Wu, Q., et al., 2021, High-precision U-Pb age constraints on the Permian floral turnovers, paleoclimate change, and tectonics of the North China block: *Geology*, v. 49, <https://doi.org/10.1130/G48051.1>

The Supplementary Information includes:

S1. Stratigraphy of the studied sections and geochronologic sampling

S2. Previous geochronology

S3. U-Pb analytical procedures, data reduction, age calculation, and interpretation

S4. Bayesian age-stratigraphic model

References cited

Fig. DR1 Stratigraphic columns of the study sections

Fig. DR2 Outcrop photos of the sections and microscope image of zircon crystals

Fig. DR3 Relative possibility diagram of the reported detrital zircon ages

Fig. DR4 Zircon U-Pb concordia and weighted mean $^{206}\text{Pb}/^{238}\text{U}$ dates diagrams

Fig. DR5 Bchron age-depth model with 95% confidence level uncertainty

Table DR1 Common lithostratigraphic nomenclature of the Carboniferous-Permian formation names in North China.

Table DR2 Analyses of detrital zircon LA-ICPMS U-Pb data in Ma et al. (2014)

Table DR3 SIMS U-Pb data for analyzed zircons from sample NC-16

Table DR4 U-Pb isotopic data for CA-ID-TIMS zircon analyses

S1. Stratigraphy of the studied sections and geochronologic sampling

The main studied sections are located in the northern North China Block. The Palougou and the Qiaotou sections are approximately 20 km apart and are located in the northwestern Shanxi Province (Baode County) near the eastern banks of the Yellow River (Fig. 1B). The Sigou Section is located 144 km to the southeast of the Palougou Section (Fig. 1B), within the Western Shanxi (Jinxi) fold belt (Tang et al., 2012). The Palougou and Sigou sections expose all five Permian formations, which in ascending order include the Taiyuan, Shansi, Lower Shihhotse, Upper Shihhotse, and Sunjiagou formations (Fig. DR1A). The Qiaotou Section exposes a more complete succession of the Shansi Formation, which is regarded as an auxiliary section for the Shansi Formation at the Palougou Section (Fig. DR1D).

The Pennsylvanian-Permian deposits are laterally continuous throughout the North China Block, although different lithostratigraphic nomenclature has been applied to these deposits across the region (Table DR1). The Taiyuan and Shansi formations are interpreted as alternating marine and terrestrial units mainly deposited in epeiric sea to paralic swamp environments (Lee, 1986; Liu, 1990; Lv and Chen, 2014). The Taiyuan Formation mainly consists of siltstone, mudstone, black shale, and coal seams, interbedded with several marine limestone beds. Abundant fusulinid and a few conodont fossils were reported from these limestones (Kong et al., 1996; Wang and Qi, 2003 and references therein; Shen et al.,

2019b). The Shansi Formation overlies conformably the Taiyuan Formation, with a thick layer of yellowish-gray, quartz pebble sandstone marking the boundary. The coal-bearing Shansi Formation has a similar lithologic composition with that of the Taiyuan Formation, except that it lacks marine limestone beds.

The Lower Shihhotse and the Upper Shihhotse formations are mainly composed of fluvial sediments. The base of the Lower Shihhotse Formation is characterized by a thick-bedded yellowish-gray pebbly quartz sandstone. The Lower Shihhotse Formation is dominated by yellowish-gray, coarse to medium-grained sandstone and gray mudstone with a few coal beds in the lower part. The boundary between the Lower Shihhotse and the Upper Shihhotse formations is marked by a set of thick-bedded grayish-yellow, lithic sandstones. The Upper Shihhotse Formation is thick and divided into two parts. The lower part mainly consists of yellowish-gray, pebbly quartz sandstone and mudstone. The upper part is dominated by reddish-brown and greenish-grey (mottled) mudstone and fine sandstone (Liu et al., 2015). Ferruginous argillic Gleysols and Argillisols, as well as channel-fill sandstones are abundant in the upper part of the Upper Shihhotse Formation (Figs. DR1B, DR2D).

The overlying Sunjiagou Formation starts with a thick layer of yellowish-gray sandstone, containing conglomerates and crossbeds (Figs. DR2A, C). It is characterized by an interval of red to purple, fine sandstone and mudstone. They are interbedded with gray

feldspathic quartz sandstone, which are interpreted to have been deposited in meandering streams. Gypsum, calcite breccias and aeolian sandstone in the basal part of the Sunjiagou Formation indicate a typical arid condition (Norin, 1924; Wang, 1993; Stevens et al., 2011). The top of the Sunjiagou Formation is approximately correlated with the Permian-Triassic boundary (Wang, 1993; Chu et al., 2015, 2019, Zhu et al., 2019).

A total of 11 samples of bentonite and tuffaceous mudstones were collected from three sections for U-Pb geochronological analysis (Tables 1 and DR4). Eight samples were collected from the Palougou Section (Fig. DR1A). Sample NC-3 was collected from a 5 mm-thick, yellowish-gray, bentonite layer, bound by two marine limestone beds in the middle interval of the Taiyuan Formation at the Palougou Section (Fig. DR2I). The lower limestone bed named the Palougou Limestone is correlated to the Wujiayu Limestone of the classic succession in Taiyuan City, Shanxi Province. This limestone occurs about 15.5 m below the NC-3 bentonite and contains abundant fusulinid fossils, including *Triticites*, *Montiparus*, *Pseudofusulina*, and *Schwagerina* (Kong et al., 1996). This fusulinid assemblage is correlated to the *Triticites* Biozone at the Yangchang Section in Guizhou, South China, which is considered of Gzhelian Age (Late Carboniferous) (Sheng and Jin, 1994). The Palougou Limestone yielded conodonts as well, including *Streptognathodus oppletus*, *S. elegantulus*, and *Idiognathodus hebeiensis* (Wan and Ding, 1987; Kong et al., 1996), which are also correlative to those in the Guizhou area substantiating the Gzhelian

Age (Wang and Qi, 2003). The upper limestone bed, named the Baode Limestone, correlated to the Maoergou Limestone of the classic successions in Shanxi Province (Kong et al., 1996), lies about 16 m above the NC-3 bentonite. Several other limestone beds occur above the Maoergou Limestone in the Taiyuan Formation in Taiyuan, Shanxi Province. These limestones show no obvious differences in fossil content, which is dominated by conodonts *Streptognathodus barskovi* together with *S. isolatus*, , as well as the fusulinid *Pseudoschwagerina* (Kong et al., 1996; Wang and Qi, 2003). Both the conodonts and the fusulinids indicate an Asselian Age (Cisuralian) (Henderson, 2018; Shen et al., 2019b) although some of the *Streptognathodus* taxa need to be reevaluated. Sample NC-4 was collected from a 5 cm-thick yellowish-gray tuffaceous bed near the top of the Taiyuan Formation at the Palougou Section (Fig. DR2J). The Upper Shihhotse Formation samples start with BD082919-1, a 7-12 cm-thick, greenish-grey bentonite from the lower massive sandstone interval and about 20 m above the base of the formation (Fig. DR2H). Further up-section, samples BD-3 and NC-16 were collected from the same tuff layer, but in different locations within the red beds (Fig. DR2F). Sample BD-2 was collected from a clay-rich bed, which is stratigraphically 68 m higher than BD-3. Sample BD083019-2 is a 5-8 cm-thick, greenish-white bentonite collected from 9 m above BD-2 (Fig. DR2G). About 10 m higher in the section, Sample NC-11 was collected from about 10 m below the base of the overlying Sunjiagou Formation. Despite a poor fossil record, several studies based on U-Pb zircon geochronology by the laser ablation-inductively coupled plasma-

mass spectrometry (LA-ICP-MS) have attempted to constrain the maximum depositional age of the Upper Shihhotse Formation (see below).

Two closely spaced bentonite layers, 3.1 m apart, were sampled from the coal beds assigned to the Shansi Formation at the Qiaotou Section (Figs. DR1D, DR2K). Sample BD-5 is from a 6 cm-thick gray bentonite layer within the coal and Sample NC-8-2 from a 4 cm-thick greyish-white bentonite, immediately below massive sandstone of the Shansi Formation. In addition to other thin ash beds, several charcoal layers are interbedded in the Shansi Formation at the Qiaotou Section, which have been interpreted as wildfire residues (Yan et al., 2016).

Sample SG-18-D-05 was collected from a 3 cm-thick greenish-grey tuffaceous bed in the base of the Sunjiagou Formation at the Sigou Section (Fig. DR1). Considering that the basal Sunjiagou Formation overlies an unconformity and that the Sigou Section is more than 140 km distant from the Palougou Section, the correlation between the two sections is not well constrained. Nevertheless, the plant fossil *Lepidopteris* from the lower part of this unit indicates a Lopingian age (Zhang et al., 2012). Furthermore, investigations on the Sunjiagou Formation from about twenty localities in Shanxi, Shaanxi, Henan and Hebei provinces in North China have yielded the *Ullmannia bronnii*-*Yuania magnifolia* plant fossil assemblage without obvious variations and thus confirm a Lopingian age for the formation (Wang and Wang, 1987, Wang, 2010).

S2. Previous geochronology

Radioisotopic ages from the Permian outcrop successions in North China have been limited to a few U-Pb zircon studies by *in-situ* analyses on tuffs or tuffaceous sedimentary beds, as well as detrital zircon provenance studies on sandstones (e.g., Li et al., 2010; Zhu et al., 2014; Yang et al., 2017). A U-Pb zircon age of 290.1 ± 5.8 Ma (MSWD = 0.58, n = 5, 95% confidence) by the secondary ion mass spectrometry (SIMS) method was reported by Cope et al. (2005) from a highly altered and strongly reworked ash bed above the thick coal beds in the northern margin of the North China Block, correlative to those of the Taiyuan and/or Shansi formations. Another U-Pb SIMS age of 296 ± 4 Ma (MSWD = 3.3, n = 14, 95% confidence) was reported by Zhang et al. (2007) from a volcanic tuff bed in the Hongmiaoling Formation in western Beijing, which was roughly correlated with the Lower Shihhotse and Upper Shihhotse formations. Yang et al. (2014) reported an age of 293.0 ± 2.5 Ma (MSWD = 0.57, n = 21, 95% confidence) by the LA-ICP-MS technique from a tuffaceous sandstone in the upper part of the Shansi Formation in southeastern North China. Although the above geochronology pointed to a Cisuralian age for much of the Permian succession in North China, they were unable to resolve its outstanding chronostratigraphic issues for the following reasons. First, the low precision of the U-Pb analyses by *in situ* techniques (internal uncertainties of 1% or more on individual analyses, and up to 4% external uncertainties) cannot fully distinguish zircons of mixed-age

populations in a tuffaceous rock (e.g., Schmitz and Kuiper, 2013). Second, untreated zircons used in *in-situ* analyses can be compromised by Pb-loss, which can have a significant effect on the accuracy of the U-Pb dates (e.g., Schaltegger et al., 2015; Wu et al., 2017). Third, the age results of Cope et al. (2005) and Zhang et al. (2007) were from units in the marginal areas of the North China Block, with ambiguous correlations to the classic Permian successions in the Shanxi Province, central North China Block.

The depositional age of the Upper Shihhotse Formation, in particular, has been controversial. We have compiled previously reported detrital zircon geochronology by the LA-ICP-MS method from the Upper Shihhotse Formation and the base of the Sunjiagou Formation across North China, based on the works of Yang et al. (2006), Liu et al. (2014), Zhu et al. (2014), Luo et al. (2017), Wang et al. (2019), Zhu et al. (2019) and Sun et al. (2020) (Fig. DR3). The relative probability diagram of Fig. DR3 distinguishes between the youngest populations of analyzed zircons (based on 3 or more overlapping analyses) and the single youngest zircon age of each study marked by the arrow. Deriving depositional age constraints from the single youngest analysis, which is likely to be affected by the substantial Pb-loss, can lead to grossly underestimated age estimates. This is particularly alarming in the case of data obtained by the *in-situ* technique (LA-ICP-MS or SIMS), which lacks the chemical abrasion pre-treatment necessary to overcome the effects of Pb loss (e.g., Wu et al., 2017). More conservative approaches to age calculation involving

youngest statistical population of multiple analyses tend to produce relatively more accurate maximum depositional ages as they are less susceptible to open system behavior in individual zircons (Coutts et al., 2019).

The limitations of *in-situ* analytical techniques in producing meaningful depositional age constraints from the non-marine Permian are apparent in the LA-ICP-MS results, e.g., the age data in Ma et al. (2014) for the northern North China Craton (Table DR2). Here the calculated weighted mean ages (2σ internal errors) from the youngest zircon populations for the Lower Shihhotse Formation (258.0 ± 4.1 Ma, $n = 28$) and the Sunjiagou Formation (254.1 ± 9.5 Ma, $n = 2$) overlap within uncertainty, even though the corresponding sampled beds (XSH and SQF) are ca. 200 meters apart in stratigraphy (Fig. 5 in Ma et al., 2014). A closer look at the XSH data reveals that the single youngest analysis was 238 ± 24 Ma and the next five youngest analyses all overlap with the Permian-Triassic boundary within uncertainty. The obvious conflict with stratigraphy might suggest the inaccuracy of the estimated ages for other units due to extensive Pb loss in analyzed zircons.

If the single youngest zircons are excluded from the detrital zircon age estimates, the bulk of previously reported geochronology constrained the maximum depositional ages of the Upper Shihhotse Formation to ca. 275-280 Ma and the basal Sunjiagou Formation to ca. 255-269 Ma, which reveals an age gap (Fig. DR3) and approaches the high-precision geochronologic results of this study (see below). The emerging depositional age gap

between the two units (Fig. DR3) is expected to be of variable duration depending on proximity to the orogenic front in the north. Also, craton-wide lithostratigraphic correlations based on presence or absence of coal beds and massive sandstone beds would likely result in diachronous formation boundaries. For example, the youngest detrital zircon age clusters from Ma et al. (2014) revealed a longer age gap (*ca.* 300 Ma-260 Ma) between the Shansi and Lower Shihhotse formations.

Recent U-Pb geochronology by the CA-ID-TIMS method of tuff beds in the subsurface (Yang et al., 2020) has provided excellent age constraints for Penchi and Taiyuan formations in southeastern North China Block.

S3. U-Pb analytical procedures, data reduction, age calculation, and interpretation

S3.1. U-Pb SIMS geochronology

Fifty-one SIMS U-Pb analyses were carried out on zircons from Sample NC-16 as an age pre-screening scheme prior to CA-ID-TIMS analyses. The zircons from NC-16 together with the zircon standard Qinghu were cast in a transparent epoxy mount. The mount was then polished to expose the interior of crystals for analyses. All zircons were documented with transmitted and reflected light photo-microscopy to select zircon domains that are free of inclusions or cracks. Cathodoluminescence images were taken to

reveal the internal zoning and select the appropriate domains of the zircon crystals. The mount was vacuum-coated with high purity gold before SIMS analyses. U, Th and Pb isotopes were measured on a Cameca IMS 1280 SIMS at the Institute of Geology and Geophysics, Chinese Academy of Sciences in Beijing, China. The analysis spot sizes are *ca.* 20 μm $\times$ 30 μm . The detailed analysis procedures have been described in Li et al. (2009). Analyses of zircon standard Qinghu were interspersed with the unknowns. The average of present-day crustal Pb isotopic composition of Stacey and Kramers (1975) was used for common Pb correction assuming that the common Pb is largely surface contamination resulting from sample preparation. The SIMS data were reduced by using Isoplot 3.75 (Ludwig, 2012). The sample date is calculated based on the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of the youngest population of zircons that overlaps within 2σ internal (analytical) uncertainty. The detailed U-Pb isotopic data and ages by the SIMS method can be seen in Table DR3.

The data from the Qinghu zircon standards yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of 159.9 ± 1.1 Ma ($n = 18$, MSWD = 0.74), which is within error of the recommended age of 159.38 ± 0.12 Ma by the CA-ID-TIMS method (Li et al., 2009). Except for four analyses with high common Pb, the other 47 analyses gave indistinguishable $^{206}\text{Pb}/^{238}\text{U}$ ratios within analytical errors and yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of 282.1 ± 1.2 Ma (MSWD = 0.53, 95% confidence interval, Fig. DR4 B).

S3.2. U-Pb CA-ID-TIMS geochronology

Seventy six single zircon grains from eleven bentonite or tuffaceous mudstone samples collected from three stratigraphic sections were analyzed for Pb and U isotopes by the CA-ID-TIMS technique at the Massachusetts Institute of Technology Isotope Laboratory. Samples were on the order of 2 to 5 kg in weight and were processed by soaking in water for 48 hours, followed by complete liquefaction in a blender. Sand-size grains were separated from the clay matrix in a sonic dismembrator device designed by Hoke et al. (2014). Heavy-mineral concentrates were achieved through step-wise magnetic as well as high-density liquid separation techniques. The final zircon selection was carried out under a binocular microscope.

The majority of samples contained mixed populations of zircons ranging from sub-rounded to multi-faceted prisms. The prismatic or acicular zircon grains containing elongate glass (melt) inclusions parallel to their long axis are shown to represent the youngest population of zircons in the samples (Ramezani et al., 2011) and were targeted for our analyses. The selected grains were pre-treated by a chemical abrasion (CA) technique modified after Mattinson (2005). Chemical abrasion was achieved by thermal annealing at 900 °C for 60 hours, followed by leaching in 29 M HF inside high-pressure vessels at 210 °C for 11.5 to 12 hours. The leached grains were fluxed in several hundred microliters of dilute HNO₃ and 6 M HCl, successively on the hot plate and in an ultrasonic

bath (1 hour each step), and rinsed with several volumes of Millipore water in between to remove the leachates. The thoroughly rinsed grains were spiked with the EARTHTIME ET535 mixed ^{205}Pb - ^{233}U - ^{235}U tracer (Condon et al., 2015; McLean et al., 2015) prior to complete dissolution in 29 M HF at 210 °C for 45 to 48 hours. The dissolved U and Pb were chemically purified using 50 μl columns of AG1X-8 anion-exchange resin. The purified U and Pb were finally loaded together onto degassed Re filaments mixed with a silica gel emitter solution and their isotopic ratios were measured on an Isotopx X62 multi-collector thermal ionization mass spectrometer equipped with a Daly photomultiplier ion counting system. Pb isotopes were measured as mono-atomic ions on a single ion-counter and were corrected for a mass-dependent isotope fractionation of $0.18\% \pm 0.05\%$ per atomic mass unit (2σ). U isotopes were measured as dioxide ions simultaneously using three Faraday collectors, while subjected to a within-run mass fractionation correction using the $^{233}\text{U}/^{235}\text{U}$ ratio of the tracer and a predicted sample $^{238}\text{U}/^{235}\text{U}$ ratio of 137.818 ± 0.045 (Hiess et al., 2012). An oxide correction based on an independently determined $^{18}\text{O}/^{16}\text{O}$ ratio of 0.00205 ± 0.00005 was also applied to the measured U isotopic ratios.

Data reduction, error propagation and U-Pb date calculation were carried out using the Tripoli and ET_Redux algorithms (Bowring et al., 2011; McLean et al., 2011). Complete Pb and U isotopic data by the CA-ID-TIMS method are given in Table DR4. Sample dates representing zircon crystallization ages are calculated based on the weighted

mean $^{206}\text{Pb}/^{238}\text{U}$ dates derived from the coherent clusters of the youngest zircon analyses in each sample, after excluding resolvably older analyses interpreted reworked or detrital. Weighted mean date uncertainties are reported at 95% confidence level in the $\pm X/Y/Z$ format, where X is the 2σ internal (analytical) uncertainty exclusive of all external errors, Y incorporates the U-Pb tracer calibration error, and Z includes Y as well as the U decay constant errors of Jaffey et al. (1971). Calculated weighted mean dates and their uncertainties are given in Table 1 and illustrated in the date distribution plots of Figure DR4. A calculated weighted mean date is interpreted as the maximum age of deposition for the corresponding bed. A set of high-resolution U-Pb dates from closely spaced ash beds that obey the stratigraphic order provide reliable estimates of the true depositional age.

Samples NC-3, NC-4, BD082919-1, BD-3, NC-16 and BD083019-2 from the Palougou Section, as well as BD-5 and NC-8-2 from the Qiaotou Section, all produced statistically robust weighted mean $^{206}\text{Pb}/^{238}\text{U}$ dates that are consistent with stratigraphic superposition (Fig. DR1). The dates of NC-16 and BD-3 are consistent with each other within analytical error (Fig. DR4 A). Here, the date of BD-3 was taken into discussion and used in the age-depth model calculation. Results from the samples in the Taiyuan Formation are also consistent with the Carboniferous-Permian marine biostratigraphy. For samples NC-11 (Palougou Section) and SG-18-D-05 (Sigou Section), scatter in data due to extensive detrital input prevented the calculation of a statistically meaningful weighted

mean date. Nevertheless, the age of the single youngest zircon from each of these two samples is consistent with stratigraphy and thus can be used to estimate the maximum age of deposition.

The only exception is Sample BD-2 from the Palougou Section, whose youngest four analyses (267.99 ± 0.20 Ma to 259.58 ± 0.17 Ma) are up to 20 m.y. younger than its predicted age based on the adjacent BD-3, BD083019-2 and NC-11 dates from the same section. Based on its physical characteristics of a paste-like, clay-rich layer and its outcrop exposures as a subhorizontal bed near the water level of a present-day creek, it is likely that the BD-2 zircons originated from topographically higher exposures (e.g., Sunjiagou Formation strata) and subsequently embedded in the sample site by modern stream flows.

Four zircon grains from Sample NC-16, which had been analyzed by the U-Pb SIMS method (zs08, zs12, zs42 and zs44) and produced the youngest ages (*ca.* 274 Ma to 278 Ma), were subsequently removed from the grain mount and reanalyzed by the CA-ID-TIMS technique (Figs. DR4A, B). They yielded CA-ID-TIMS dates of 283.92 ± 1.15 Ma, 284.04 ± 0.46 Ma, 284.02 ± 0.39 Ma and 283.32 ± 0.48 Ma, respectively. These (excluding zs44), combined with another six CA-ID-TIMS zircon analyses from NC-16 yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of $284.04 \pm 0.10/0.18/0.35$ Ma ($n = 9$, MSWD = 0.25) (Fig. DR4 A). The slightly younger weighted mean age from the SIMS method along with the resolvably younger CA-ID-TIMS age of zs44 point out to the effects of persistent Pb-loss, which is more pronounced in the untreated (by chemical abrasion) SIMS analyses.

The large number of zircon analyses from Sample NC-16 by both methods and the lack of any significant age outliers strongly suggest that the tuff layer of NC-16 (and BD-3) from the Upper Shihhotse Formation was a primary volcanic ash bed, which is unlikely to contain reworked material from an older volcanic source. These results further support a Cisuralian depositional age for the Upper Shihhotse Formation.

S4. Bayesian age-stratigraphic model

In this study we use a Bayesian interpolation statistical algorithm to construct an age-stratigraphy model for the Cisuralian strata in Baode area, Shanxi Province to provide temporal calibration for the lithological boundaries in this area (Fig. DR5). Our model uses the Bchron software package (Haslett and Parnell, 2008; Parnell et al., 2008) and is essentially similar to that in Shen et al. (2019a). The model is derived from our U-Pb dates and their stratigraphic positions from the Palougou Section with clear superposition and independent of any correlation assumptions. The lower and upper boundary ages for the Shansi Formation at the Palougou Section are consistent with those at the Qiaotou Section despite the large uncertainties.

Our age model indicates an overall sediment accumulation rate of 22.1 ± 0.2 m/m.y. for the Permian succession below the Sunjiagou Formation at the Palougou Section. There is no evidence for any drastic changes in the sediment accumulation rate throughout the succession. This suggests that faster expected sediment accumulation in the red beds of the

top of the Upper Shihhotse Formation was compensated by depositional gaps.

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