High-precision U-Pb age constraints on the Permian floral turnovers, paleoclimate change, and tectonics of the North China block

Qiong Wu1, Jahandar Ramezani2, Hua Zhang3,4,*, Jun Wang3,4, Fangui Zeng5, Yichun Zhang3,4, Feng Liu3,4, Jun Chen6, Yaofeng Cai3,4, Zhangshuai Hou7, Chao Liu3, Wan Yang3, Charles M. Henderson8 and Shu-zhong Shen1,4,9*

1State Key Laboratory for Mineral Deposits Research and School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China
2Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
3State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China
4Center for Excellence in Life and Paleoenvironment, Chinese Academy of Sciences, Nanjing 210023, China
5Department of Earth Science & Engineering, Taiyuan University of Technology, Taiyuan 030024, China
6State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
7Geology and Geophysics Program, Missouri University of Science and Technology, Rolla, Missouri 65409, USA
8Department of Geoscience, University of Calgary, Calgary, AB T2N 1N4, Canada
9Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research and Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing 100101, China

ABSTRACT

The Permian marine-terrestrial system of the North China block provides an exceptional window into the evolution of northern temperate ecosystems during the critical transition from icehouse to greenhouse following the late Paleozoic ice age (LPIA). Despite many studies on its rich hydrocarbon reserves and climate-sensitive fossil flora, uncertain temporal constraints and correlations have hampered a thorough understanding of the records of geologic, biologic, and climatic change from the North China block. We present a new chronostratigraphy based on high-precision U-Pb chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) geochronology of tuffs from a near-complete latest Carboniferous–Permian succession in North China. The results indicate that the predominance of continental red beds, climate aridification, and the disappearance of coals and characteristic tropical flora were well under way during the Cisuralian (Early Permian) in the North China block, significantly earlier than previously thought. A nearly 20 m.y. hiatus spanning the early Kungurian to the mid-Guadalupian (or later) is revealed in the northern North China block to have close temporal and spatial associations with the closure and/or subduction of the Paleo-Asian Ocean and its related tectonic convergence. This long hiatus was concomitant with the prominent loss of the highly diverse and abundant Cathaysian floras and the widespread invasion of the monotonous Angaran floras under arid climate conditions in the North China block. Similarities in the floral and climate shift histories between Euramerica and North China suggest that aside from the regional tectonic controls and continental movement, extensive volcanism during the Cisuralian may have played a major role in the global warming and aridification in the aftermath of the LPIA.

INTRODUCTION

The North China block occupied northerly tropical to subtropical paleolatitudes (Boucot et al., 2013), marginal to the Paleo-Asian Ocean (PAO), during the critical Cisuralian (298.9–273.0) transitions from an icehouse to a greenhouse world (Fig. 1). The late Carboniferous to Permian marine and marginal-marine to terrestrial sequences in North China preserve highly diverse and abundant plant fossils in addition to their significant economic hydrocarbon resources (Yang et al., 2005; Wang, 2010; Liu et al., 2015). These characteristics provide a unique opportunity to investigate the interactions among terrestrial biotic evolution, regional tectonics, and global climate change during a critical period of geologic history. However, poor constraints on age and correlation have hampered a deep understanding of those events in the North China block. In the absence of diagnostic marine fossils from key intervals, stratigraphic correlation within and beyond North China has relied on uncalibrated palynostratigraphy and magnetostratigraphy (Wang, 2010; Liu et al., 2015) and magnetostratigraphy (Embleton et al., 1996). Detrital zircon geochronology by U-Pb in situ analyses from Permian volcanioclastic sandstones (e.g., Zhu et al., 2014;
Yang et al., 2017) generally lacked the necessary precision or stratigraphic range to place reliable constraints on depositional ages.

We report high-precision U-Pb zircon geochronology by the chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) method focused on bentonitic tuffs from the Permian succession in North China. The results necessitate fundamental revisions to the traditional Permian terrestrial depositional history and chronostratigraphy of the North China block and provide a new timeline and important insights for the history of continental collision, floral turnovers, and paleoclimate change as recorded in the North China block.

STRATIGRAPHY AND GEOLOGIC SETTING

Paleozoic epicontinental deposition in the North China block was interrupted by a long period of craton-wide non-deposition and/or erosion from the Late Ordovician to Late Carboniferous (Yang et al., 2005). A late Carboniferous marine transgression led to the deposition of the Penchi Formation, overlain by the Carboniferous–Permian Taiyuan Formation, in shallow-marine and tidal-flat environments. The latter consists of alternating marine limestone and shale along with extensive coal seams that transition upward into lagoon swamp and shoreline deposits. The overlying Permian successions are predominated by fluvial-deltaic deposits with coal interbeds of the Shansi and Lower Shihhotse Formations, whereas the Upper Shihhotse Formation marks a transition into mottled purple-red, fluvial and shallow-lacustrine mudstone, siltstone, and intercalated channel sandstone without coals (Yang et al., 2005). The overlying Sunjiagou Formation, which was deposited in a fluvial environment, is composed of typical red beds interbedded with stream channel-fill sandstone (Liu et al., 2015). Carboniferous–Permian basin evolution in North China was largely controlled by convergent tectonics during the closure of the PAO along the northern margin of the North China block (Zhu et al., 2014).

The age and regional correlation of the Penchi and Taiyuan Formations have been well constrained by fusulin and conodont fossils from their marine strata (see the Supplemental Material) as well as new U-Pb CA-ID-TIMS geochronology from the subsurface of southeastern North China (Yang et al., 2020). However, the correlation of the Permian succession above the Taiyuan Formation has long been a subject of debate. The Shansi and Lower Shihhotse Formations were roughly assigned to the Cisuralian, the Upper Shihhotse Formation to the Guadalupian (273.0–259.5 Ma), and the Sunjiagou Formation to the Lopingian (259.5–251.9 Ma) in the classic area of Shanxi Province in North China, based on fossil plant and palynological analyses (Wang, 2010; Liu et al., 2015).

Limited tuff zircon geochronology by in situ techniques previously resulted in U-Pb age estimates of 293.0 ± 2.5 Ma for the Shansi Formation (Yang et al., 2014), 290.1 ± 5.8 Ma for a northerly correlative of the Taiyuan and/or Shansi Formations (Cope et al., 2005), and 296 ± 4 Ma for a presumed correlative unit of the Lower and Upper Shihhotse Formations (Zhang et al., 2007). These data have been unable to resolve outstanding Permian chronostratigraphic issues in North China (see the Supplemental Material for a complete review).

METHODS AND RESULTS

We collected 11 bentonitic tuff and tuffaceous mudstone samples from the Palougou, Qiaotou, and Sigou sections in Shanxi Province, northern North China (Fig. 1), for U-Pb geochronology by the CA-ID-TIMS method. These samples encompass the middle Taiyuan to basinal Sunjiagou Formations. The weighted mean 206Pb/238U dates of the analyzed zircons along with a Bayesian interpolation algorithm are used to construct a statistically robust chron stratigraphic framework for the Permian succession of North China, from which the ages of lithostratigraphic boundaries, floral changes, and climate proxies can be extrapolated. Detailed descriptions of the stratigraphy, tuff samples, U-Pb analytical procedures, data reduction, age interpretation, reliability, and Bayesian modeling are provided in the Supplemental Material. The U-Pb geochronological results are summarized in Table 1.

DISCUSSION

A set of five new weighted mean 206Pb/238U dates from bentonites of the Palougou section forms the basis of a Bayesian age-stratigraphic model, which for the first time provides a near-complete temporal calibration for the Permian system of North China (Fig. 2; Fig. S5 in the Supplemental Material). The Carboniferous-Permian boundary is precisely constrained at a major coal seam immediately below the dated tuff bed NC-3, based on the marine boundary calibration from the southern Ural Mountains (Russia) (Ramezani et al., 2007) and consistent with its biostratigraphic placement in the Taiyuan Formation (see the Supplemental Material). Results from the Qiaotou section provides a direct correlation of the major Asselian (298.9–293.5 Ma) coal seams (Shansi Formation) to the Palougou section (Figs. S1 and S5). The new chronostratigraphy assigns the interval...
from the upper Taiyuan Formation to the top of the Lower Shihhotse Formation to Asselian, whereas the Upper Shihhotse Formation coincides with the latest Asselian to early Kungurian (283.5–273.0 Ma) in northern North China. This is in sharp contrast to previous assignments of the Upper Shihhotse Formation to Guadalupian–early Lopingian time (e.g., Stevens et al., 2011; Liu et al., 2015). A previously reported occurrence of the mid-Guadalupian Illawarra geomagnetic polarity reversal from the Upper Shihhotse Formation (Embleton et al., 1996) is not supported by our geochronology. Instead, the possibility of multiple Cisuralian normal polarities during the long Kiaman reverse polarity superchron (Hounslow and Balabanov, 2018) should be investigated. The Sunjiagou Formation in Baode was constrained to younger than ca. 269 Ma by detrital zircon ages and to Lopingian by integrated biostratigraphic data (Zhu et al., 2019), which is consistent with our date from the Sigou section.

Our new geochronology reveals a ∼20 m.y. hiatus during the Cisuralian-Guadalupian transition in the northern North China block. Excluding one upper Upper Shihhotse Formation sample (BD-2) suspected of being compromised by young detrital zircon contamination (see section S3.2 in the Supplemental Material), our age model constrains the hiatus to between the topmost Upper Shihhotse Formation date of 280.98 ± 0.11 Ma and the youngest analyzed Sunjiagou Formation zircon of 261.75 ± 0.29 Ma (Fig. 2). A critical

Figure 2. Compilation of Permian global events in parallel with Earth system changes in the North China block. Red dashed line represents the unconformity from the late Cisuralian to Guadalupian (ca. 280–260 Ma) between the Upper Shihhotse and Sunjiagou Formations. LSh—Lower Shihhotse. Red triangles indicate dated samples. Floral turnover patterns in the North China block are modified from Wang (2010) and references therein. Quantitative relation of Permian spore and pollen in the North China block is after Liu et al. (2015). Cisuralian glacial deposits are after Soreghan et al. (2019). Glacial intervals in Australia are after Garbelli et al. (2019).

Note: Sample locations are shown in Figure S1 (see text footnote 1).

1X—internal (analytical) uncertainty in the absence of all external or systematic errors; Y—includes X and the U-Pb tracer calibration error; Z—includes X and Y as well as the uranium decay constant errors.

MSWD—mean square of weighted deviates.

n—number of analyses included in the calculated weighted mean date out of the total number of analyses (N).

Sample BD-2 is considered contaminated, and its analyses do not represent a true depositional age.

TABLE 1. SUMMARY OF CALCULATED U-Pb DATES AND THEIR UNCERTAINTIES

| Sample   | Latitude | Longitude | Section | Formation | Pb/Pb (U-Pb) Age (Ma) | Error (2σ) | MSWD | n | N |
|----------|----------|-----------|---------|-----------|------------------------|------------|------|---|---|
| BD083109-2 | 111°05'45.05" | 38°45'55.94" | Palougou | Upper Shihhotse | 280.98 | 0.11 | N/A | N/A | 1 | 6 |
| BD-2     | 111°05'45.05" | 38°45'55.94" | Palougou | Upper Shihhotse | 289.58 | 0.17 | N/A | N/A | 1 | 10 |
| NC-6     | 111°05'45.05" | 38°45'55.94" | Palougou | Upper Shihhotse | 280.04 | 0.10 | 0.18 | 0.35 | 0.25 | 9 | 10 |
| NC-4     | 111°05'45.05" | 38°45'55.94" | Palougou | Upper Shihhotse | 295.346 | 0.080 | 0.13 | 0.34 | 0.97 | 5 | 7 |
| NC-3     | 111°05'45.05" | 38°45'55.94" | Palougou | Upper Shihhotse | 298.18 | 0.32 | 0.37 | 0.49 | 0.96 | 4 | 6 |

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evaluation of existing in situ U-Pb detrital zir- con geochronology substantiates a similar hia-
tus in the Permian successions of North China,
although its duration may vary as a function of
proximity to the collisional zone in the north of
the North China block (Fig. S3; Table S2). Paleosols
in the upper half of the Upper Shih-
hotse Formation may account for minor hiatuses
before the single major unconformity associated
with the basal channel (conglomeratic) sand-
stone of the overlying Sunjiagou Formation
(Fig. S2). An analogous unconformity has also
been reported from correlative Permian succes-
sions in eastern Xinjiang (Yang et al., 2010) and
Inner Mongolia (Tang and Yan, 1993). These ar-
eas constituted the southern margins of the PAO,
the middle segment of which underwent tectonic
convergence (uplift and erosion) associated with
subduction generating arc-continent and retroar-
cold-thrust deformation or ocean closure leading
to continental collision (ca. 280–265 Ma: Zhao
et al., 2018; Xiao et al., 2018).

A highly diverse Cathaysian flora and ex-
tensive coal deposits preserved in the Taiyuan
and Shansi Formations indicate a humid climate
(Wang, 2010). The climate became more arid
from the late Asselian with the increase of xe-
rophytic plants and decrease of coal deposits in
the upper Shansi Formation (Liu et al., 2015).
The early main groups of gymnosperms (e.g.,
early ginkgoaleans and conifers) evolved after-
ward (Fig. 2; Wang, 2010). A notable change to
a more arid condition occurs across the major
unconformity, which separates the upper Upper
Shihhotse Formation subhumin paleosols con-
taining abundant flora from overlying Sunjiagou
Formation aeolian sandstone, carbonate brec-
cias, and gypsum with few plant fossils. Aridifi-
cation trends and analogous fossil-poor red beds
have also been recorded in middle to low paleo-
latitude during the Cisuralian to Guadalupian,
concomitant with deglaciation of the late Paleoz-
ic ice age (LPIA) and surge of atmospheric
CO2 (Tabor and Poulsen, 2008; Boucot et al.,
2013; Schneider et al., 2019; Sorenson et al.,
2019; Richey et al., 2020), except for Tethyan
archipelagos where the ocean may have modu-
lated climate (Figs. 2 and 3).

Northward continental drift into a subtropi-
cal or temperate arid climatic zone (Rees et al.,
1999; Tabor and Poulsen, 2008) and/or a regional
rain-shadow effect caused by orographic uplift
associated with tectonic convergence (Cope
et al., 2005) may have contributed to the late As-
selian to Guadalupian aridification in the North
China block. However, these regional effects do
not explain a global-scale climate transition at
this time. An increase in atmospheric CO2 has
long been considered the major driving force for
the demise of the LPIA and subsequent global
aridification, presumably due to elevated sur-
face temperature and evaporation, which thus
reduced soil moisture and the source of conti-
nental convective precipitation (Poulsen et al.,
2007; Peyser and Poulsen, 2008). The surge in
atmospheric CO2 was probably related to exten-
sive large igneous province (LIP) volcanism dur-
ing the Cisuralian (e.g., Skagerrak-Centered LIP,
Panjal Traps, Tarim LIP; Torsvik et al., 2008;
Xu et al., 2014; Shellnutt, 2018; Fig. 1A), as
suggested by the coincidence between LIPs and
pCO2 excursions (Fig. 2). The moderate increases
of pCO2 in between may have been associated
with widespread wildfires (Yan et al., 2016).
Furthermore, the warming phases associated with
high pCO2 were indicated by low δ13C values
from Permo-Carboniferous coals in North China
(Zhang et al., 1999), significant retreat of the
LPIA (Sorenson et al., 2019), stronger terrestrial
chemical weathering (Yang et al., 2014, 2020,
and references therein), and interglacial intervals
in Australia (Garbelli et al., 2019). Thus, frequent
and extensive volcanism during the Cisuralian
may have been responsible for reducing effects of
the LPIA and global aridification under such
CO2-forced climate conditions.

The major floral disappearances in the top-
most Upper Shihhotse Formation had previously
been attributed to the late Capitanian Emeishan
LIP (Bond et al., 2010; Stevens et al., 2011).

Our new geochronology questions that scenario
and instead indicates a temporal coincidence
with the convergent tectonics of the PAO and
the third phase of the Tarim LIP during the Kun-
gurian (Xu et al., 2014). Both convergent tectonics
and extensive volcanism may have profoundly
influenced the local environments and climate,
which in turn led to floral extinction at the top of
the Upper Shihhotse Formation and possibly the
Olson’s gap of tetrapods from the late Cisuralian
to the middle Guadalupian (Lucas, 2018). Pro-
gressive contraction (closure) of the central to
eastern segment of the PAO during the Permian
(to Early Triassic) (Eizenhöfer and Zhao, 2018)
provided a pathway for the widespread inva-
sion of Angaran flora to the North China block,
as recorded in the lower Sunjiagou Formation
(Wang, 2010). We interpret the abrupt floral dis-
appearances at the top of the Upper Shihhotse
Formation as an extinction event, but further
work is needed to rule out the possibility that it is
an artifact of stratigraphic truncation associated
with the sub-Sunjiagou unconformity.

CONCLUSIONS

New high-precision U-Pb geochronology
necessitates major revisions to the temporal
framework for the Permian terrestrial system
in North China. The Upper Shihhotse Formation
spans the latest Asselian to the early Kungrui-
ian, as opposed to its previous Wordian to Wuchiap-
ingian age assignments. A major depositional
gap during the late Cisuralian to Guadalupian in
the northern North China block may have been
caused by convergent tectonics associated with
the closure and/or subduction of the PAO. The
great loss of highly diverse and abundant Cathay-
sian floras and the widespread invasion of the
Angaran floras under arid climate conditions in
the North China block happened during the late
Cisuralian to Guadalupian, but its exact timing is
uncertain due to the long hiatus. The Cisuralian
global aridification may have been associated
with extensive LIP volcanism and the rise of at-
mospheric CO2 in the waning stages of the LPIA.
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