figs. 2, 7; Table 1) (see Section 5.4). This suggests an intimate relationship between the colliding crustal blocks bordering the basin and the resulting Triassic sediments (e.g., Zhang et al., 2012), as opposed to a dominant contribution from the Qinling-Dabie Orogen (Figs. 2-4) (Nie et al., 1994; Weislogel et al., 2006). Contributions from the Qinling Orogenic Belt proto-source are considered to be low (1.8%-18.3%; Table 1) and do not represent a major source for the basin (Weislogel et al., 2006, 2010;

Enkelmann et al., 2007; Gong et al., 2021). Although the Qinling Orogenic Belt apparently reached a high elevation (see Section 5.5; Supplementary Table S3), relatively less detritus from this source (Table 1) is documented in the Songpan-Ganzi basin. Topographic barriers may have separated the Qinling Orogenic Belt from the basin (Yan et al., 2016; Li et al., 2017), although additional evidence (e.g., facies distribution) would be needed to test this. In addition, the concentration of rare metal elements (e.g., Li) in the sandstones of the eastern depocenter is similar to that within intermediate-felsic rocks in the Qinling Orogenic Belt (Hu et al., 2022). The Qinling-derived debris (e.g., zircons) in the western depocenter is mainly documented during the Late Triassic (Ding et al., 2013; Table 1). One option is that this detritus originated in the eastern depocenter and was subsequently incorporated into the western depocenter as a result of sediment recycling during convergence and collision of the Qiangtang and South China blocks with Eurasia. Axial transport to the Songpan-Ganzi basin from the Qinling-Dabie orogenic belts (Figs. 2-3) via orogen-parallel routes (Fig. 10) (Weislogel et al., 2006) seems to have been insignificant.

The South China Block was a significant contributor to the southeastern depocenter, accounting for, on average, ~15.0% of zircon grains (Table 1). It was also a minor contributor to the central and western regions, averaging 3.4% and 5.8%, respectively (Table 1). The back-arc basin model envisages westward transport of detritus from the continental hinterland of the back-arc basin, represented by the western margin of the South China Block (Ding et al., 2013). Clastic sediments would therefore be expected to decrease in volume and overall grain size in a westerly direction. Also, the relatively proximal sediments in the east should have a prominent South China Block-affinity in the zircon distribution. In reality, there are abrupt changes and variation in zircon abundances between the eastern and the westerly parts of the basin that differ from the expected patterns in the back-arc basin model. However, these features are fully consistent with the preferred continental collision model.

The similarities of zircon populations of > 700 Ma in both the South Qinling Belt and the South China Block suggest that the zircons found in the South China Block, previously believed to have been transported over long distances (Ding et al., 2013), may instead have originated more locally from the western South Qinling Belt (Fig. 11). Alternatively, these zircons could have been derived from previously deposited (Paleozoic) sandstones within the basin, or from the inferred cratonic basement of the South China Block even of the unexposed basement of the Songpan-Ganzi basin (e.g., Wang et al., 2016) (see Section 4.1).

For the Dabie Orogen to the east of the Qinling Orogenic Belt (Fig. 2), there is limited evidence of magmatism during the Triassic and thus paleo-elevation estimates are not available However, there are compositional similarities between the basement of the Dabie Orogen and that of the South Qinling Belt (Wu and Zheng, 2013). It is therefore plausible that the zircon in the Dabie Orogen originated from the South Qinling Belt. In addition, there is no evidence of metamorphism (e.g., mica with high Si content) in the sedimentary rocks of the Dabie Orogen (Enkelmann et al., 2007), suggesting that this region was not a contributor to the Songpan-Ganzi basin. The primary source of Paleoproterozoic to Archean-aged detrital zircons is believed to have been the North China Block (Fig. 6), although it is possible that these zircons could have originated in the North Qaidam region, with or without sediment recycling (Table 1) (Figs. 2, 10).

Igneous zircons derived from the East Kunlun region is prevalent in some samples from the northeastern, central, and western depocenters (Table 1). This can be attributed to ongoing surface uplift and rapid exhumation of the East Kunlun Orogen (Mock et al., 1999; Jolivet et al., 2001; Liu et al., 2005; Dai et al., 2013). Our calculations suggest that the East Kunlun region may have reached a paleo-elevation of ca. 4000-5000 m. Paleocurrents measured in the East Kunlun region are consistently southwards (Liu et al., 2020 and references therein), which is consistent with a regional paleogeography in which Paleotethys lay to the south (Fig. 3).

The inferred, rapid exhumation rate during the Late Triassic (~0.8 km/Ma; Dai et al., 2013) and the estimated denudation thickness (0.4-1.2 km; Liu et al., 2020) of the East Kunlun region suggest that this region could also have contributed a significant amount of sediment into the Songpan-Ganzi basin to the south (Fig. 3).

The zircon grains that originated from the Qiangtang Block are likely to have been transported during the Middle Triassic, especially to the western, central, and southeastern depocenters (Table 1; Ding et al., 2013; Gong et al., 2021). As noted above, the lack of metamorphic detritus in the Songpan-Ganzi basin (Enkelmann et al., 2007) suggests that the ultra-high pressure metamorphic rocks of the Qiangtang region did not represent a significant source (cf. Zhang et al., 2008). Despite the relatively modest calculated paleo-elevation of North Qiangtang region (1000-3000 m) (see Section 5.5), this region contributed > 10% of detrital zircons (Table 1), mainly to the southeastern and western depocenters (Fig. 10), which is consistent with rapid erosion rate in the North Qiangtang Block.

Paleomagnetic data suggest that the North Qiangtang Block was situated within the range of ~25°S to ~25°N between 300 Ma and 200 Ma (Song et al., 2017, 2020). Regions that were located at relatively low latitudes could have experience intense tropical weathering (Deng et al., 2022; Zhang et al., 2022). This could help to explain why, despite its inferred relatively low elevation, the northern Qiangtang block contributed substantially to the zircons to the Songpan-Ganzi basin (Fig. 3).

As noted above, the Songpan-Ganzi basin was situated well below sea level until the Carnian (Fig. 10c) and was then uplifted to form a plateau-like feature (3000-4000 m) during the Norian to Rhaetian (Fig. 10d). Far-away sedimentary sources to the Songpan-Ganzi basin probably terminated before the Norian, although this is inconsistent with some previous interpretations (Weislogel et al., 2006, 2010; Enkelmann et al., 2007; Ding et al., 2013; Jian et al., 2019; Gong et al., 2021).

The zircon age populations from the Upper Triassic sandstones of the southwestern Sichuan Basin are distinct (Yan et al., 2019), as these formations (e.g., Xiaotangzi Formation) are characterized by a relatively high proportion of Paleozoic zircons compared to those of the underlying lithologies (e.g., Ma'antang Formation) (Yan et al., 2019). A similar pattern of Paleozoic zircons is commonly documented in the Songpan-Ganzi basin, suggesting that uplift of the basin was underway since the Norian, thereby making it possible to contribute sediment to the Sichuan Basin (Fig. 4).

In summary, the inferred sedimentary processes affecting the Triassic Songpan-Ganzi basin are consistent with the syn-collisional basin model, related to final closure of Paleotethys (e.g., Nie et al., 1994; Weislogel et al., 2006; Tang et al., 2023) (Fig. 3a). The sediments of the Songpan-Ganzi basin were contributed from multiple sources that were located in adjacent crustal units; this resulted in the observed local variations in sediment compositions within the different depocenters.

Our main conclusions are that: (1) the Qinling Orogenic Belt, despite its considerable calculated elevation, was only a minor contributor to the eastern depocenter; (2) input from the South China Block was minor, mainly restricted to the southeastern depocenter; (3) the East Kunlun Orogen, characterized by calculated high elevation, supplied all of the depocenters of the Songpan-Ganzi basin; (4) the North Qiangtang Block, despite its calculated lower elevation, represented the dominant source of zircons found in the western, central and southeastern depocenters; (5) the Songpan-Ganzi basin underwent uplift during the Norian which triggered detrital supply to the Sichuan Basin.

It should, however, be emphasize that elevation may not have been the dominant control of the source contributions in all cases, as indicated by the above comparison of different sediment inputs from the North Qiangtang Block versus the Qinling Orogenic Belt. This supports some recent studies (Deng et al., 2022; Zhang et al., 2022) that have emphasized the importance of climate-related weathering in preference to e.g., tectonic uplift, relief and/or physical erosion processes. The results of our simulations (Fig. 9; Table 1) also suggest that zircon that were derived from different sources subsequently mixed within the basin, which may represent the effects of differential syn-collisional uplift.

This study has shown that by integrating statical analysis of detrital zircon age distributions with paleo-elevation calculations, it then became possible to estimate the contributions of sediment sources and also help to track the sediment pathways from source to sink. This combined approach has been shown to provide valuable insights to the complex sedimentary processes involved in the basin development within a complex region of on-going continental collision. We suggest that this combined approach should in future be applied to some other sedimentary basins of different ages; e.g., the Late Cretaceous-Eocene Mozambique Basin (Reading and Richards, 1994; Castelino et al., 2017), the Late Cretaceous-Miocene NW Sabah Basin (Malaysian Borneo) (van Hattum et al., 2006), or the modern easternmost Mediterranean Sea (Sagy et al., 2020).

7. Conclusions

The combination of detrital zircon geochronology through the application of source unmixing, and calculated paleo-elevations using empirical equations based on geochemical data from magmatic rocks, provide valuable insights into sedimentary source-to-sink relationships and the implications of changing paleo-altitudes in adjacent orogenic units.

For the Songpan-Ganzi basin sandstones specifically:

- Analysis of detrital zircon U-Pb age distributions, including both literature and original data (n=63), reveals the presence of five dominant populations: 300-200 Ma, 500-360 Ma, 1000-700 Ma, 2000-1600 Ma and 2600-2400 Ma.
- Multidimensional scaling and Monte Carlo Mixture modelling suggest a close relationship between the sandstones in the Songpan-Ganzi basin (sink) and the neighboring crustal units (proto-sources). Specifically, the North China Block (average contribution 12.3%), the North Qaidam Block (average contribution 14.8%), the East Kunlun magmatic rocks (average contribution 15.0%) and the Qiangtang magmatic rocks (average contribution 15.3%) are identified as the major zircon contributors for the Songpan-Ganzi basin .
- The input of detrital zircon from the Qinling Orogenic Belt, despite its calculated high elevation, was relatively minor and primarily restricted to the eastern part of the basin. Detrital zircons originating from the Qinling Orogenic Belt were mainly mixed with detritus derived from other sources and incorporated into the western depocenter during the Late Triassic, suggesting long-distance transport

and/or recycling from the eastern part of the basin during on-going continental collision.

- Zircons derived from the South China Block primarily occur in the southeastern depocenter and to a lesser extent in the western depocenter. This distribution is consistent with the collision-related hypothesis of the Songpan-Ganzi basin but does not conform to the expected age populations in the alternative back-arc basin model.
- Zircons associated with the East Kunlun region were largely supplied to the Songpan-Ganzi basin as a result of an inferred rise in paleo-elevation (4000-5000 m), associated with rapid exhumation of the East Kunlun Orogen.
- The North Qiangtang Block, despite its inferred relatively low elevation, contributed more than 10% of the detrital zircons to the four depocenters; this is attributed to rapid erosion rate of this crustal block, possibly influenced by climatically controlled weathering.
- The integrated method used in provenance analysis of Triassic sandstones from the Songpan-Ganzi basin and the related magmatic rocks enables the identification of different sources of detrital zircons. These sources were mainly the adjacent crustal units. The resulting sediments mainly accumulated in four main nearby depocenters within the Songpan-Ganzi basin. There is also some evidence of sediment mixing and recycling within the basin during ongoing continental collision.
- Basin-filling was primarily controlled by tectonically controlled surface uplift combined with denudation of the adjacent mountain relevant belts, potentially

enhanced by climatically controlled weathering.

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Figure captions

Fig. 1 Flowchart showing the integrated method proposed here to aid understanding and interpretation of source-to-sink relationships of basin (including key definitions, plots and step-by-step methods) (a) source unmixing of detrital zircon geochronological data; (b) paleo-elevation estimates of intermediate-composition magmatic rocks of neighboring crustal units.

Fig. 2 Distribution of the major continental and smaller microcontinental blocks in China and adjacent areas (modified after Li et al., 2018). The Songpan-Ganzi basin is highlighted. Yellow labels mark the general positions of proto-source candidates: (1) North China Block (NCB); (2) North Qaidam Block (NQB); (3) South China Block (SCB); (4) North Qinling Belt (NQB); (5) East Kunlun Orogenic Belt (EKOB); (6) North Qiangtang Block (QB); (7) Yidun Terrane (YT); (8) western Southern Qinling Belt (WSQB); (9) eastern Southern Qinling Belt (ESQB); (10) East Kunlun magmatics (EKM); (11) Qinling magmatics (QLM); (12) Qiangtang magmatics (QTM). In addition, red and black bold lines mark sutures and major faults between the continental and microcontinental blocks. 1-Mianlue-A'nyemaqen-Kunlun Suture; 2-Jinshajiang Suture; 3-Longmenshan Fault; 4-Luonan-Luanchuan Fault; 5-Shangdan Suture; 6-Longmu Co-Shuanghu Suture; 7-Banggong Co-Nujiang Suture.

Fig. 3 Alternative tectonic hypotheses for the Songpan-Ganzi basin. (a) Syn-collisional or remnant ocean basin hypothesis (Zhou and Graham, 1996; Nie et al., 1994; Weislogel et al., 2006; Wang et al., 2016). This is revised to include the probable South China Block affinity of the Songpan-Ganzi Basin basement (e.g., Wang et al., 2016; Wu et al., 2019); (b) Back-arc basin hypothesis associated with rifting of the Yidun Terrane from Qinling, driven by rollback of Paleotethyan oceanic lithosphere (e.g., Klimetz, 1983; Gu, 1994; Pullen et al., 2008; Ding et al., 2013). Abbreviations: AS, A’nyemaqen-Kunlun Suture; SS, Shangdan Suture; MS, Mianlue Suture; LS, Longmen Shan Thrust; GS, Ganzi-Litang Suture; JS, Jinshajiang Suture.

Fig. 4 Tectonic map showing the major terranes, suture zones and the Songpan-Ganzi basin (modified after Ding et al., 2013). Locations of the newly analyzed samples (n=7) are highlighted, together with the general positions for the compiled data. Blue dashed lines mark the boundaries of the Songpan-Ganzi basin. Blue labels mark the general positions of potential sources: (1) North China Block (NCB); (2) North Qaidam Block (NQB); (3) South China Block (SCB); (4) East Kunlun Orogenic Belt (EKOB); (5) North Qiangtang Block (QB); (6) Yidun Terrane (YT); (7) western Southern Qinling Belt (WSQB); (8) East Kunlun magmatics (EKM); (9) Qiangtang magmatics (QTM). See Figure 2 for detailed proto-source locations.

Fig. 5 Restored Triassic isopachs of the Songpan-Ganzi basin based on Source Parameter Imaging (Zhang et al., 2019). Paleocurrent data are shown in black arrows (Weislogel et al., 2006; Ding et al., 2013; Jian et al.,2019). General locations of the northeastern (a), southeastern (b), central (c) and western (d) depocenters are highlighted. Blue labels mark the general positions of potential sources: (1) North China Block (NCB); (2) North Qaidam Block (NQB); (3) South China Block (SCB); (4) East Kunlun Orogenic Belt (EKOB); (5) North Qiangtang Block (QB); (6) Yidun Terrane (YT); (7) western Southern Qinling Belt (WSQB); (8) East Kunlun magmatics (EKM); (9) Qiangtang magmatics (QTM). See Figure 2 for detailed proto-source locations.

Fig. 6 Kernel density estimate (KDE) plots of U-Pb ages of detrital zircon from the newly analyzed Triassic sandstones of the Songpan-Ganzi basin and related sources. Vertical color bars indicate common peaks associated with specific orogenic events and regions. The detrital zircon age range of ~2600-2400 Ma is related to the crustal growth and cratonization in the North China Block (Zhao et al., 2005; Wang et al., 2017), the age range of ~2000-1600 Ma is related to the orogenesis and subsequent rifting magmatism in the North China Block (Zhai, 2010), the age range of 1000-700 Ma is related to the amalgamation and breakup of the Rodinia supercontinent (Wang and Li, 2003; Zhao et al., 2011), the age range of 500-360 Ma and 300-200 Ma are primarily related to the subduction and continental collision of Prototethys and Paleotethys, respectively (Li et al., 2018; Dong et al., 2018; Hu et al., 2020a; Wu et al., 2020). The North China Block data are from Kröner et al. (1988), Darby and Gehrels (2006), Xia et al. (2006a, 2006b), Tung et al. (2007), Li et al. (2008), Liu et al. (2011) and Wan et al. (2011b); the North Qaidam Block data are from Sun et al. (2019, 2022), and references therein; the South China Block data are from Liu et al. (2008), Sun et al. (2008, 2009), Wang et al. (2010, 2012, 2013); the North Qinling Belt data are from Diwu et al. (2010, 2014), Wan et al. (2011a), Zhu et al. (2011), Shi et al. (2013), Zhang et al. (2015) and Zhao et al. (2015); the western South Qinling Belt data are from Chen et al. (2010), Wu et al. (2012), Wang et al. (2014) and Yan et al. (2016a); the eastern South Qinling Belt data are from Duan (2010), Ling et al. (2010), Dong et al. (2013) and Yan et al. (2016b); the East Kunlun Orogenic Belt data are from Huang et al. (2017) and Wu et al. (2019); the North Qiangtang Block data are from Pullen et al. (2008), Gehrels et al. (2011) and He et al. (2011); the Yidun Terrane data are from Reid et al.

(2007) and Tian et al. (2020); the Qinling magmatics data are from Hu et al. (2020b), and references therein; the East Kunlun magmatics data are from Dong et al. (2018) and references therein; finally the Qiangtang magmatics data are from Lu et al. (2019) and references therein.

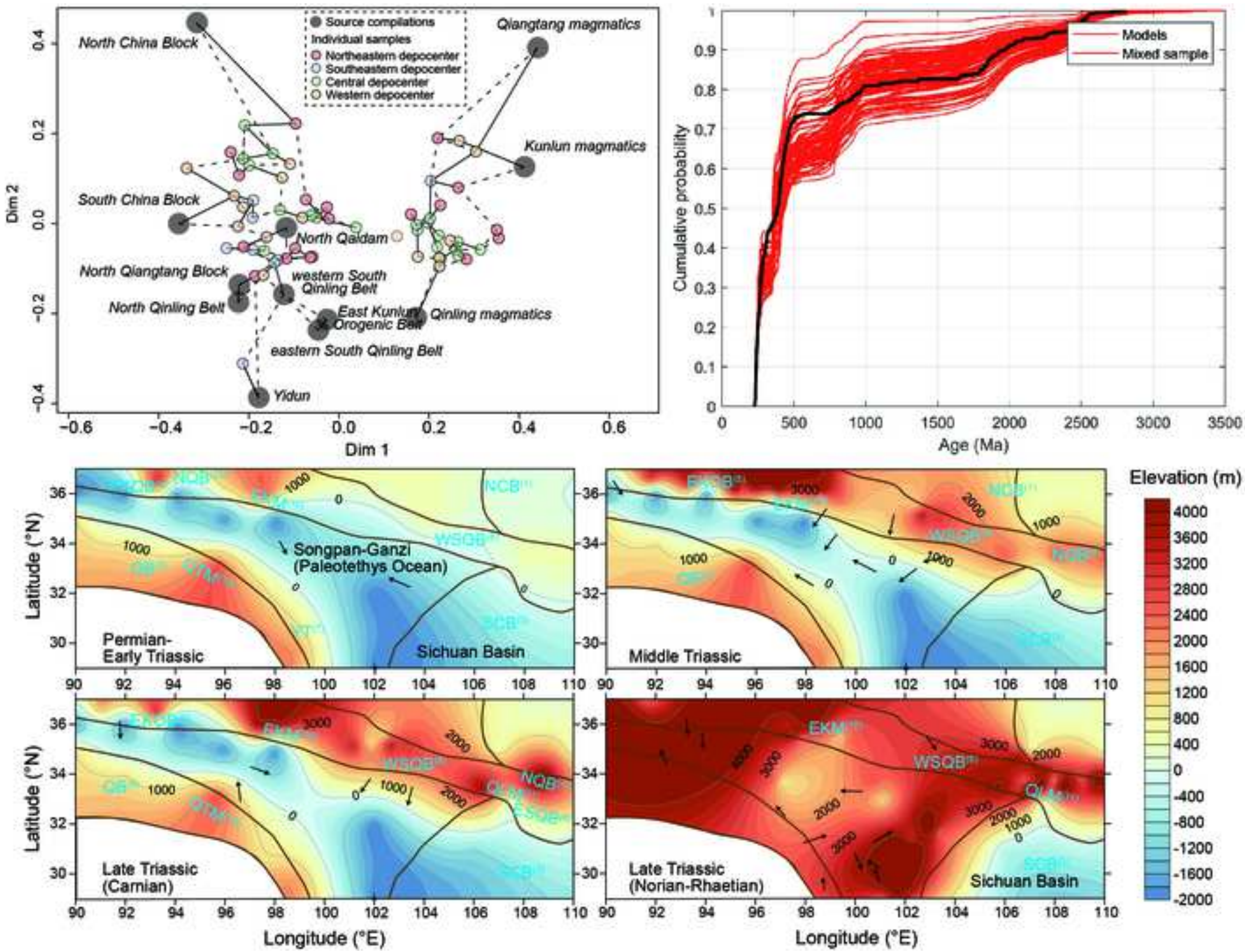
Fig. 7 Non-metric multidimensional scaling (MDS) plot comparing the detrital zircon age component older than 227 Ma from the Songpan-Ganzi basin. The MDS plot compares the >227 Ma age component of individual samples from the Songpan-Ganzi basin. Two unique similarity clusters are apparent in the MDS plot. One cluster indicates similarity between the Songpan-Ganzi basin sediments and the major continent blocks (North China Block, South China Block, North Qaidam, North Qiangtang Block, North Qinling Belt and the western South Qinling Belt). A second cluster indicates similarity between the sandstones and the Qiangtang, Kunlun and Qinling magmatics.

Fig. 8 Non-metric multi-dimensional scaling (MDS) maps (based on Kuiper distance) of detrital zircon U-Pb ages of samples compiled for the (a) northeastern, (b) southeastern, (c) central (c) and (d) western depocenters of the Songpan-Ganzi basin. Data from this study, and from Bruguier et al. (1997), Weislogel et al. (2006), Ding et al. (2013) and Jian et al. (2019) are compiled. The maps were constructed using 'Provenance'-an R package for statistical provenance analysis (Vermeesch et al., 2016).

Fig. 9 Example of model results of group 3 samples (2004T069, 18MK37, 18BPG20 and 18SGN07) from the northeastern depocenter of the Songpan-Ganzi basin. Sources: 1-North China Block; 2-North Qaidam Block; 3-South China Block; 4-North Qinling Belt; 5-East Kunlun Orogenic Belt; 6-North Qiangtang Block; 7-Yidun Terrane; 8-western Southern Qinling Belt; 9-eastern Southern Qinling Belt; 10-East Kunlun magmatics; 11-Qinling magmatics; 12-Qiangtang magmatics.

Fig. 10 Contour map showing the calculated paleo-elevation of the Songpan-Ganzi basin and the surrounding crustal units from Permian-Early Triassic to Late Triassic (Norian-Rhaetian). Black stars refer to the paleo-bathymetry from the fossil record (see Sections 3.2 and 4.2), white stars represent the calculated paleo-elevations of the magmatic rocks (Supplementary Tables S3-S4). Paleocurrent data, shown as black arrows, are from Weislogel et al. (2006), Ding et al. (2013) and Jian et al. (2019). Blue labels mark the general positions of proto-source candidates: (1) North China Block (NCB); (2) North Qaidam Block (NQB); (3) South China Block (SCB); (4) North Qinling Belt (NQB); (5) East Kunlun Orogenic Belt (EKOB); (6) North Qiangtang Block (QB); (7) Yidun Terrane (YT); (8) western Southern Qinling Belt (WSQB); (9) eastern Southern Qinling Belt (ESQB); (10) East Kunlun magmatics (EKM); (11) Qinling magmatics (QLM); (12) Qiangtang magmatics (QTM). Faults: 1-Shangdan Suture; 2-Mianlue-Anemaqen Suture; 3-Jinshajiang Suture; 4-Longmu Co-Shuanghu Suture; 5-Longmenshan Fault.

Graphical Abstract



- A combined method is proposed to help reconstruct source-to-sink sediment transport
- Source proportions are tested using simulations of detrital zircon age populations
- Paleo-elevation calculations of adjacent blocks shed light on sediment provenance
- The method leads to a new interpretation of sediment sources, supply and deposition

Figure 1 Click here to access/download;Figure;Figure 1.jpg

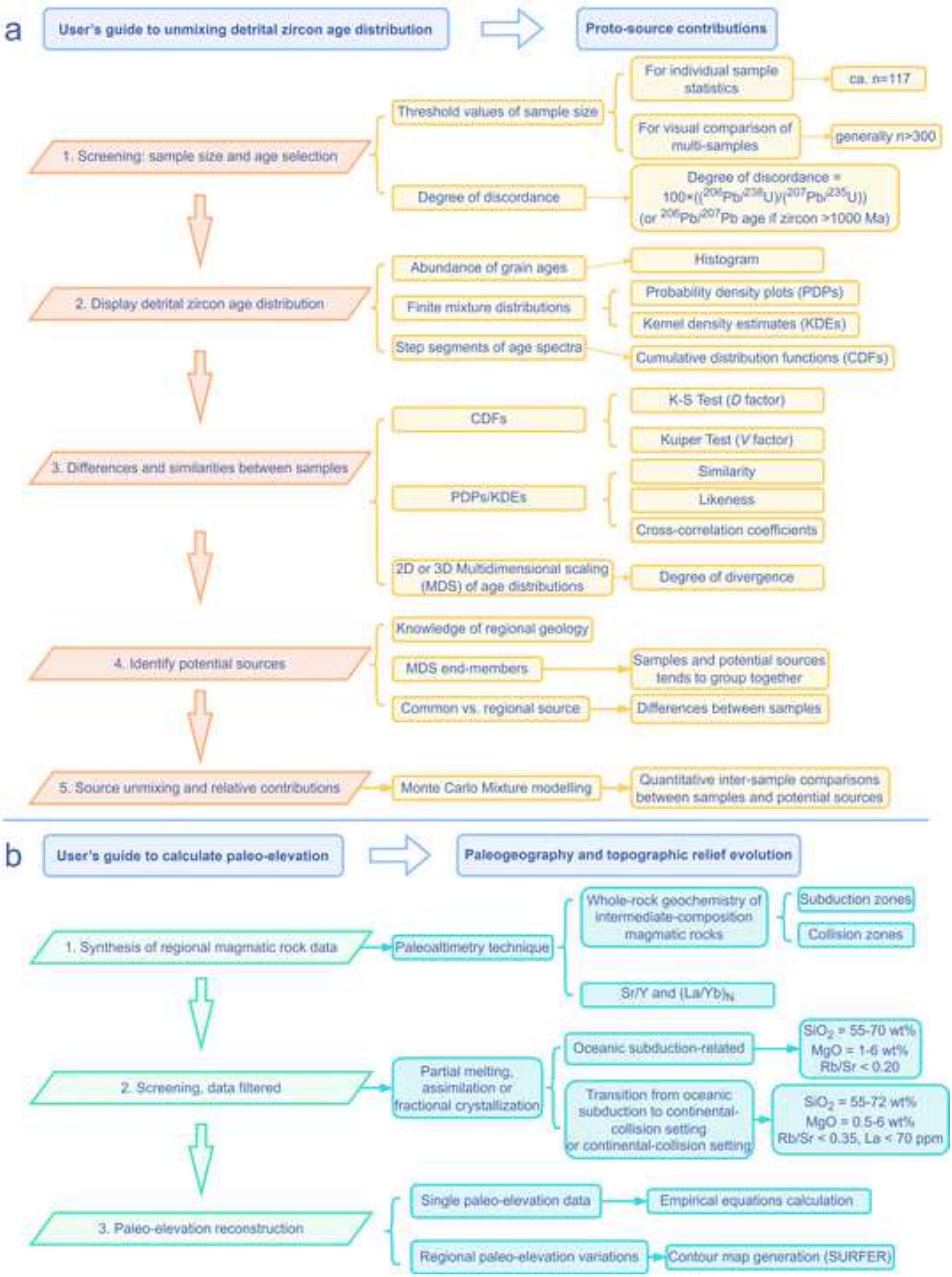


Figure 2 Click here to access/download;Figure;Figure 2.jpg

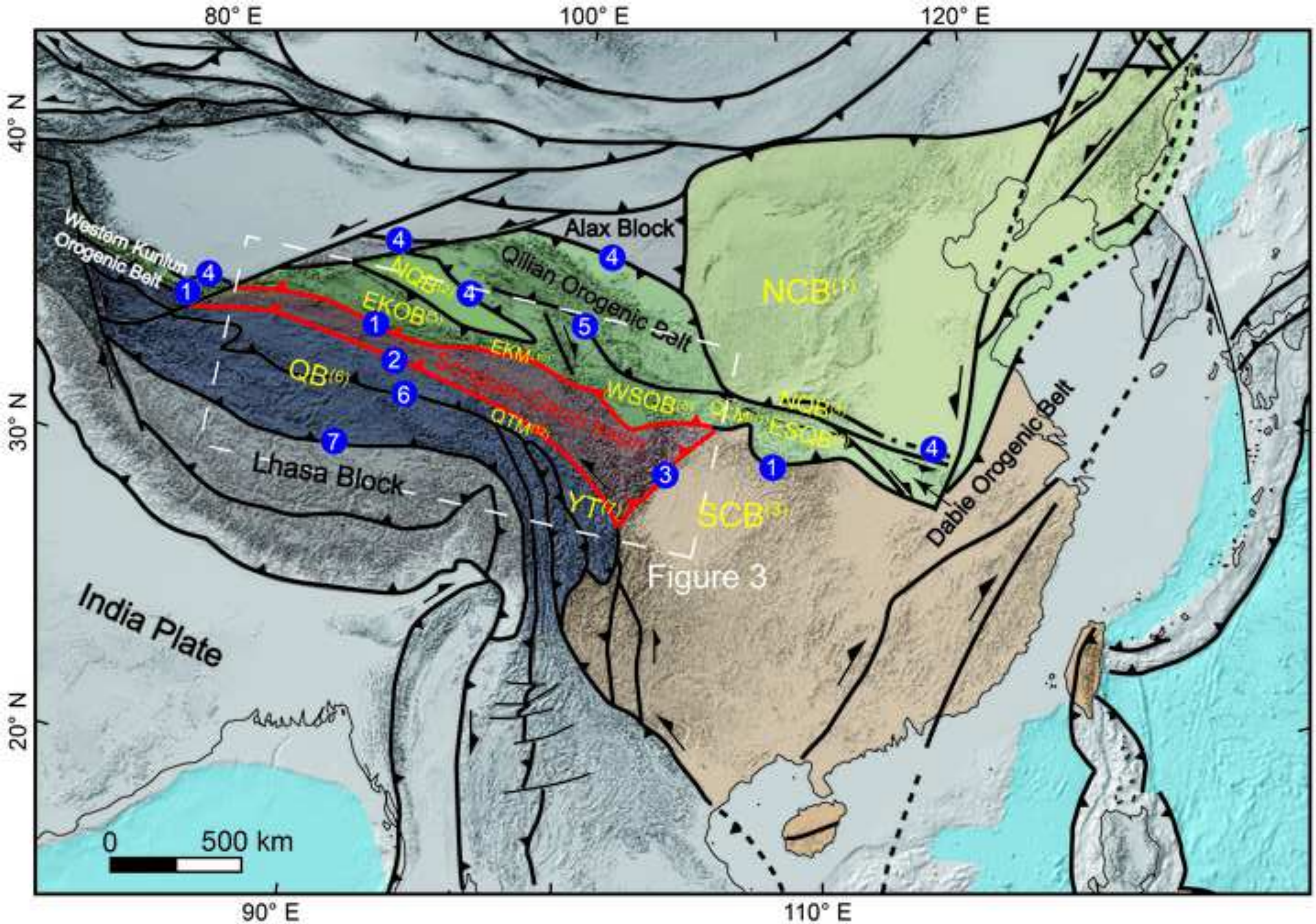


Figure 3

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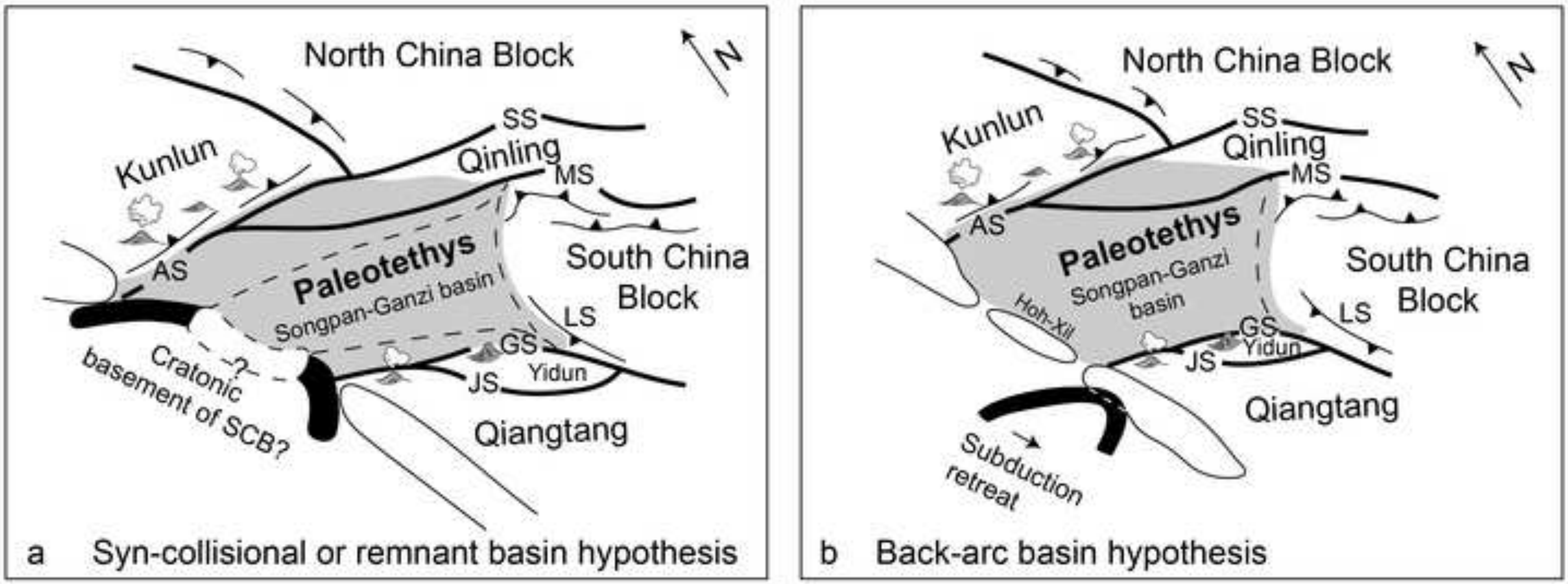

Figure 4

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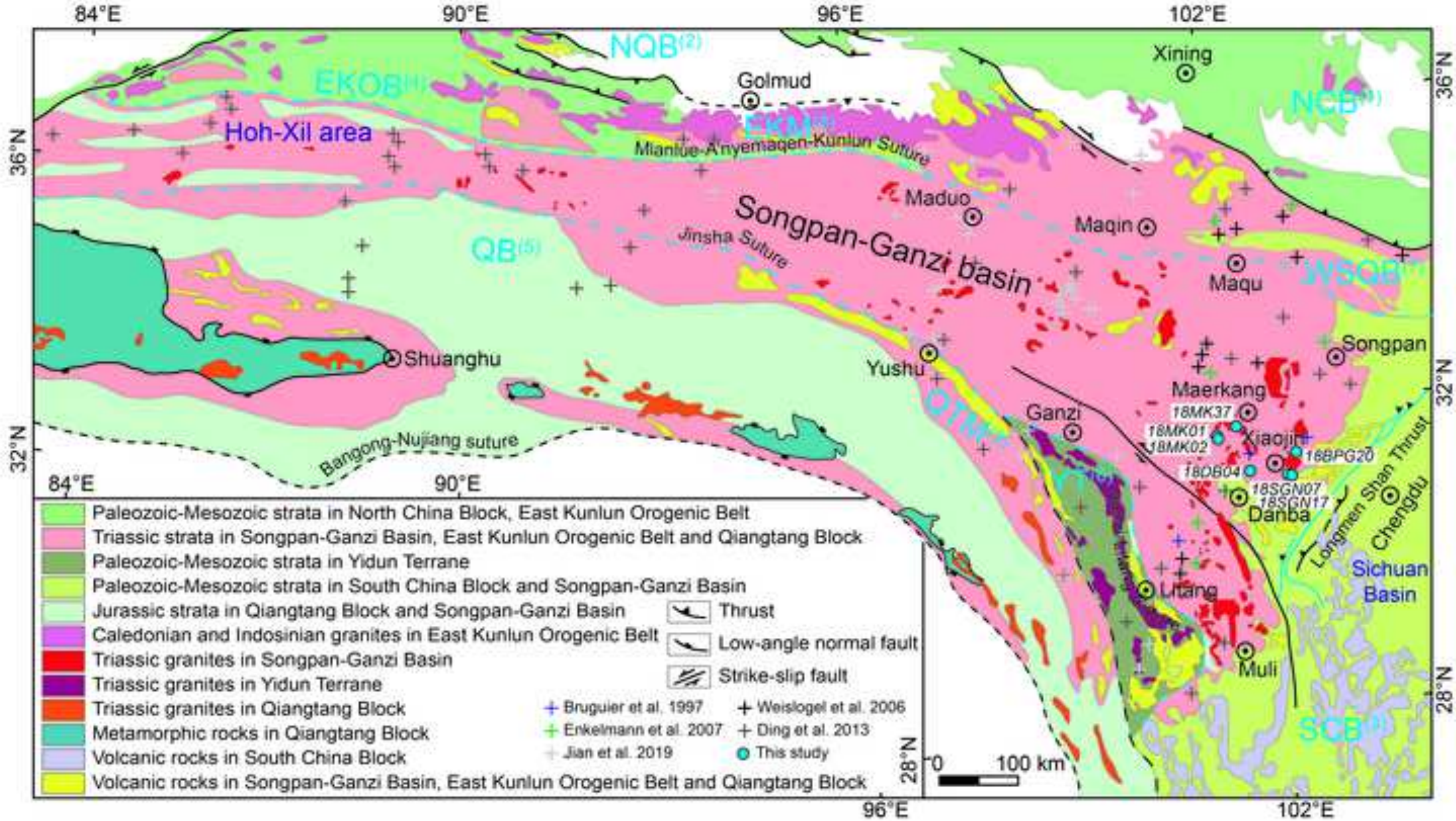

Figure 5

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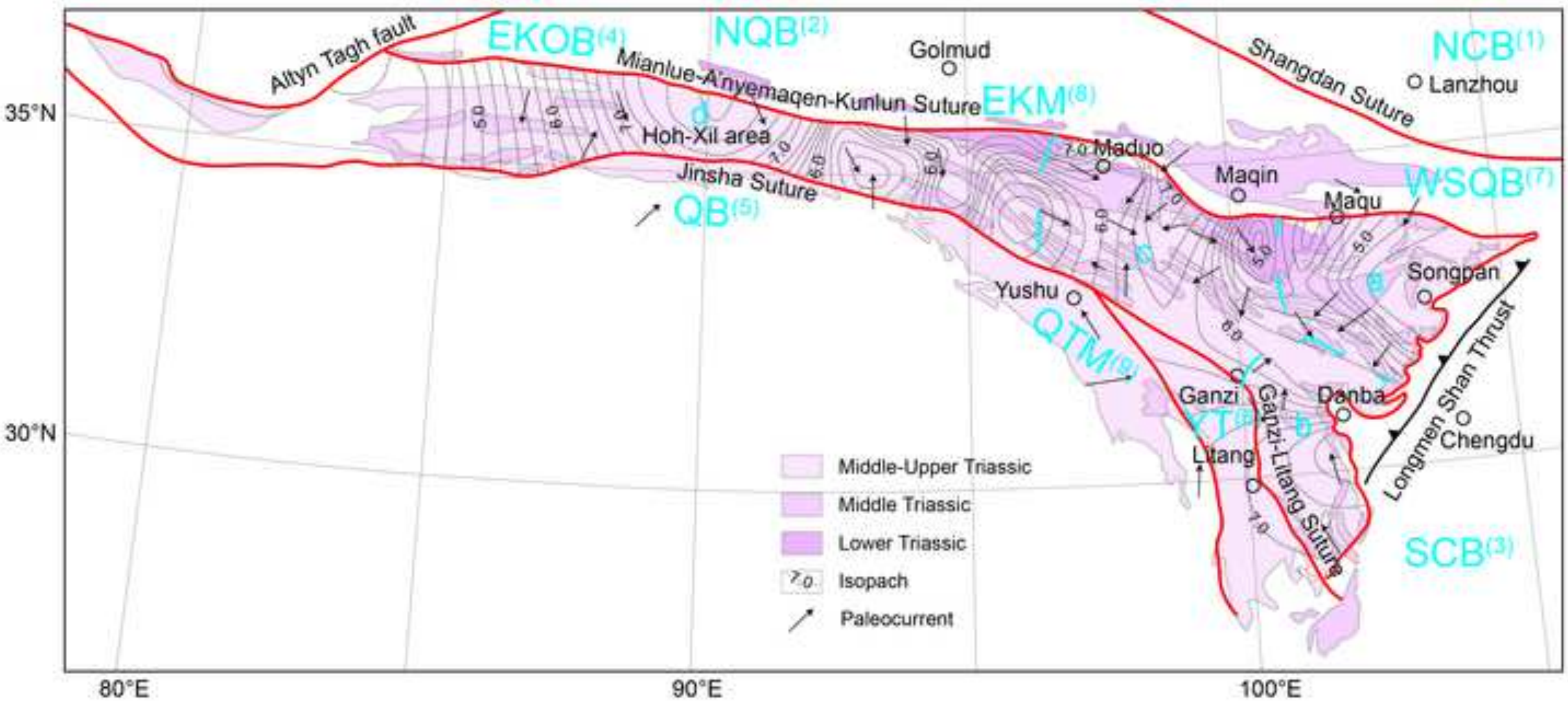

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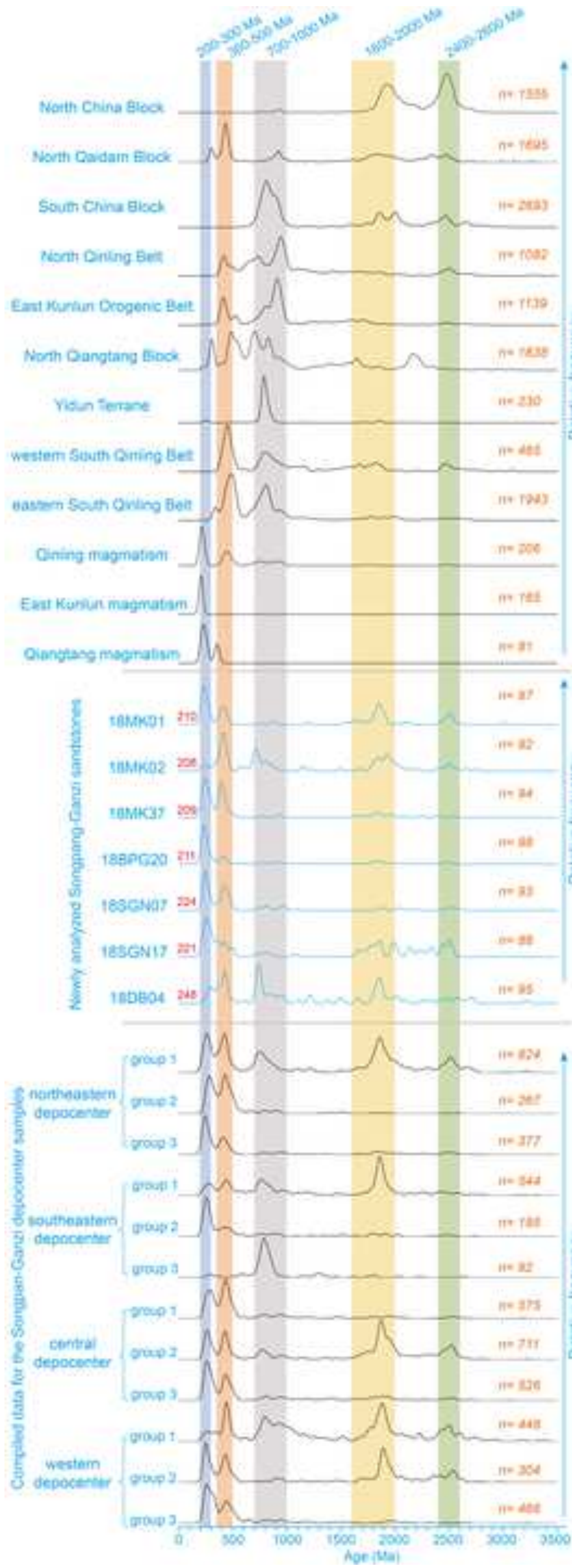

Figure 7

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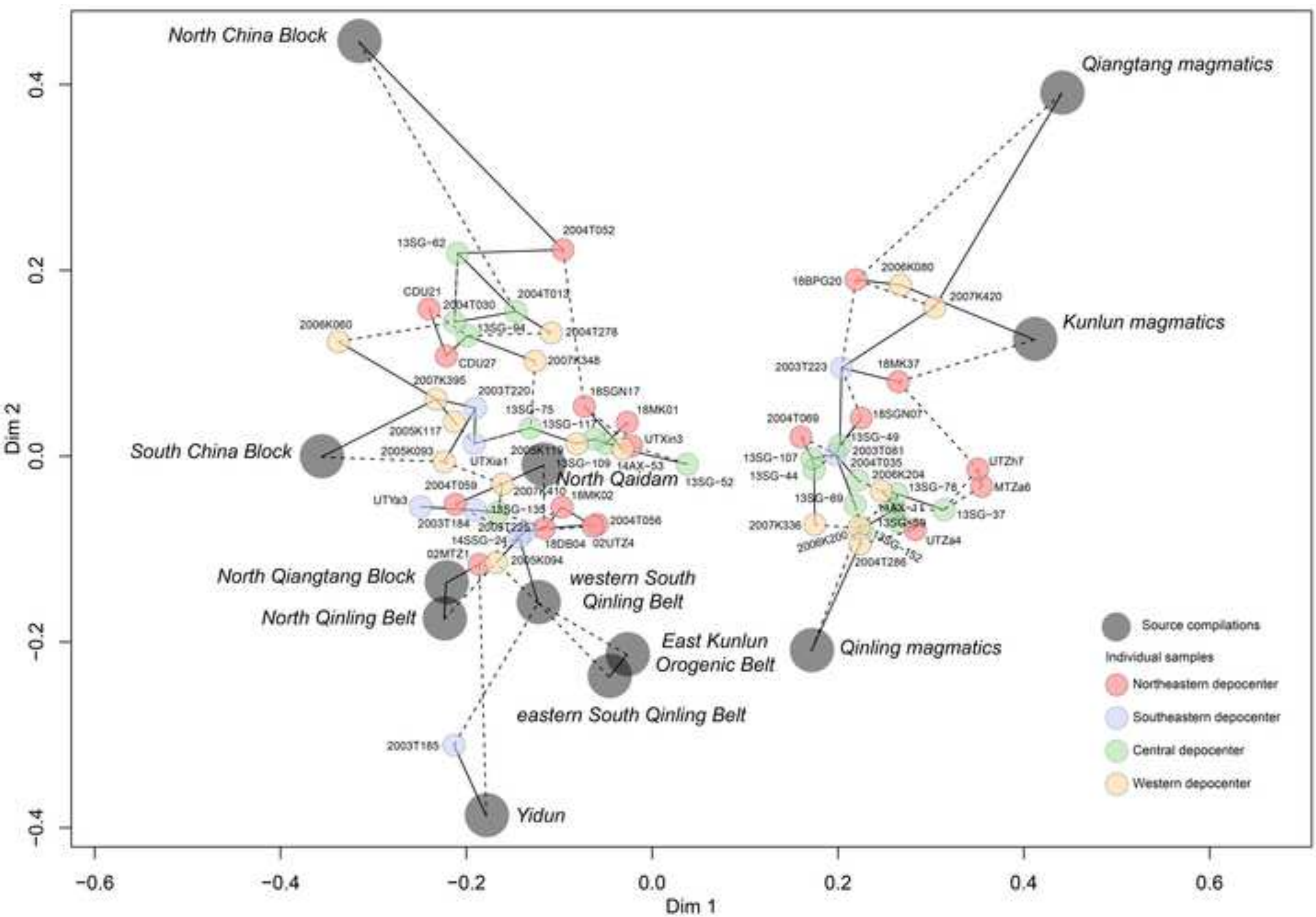

Figure 8

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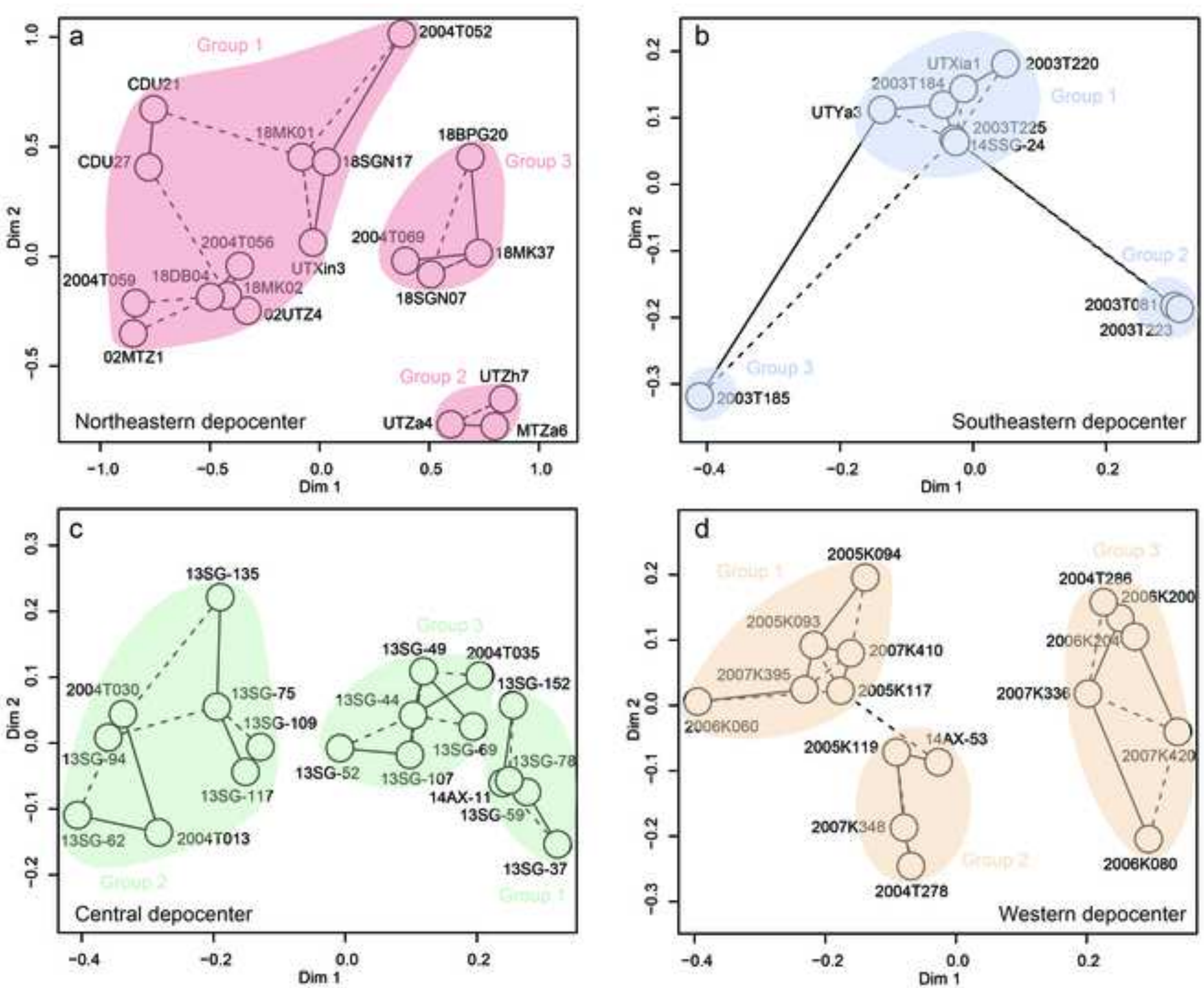

Figure 9

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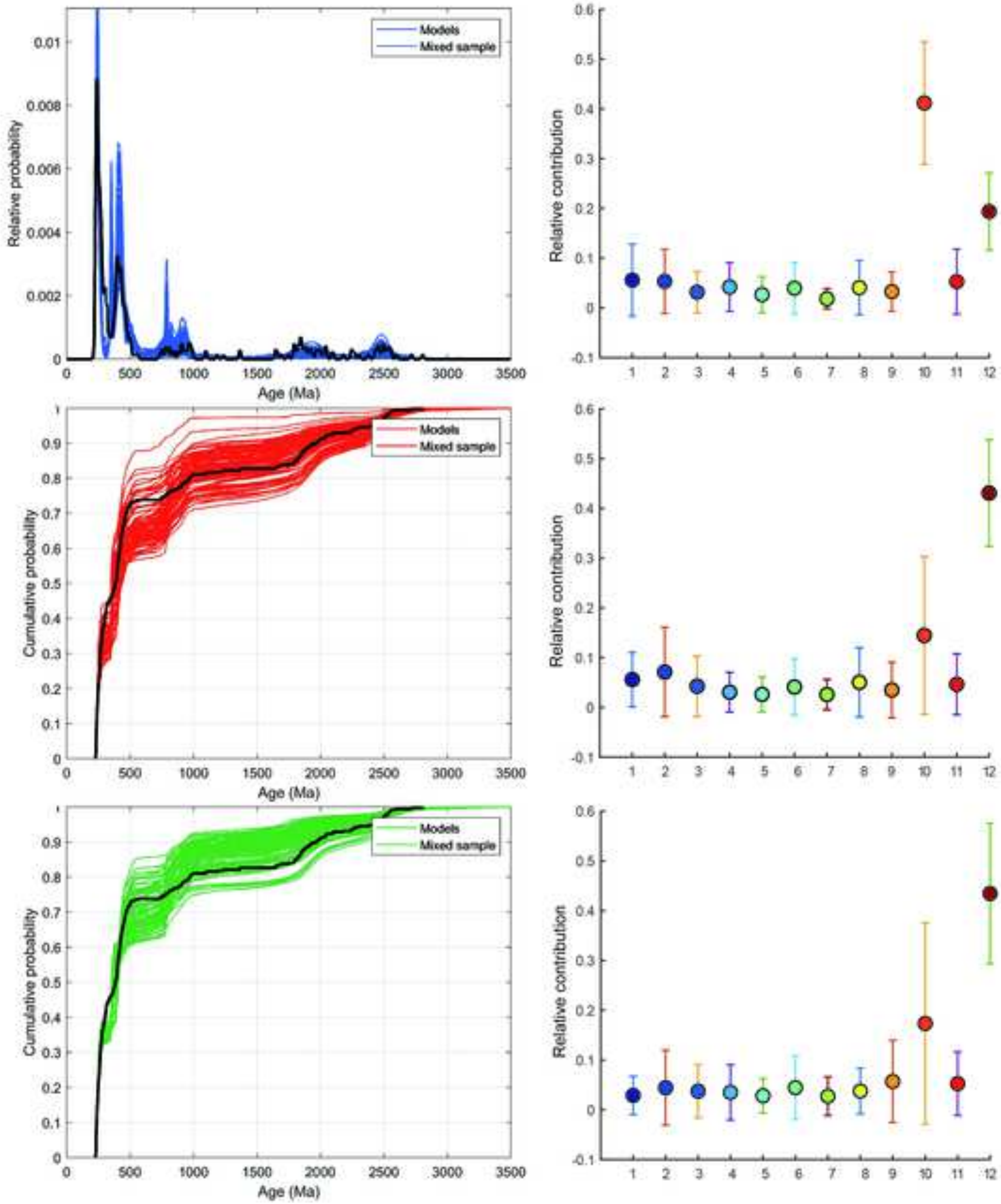

Figure 10

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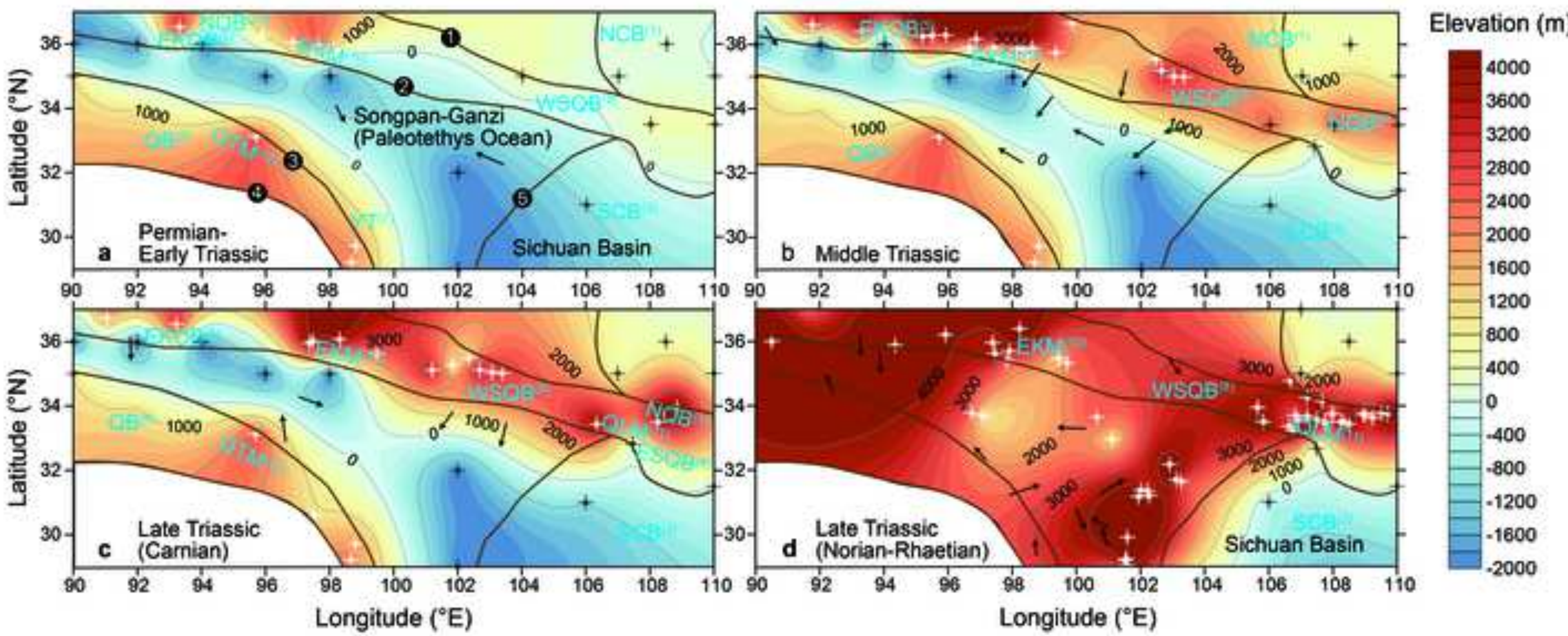

Table (Editable version) Click here to access/download;Table (Editable version);Table 1.xlsx

Table 1 Model results showing source contributions (%) based on cross-correlation coefficient (top row), Kuiper test V statistic (middle row) and K-S test D statistic (bottom row)

		Cratonic basement (detrital zircon)									Magmatics (igneous zircon)			Comparison met	
Depocenter	Subgroup	North China Block	North Qaidam Block	South China Block	North Qinling Belt	East Kunlun Orogenic Belt	North Qiangtang Block	Yidun Terrane	western South Qinling Belt	eastern South Qinling Belt	East Kunlun	Qinling	Qiangtang	R^2	V
northeastern depocenter	NE-G1	18.24	30.31	7.46	4.19	3.91	4.68	1.91	5.95	3.42	7.35	4.31	8.26		
	NE-G1	19.29	32.79	5.22	4.71	4.48	4.37	2.67	4.47	3.45	7.15	3.61	7.78	0.571	0.124
	NE-G1	21.35	24.24	7.10	4.91	4.89	4.90	2.68	5.17	3.63	9.76	4.50	6.87		
	NE-G2	2.14	39.69	1.58	2.34	16.00	3.86	0.98	4.23	6.27	8.69	7.00	7.22		
	NE-G2	0.69	2.41	1.41	1.83	5.69	1.50	1.50	2.23	4.61	67.87	5.38	4.89	0.569	0.342
	NE-G2	1.61	5.68	1.96	2.87	7.82	3.24	2.22	3.38	8.13	43.14	10.37	9.60		
	NE-G3	5.31	4.69	3.81	4.35	3.42	3.77	1.89	4.07	2.78	42.20	4.15	19.57		
	NE-G3	6.41	6.78	4.04	3.12	2.86	3.43	2.54	4.31	3.50	15.86	5.32	41.84	0.809	0.175
	NE-G3	4.71	5.02	3.13	2.59	4.36	3.43	3.03	4.68	4.41	13.35	4.87	46.43		
southeastern depocenter	SE-G1	14.16	24.19	22.09	3.85	3.16	6.97	2.10	9.64	5.82	2.16	3.02	2.84		
	SE-G1	15.81	26.92	11.75	8.48	4.09	9.77	3.03	12.71	2.70	1.34	2.06	1.34	0.352	0.188
	SE-G1	13.59	23.75	10.74	9.33	5.96	8.12	4.18	11.08	5.00	2.59	3.26	2.41		
	SE-G2	5.02	8.23	3.32	3.73	4.05	3.89	1.74	4.22	4.07	24.56	5.64	31.53		
	SE-G2	2.37	5.94	3.78	2.61	4.01	3.27	3.03	4.44	3.67	7.95	2.90	56.04	0.597	0.225
	SE-G2	3.42	5.41	3.65	3.56	3.53	4.84	4.22	3.72	4.19	13.26	4.34	45.85		
	SE-G3	1.18	1.54	69.15	3.51	1.94	4.41	5.94	2.62	4.51	1.40	2.40	1.41		
	SE-G3	2.31	2.89	5.92	6.69	4.24	7.12	56.78	3.08	4.07	1.92	3.26	1.72	0.693	0.220
	SE-G3	2.19	3.57	4.68	7.62	4.27	7.46	56.31	3.89	4.44	1.35	2.66	1.57		
central depocenter	C-G1	1.98	48.65	1.80	3.73	8.37	2.82	1.11	4.45	5.36	10.52	5.36	5.85		
	C-G1	1.42	5.02	1.72	2.96	8.05	3.52	2.70	2.71	5.23	50.09	6.61	9.97	0.683	0.222
	C-G1	2.20	8.46	2.37	3.49	11.84	3.60	2.58	6.92	5.03	37.70	7.14	8.67		
	C-G2	38.19	18.17	4.99	3.28	3.52	4.68	1.28	4.85	3.76	8.28	4.79	4.21		
	C-G2	39.58	17.08	5.33	4.52	4.16	5.49	2.12	5.32	4.87	3.72	3.48	4.35	0.513	0.168
	C-G2	33.55	20.42	5.31	3.90	4.06	4.72	3.13	5.42	4.28	5.95	4.24	5.02		
	C-G3	3.53	26.76	2.73	3.97	6.39	3.58	1.19	5.59	5.80	20.43	5.48	14.58		
	C-G3	2.29	10.36	2.84	3.40	4.73	3.04	3.05	5.03	5.41	15.14	4.06	40.65	0.597	0.195
	C-G3	3.27	11.80	3.63	5.51	5.55	4.73	2.98	4.60	5.33	23.01	4.56	25.01		
western depocenter	W-G1	21.34	16.45	14.91	9.00	6.41	7.44	1.76	11.99	4.42	1.55	3.29	1.44		
	W-G1	20.15	18.10	7.72	18.29	4.66	10.30	2.24	11.31	2.57	1.26	1.90	1.51	0.669	0.149
	W-G1	25.45	12.78	9.73	14.00	5.58	9.03	2.61	11.61	3.31	1.90	2.37	1.62		
	W-G2	32.71	14.85	3.40	3.10	3.91	3.90	1.15	3.57	3.29	19.20	4.49	6.44		
	W-G2	37.40	9.53	4.22	3.09	3.95	3.80	2.07	4.54	3.68	12.17	4.30	11.25	0.588	0.159
	W-G2	32.93	10.91	5.10	3.83	4.81	4.42	2.50	5.08	3.58	11.83	4.68	10.33		
	W-G3	3.02	21.46	2.21	2.84	10.41	3.44	1.50	4.57	8.42	11.22	8.68	22.23		
	W-G3	1.37	4.35	1.68	2.73	5.53	4.50	2.14	4.10	7.53	13.41	4.86	47.80	0.580	0.238
	W-G3	2.91	5.15	2.84	4.14	6.96	4.75	3.23	4.14	7.24	20.07	6.72	31.85		
Average		12.31	14.84	7.04	4.89	5.49	4.91	5.45	5.55	4.66	14.98	4.61	15.28		

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Declaration of interests

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

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