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Journal of Asian Earth Sciences

Late Paleozoic tectonic evolution of the North Tianshan Belt: New structural and geochronological constraints from meta-sedimentary rocks and migmatites in the Harlik Range

--Manuscript Draft--

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First Author:	Xinghua Ni
Order of Authors:	Xinghua Ni Bo Wang, PhD Dominique Cluzel Jiashuo Liu Zhiyuan He
Abstract:	<p>The North Tianshan Belt (NTB) formed by the subduction and accretion of the Junggar Ocean is a key area for reconstructing the Paleozoic tectonic evolution of the southern Central Asian Orogenic Belt (CAOB). Despite numerous studies, the interpretation of the late Paleozoic tectonic evolution of the NTB meets no consensus yet. We conducted field investigations and LA-ICP-MS zircon U-Pb dating on metamorphic rocks from the Julideneng Metamorphic Complex (JMC) in the Harlik Range, which is located between the Turpan-Hami Basin to the south and the East Junggar Belt to the north. The metamorphic rocks are exposed in a NW-SE striking, ~10 km-wide belt and mainly composed of migmatites, garnet-sillimanite mica schists, andalusite schists, and low-grade meta-sandstones. Detrital zircons from the low-grade meta-sandstone yielded ages of 1400 Ma to ~425 Ma. Three micaschists contain zircon populations of from 2500 Ma to ~346 Ma, and a youngest age peak at ~322 Ma. Two samples of leucocratic dykes in migmatites yielded comparable age populations with two major peaks at 322 Ma and 297 Ma. On the basis of structural features, zircon textures and U-Pb ages, combined with already published data, we propose that: (1) the meta-sedimentary rocks of the JMC were deposited after 425 Ma and before 322 Ma; (2) the Precambrian detrital zircons in the meta-sedimentary rocks were probably derived from the Central Tianshan Block; and (3) the migmatization and coeval granitic plutonism occurred at ~322-297 Ma, most likely associated with crustal thinning resulted from continent-based intra-arc or back-arc or post-orogenic extension.</p>
Suggested Reviewers:	<p>Johan de Grave Ghent University johan.degrave@ugent.be Expert in geology of the CAOB, Tianshan belt and geochronology</p> <p>Flavien Choulet University of Franche-Comté flavien.choulet@univ-fcomte.fr Expert in tectonics of the CAOB and Junggar domain</p> <p>Yuruo Shi Chinese Academy of Geological Sciences shiyuruo@bjshrimp.cn Expert in the CAOB, Tianshan belt and in geochronology</p> <p>Wei Xie Hohai University weixie@hhu.edu.cn</p>

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Opposed Reviewers:	

Dr. Bo Wang

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Dear Editor-in Chief Prof. Zhou,

Dear the Editor Prof. Uysal,

February 3, 2021

Thank you very much for your efforts and positive evaluation on our manuscript. We also appreciate very much both reviewers for their constructive comments and thoughtful suggestions. All the comments and suggestions were carefully considered and the manuscript was revised accordingly.

All the comments and concerns were replied in the point-by-point answers to the reviewers. In addition, we have read through the manuscript carefully for several times, and corrected and revised the text, figures and tables. The English of the text was also polished by several colleagues who are good at English writing. We also checked the reference list and citations. Moreover, we append the short biography of each author at the end of this letter. We hope that the manuscript has been satisfactorily improved to fit the publication in the journal.

Your consideration and handling of this manuscript are greatly appreciated.

Sincerely,

Bo Wang

On behalf of coauthors



Xinghua Ni is a Ph.D. Candidate at School of Earth Sciences and Engineering of Nanjing University, China, where he started his Ph.D. subject since 2020. He received his M.Sc. degree in 2020 at Nanjing University. His research involves Paleozoic tectonic evolution of the Tianshan Orogenic Belt, focusing on metamorphism, structural geology, geochronology and geochemistry.



Bo Wang is a Professor at School of Earth Sciences and Engineering of Nanjing University, China. He received his joint Ph.D. degree from Nanjing University (China) and Université d'Orleans (France) in 2006. His main research interests include structural and kinematic analysis of deformed rocks, tectonic evolution of orogenic belts, plate tectonics and continental reconstruction, mainly in the Tianshan and South China.



Dominique Cluzel is professor emeritus at the Institut des Sciences Exactes et Appliquées (Institute of Pure and Applied Sciences), University of New Caledonia. He researches on Structural Geology and Geodynamics through a multidisciplinary approach. His current research interests are tectonics and geodynamic evolution and mineral resources of New Caledonia, Paleozoic geodynamic evolution of the Central Asian Orogenic Belt (Xinjiang Region, China).



Jiashuo Liu is a Ph.D. Candidate at School of Earth Sciences and Engineering of Nanjing University, China, where he started his Ph.D. subject since 2020. Before that, he studied as a Master student at Nanjing University in 2018. His research interests focus on the evolution of orogenic belts using the structural geology, geochronology and geochemistry, and the thermal modeling related to Raman spectrum of carbonaceous material.



Zhiyuan He received his M.Sc. degree in 2018 from Nanjing University. His research involves Paleozoic tectonics and structural geology of the Tianshan, focusing on regional ductile shear zones. He is currently undertaking Ph.D. research at the Ghent University using an integrated approach of field mapping, structural geology and thermochronology to reveal the thermal-tectonic history of the Tianshan and Junggar.

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Signed by the corresponding author:

A handwritten signature in black ink, consisting of a stylized, cursive script that appears to be the name 'Z. Li'.

Research highlights:

- **Protoliths of the Julideneng Metamorphic Complex** were deposited between 425 Ma and 322 Ma.
- **Metamorphism/migmatization occurred at ~322-297 Ma in continent-based intra-arc/back-arc or post-orogenic setting.**
- Precambrian detrital zircons were likely derived from the Central Tianshan.
- Accretionary orogeny in the North Tianshan terminated in the Permian.

Ms. Ref. No.: JAES-D-20-00960

Title: Late Paleozoic tectonic evolution of the North Tianshan Belt: New structural and geochronological constraints from meta-sedimentary rocks and migmatites in the Harlik Range

Journal of Asian Earth Sciences

Dear Dr. Wang,

The reviewers/editor have commented on your above paper and they ask you to undertake minor revision.

Please carefully address the issues raised in the comments. If you are submitting a revised manuscript, please also:

- a) explain how and where each point of the reviewers' and Editor's comments has been incorporated (point by point) in a separate "Detailed Response to Reviewers" file. Your response must be made very clear.
- b) indicate all the corrections "in red" in the revised manuscript, so that the Editor could easily identify the places of change. (that is a version use a size 12-point font and without annotations)
- c) should you disagree with any part of the reviews, please explain why.

Your revision should be resubmitted within 45 days. I look forward to receiving your revised manuscript.

Yours sincerely,

On behalf of Editor-in Chief Mei-Fu Zhou

Miss Diane Chung

Journal of Asian Earth Sciences

Dear Editor-in Chief Prof. Zhou,

Dear the Journal Manager Miss Chung,

Thank you very much for sending us the referee's reports and for your positive evaluation on our manuscript JAES-D-20-00960. In careful consideration of the referee's helpful comments and suggestions, we have revised our manuscript seriously. In the following, we reply point-by-point all the comments and suggestions raised by both reviewers. We hope the manuscript has been satisfactorily improved and it will be accepted for publication in the journal.

Thanks again for your kind consideration.

Best regards,

Bo Wang and co-authors

Reviewers' comments:

Dear Dr. Wang,

Thank you for submitting your manuscript to JAES. The review process of your manuscript has now been completed and I received the comments from two expert. Both reviewers agree that the manuscript is well prepared and contains valuable data which deserve to be published. However, they both think that the current version needs some minor improvements before publication. Below, you will find the suggestions provided by two reviewers, and I believe that implementation of their comments will make your manuscript better in shape. Therefore, I kindly ask you to take into account all the comments, given below, in revision of your manuscript, and have the revised text polished for English language before re-submission.

Kind regards,

Ibrahim Uysal

Editor

Dear the Editor Prof. Uysal,

Thanks a lot for your handling and positive evaluation of our manuscript. We considered carefully all the constructive comments and suggestions by both reviewers, and revised the manuscript accordingly. The English of the text was also polished by several colleagues who are good at English writing. In the following, we reply point-by-point to all the comments and suggestions.

Best regards,

Bo Wang and co-authors

Reviewer #1: This paper presents field relationship and structures, geochronological and zircon isotopic data of meta-sedimentary rocks and migmatites in the Harlik Range, and further discusses their petrogenesis and late Paleozoic tectonic evolution of the North Tianshan Belt. The study is valuable, but this paper can be accepted with moderate revision.

Thanks a lot for the positive opinion by Reviewer #1.

1. It is important to distinguish different zircon groups due to different origins. It should be better if type 1-4 are labeled besides the zircons in figures.

A: Thanks for this meaningful suggestion. In revised Fig. 5 different types of zircons are grouped and labeled in order better to distinguish their origins.

Authors have discussed the type 3 zircons in 12TS119E are of hydrothermal origin (line 412-415). How about type 3 zircons in 12TS119A and 12TS119B? How about the Th/U ration? Not metamorphic origin? What the age of type 3 zircons in 12TS119A?

Check if type 3 zircons from these 3 samples have similar Th/U. From what you described in the text, Th/U ratios of type 3 zircons differ from these 3 samples

A: Based on the morphology, Th/U ratios and REE patterns of the zircons, we concluded that the type 3 zircons in sample 12TS119E are similar to hydrothermal zircons (Hoskin, 2005). Actually, as we discussed in line 396-398, the three youngest zircons in sample 12TS119B also belong to type 3, displaying homogeneous dark to black CL images (Figs. 5c and S1) and Th/U ratios around 0.4 (Table S1; Fig. 6f). Although we do not have REE patterns of these zircons, it is quite possible that they are also of a hydrothermal origin.

However, there is no type 3 zircon in sample 12TS119A, from which all zircons belong

to the type 1 and type 2 (Figs. 5b and S1). The youngest nine ages are obtained exclusively from type 2 zircons with Th/U ratios mostly lower than or near 0.4 (Table S1; Fig. 6d), showing bright or dark cores characterized by surface-controlled alteration (Corfu et al., 2003) and encircled by thin and dark rims (Figs. 5b and S1) (line 386-390). This kind of zircons was considered to be related with metamorphic event (Hoskin and Schaltegger, 2003) (line 359-367). Therefore, the youngest age (~322 Ma) of these zircons probably corresponds to the timing of the metamorphism (line 467-469).

For zircon morphology, how about migmatite samples? 2 out of four types are shown in migmatite samples ? Any meaning? Maybe it needs further discussion.

A: Thanks for this important comment.

Indeed, as suggested by the reviewer, there are two types of zircons in the migmatite samples. A few grains with vague dark rims are similar to type 1 zircons and they yielded ages mostly of ~322 Ma and minor older ages, and the other zircons without visible rims are comparable with type 4 zircons and they yielded ages of ~322 Ma and 297Ma (Fig. 8) (line 471-478). However, all the dated zircons display clear oscillatory zoning, Th/U ratios higher than or close to 0.4 (Fig. 8) and steeply-rising REE patterns characterized by enrichment of HREE relative to LREE, mostly positive Ce anomalies and negative Eu anomalies (Figs. 7c and 7d), indicating a magmatic origin (line 422-425 and 438-441). In addition, we calculated the apparent temperature of zircon crystallization by using Ti-in-zircon thermometer (Watson et al., 2006), which was not presented in the manuscript. As shown in figures below (Fig. R1), zircons of different ages don't show significant difference in apparent crystallization temperature. As these zircons yielded two U-Pb ages at ~322 Ma and ~297Ma, and sometimes different zircons yielded same ages, while similar zircons sometimes yielded different ages,

we proposed that these two ages likely represent two episodes of zircon crystallization (similar origin), and the dark rims of some zircons may have resulted from slight overgrowth during the second episode of crystallization at 297 Ma (line 475-478).

We have discussed in the revised manuscript the origins and meanings of zircons from the migmatite samples on the basis of their texture and morphology. On the fact that detrital zircons in meta-sedimentary rocks have complex textures, we divided them into four types. But considering that zircons of the migmatites are relatively simple, we do not recommend classifying them in order not to make things complex.

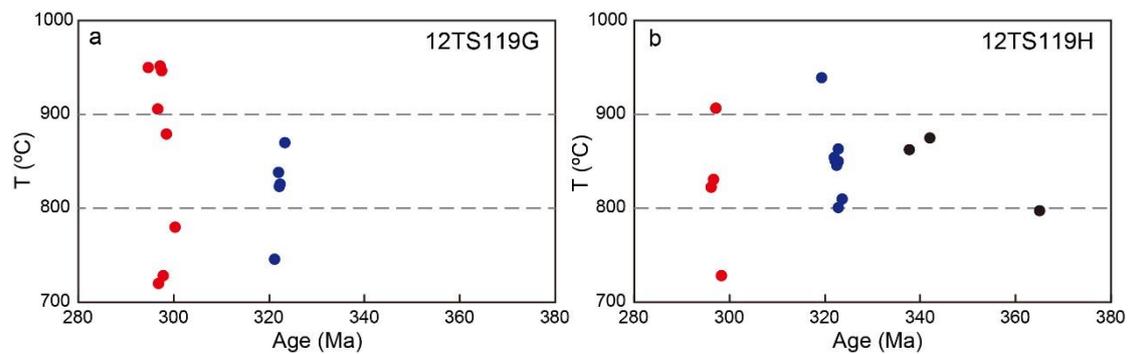


Fig. R1 Calculated crystallization temperature of zircons from two migmatite samples.

What's the temperature for hydrothermal zircon? It seems that the hydrothermal zircon ages are older than metamorphic and magmatic ages you discussed in Section 6.1.

A: Yes, we also calculated the apparent temperatures for zircons of the schist sample 12TS119E by using Ti-in-zircon thermometer (Watson et al., 2006). The results show that the hydrothermal zircons (green spots in Fig. R2) have apparent crystallization temperatures at 780-1080 °C. Such high temperatures probably correspond to Ti-rich fluids that form the hydrothermal zircons. The reason why ages of the hydrothermal zircons are older than metamorphic age may be resulted from age mixing between primary cores and recrystallized areas or overgrowths (line 469-470) (Corfu et al., 2003) or fluids-related high U and Th

abundances (Zhao et al., 2014). This can be additionally proved by the weak concordance of the ages for these hydrothermal zircons (Fig. 6g).

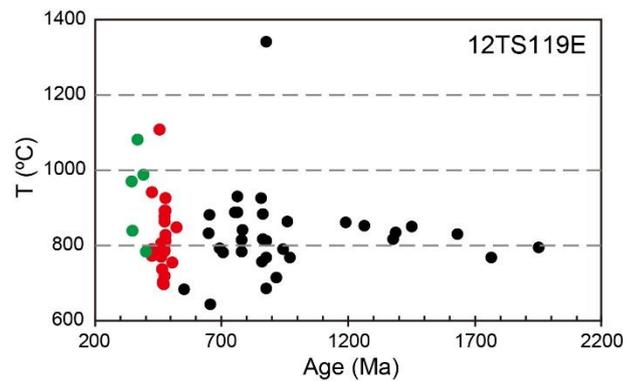


Fig. R2 Calculated crystallization temperature of zircons from the schist sample 12TS119E.

2. The metamorphic ages are constrained to be 322Ma and 297Ma, so should the deposition age of the meta-sedimentary rocks be between 425 and 322Ma at least? Line 41 is not consistent with Line 629.

A: I guess the reviewer was supposed to say, “Line 451 is not consistent with Line 629”. Yes, the metamorphism is suggested to occur during 322 Ma to 297 Ma, so the deposition age of protoliths of the meta-sedimentary rocks can be roughly constrained between 425 and 322Ma. The crosscutting granite pluton dated at 320 ± 3 Ma (Song et al., 2018) provides additional evidence. We rephrased this sentence as follows: “The metamorphic ages at 322 Ma and 297 Ma provide a constraint on the minimum sedimentary age (see discussion below). Thus, the deposition of protoliths of the meta-sedimentary rocks may have occurred between 425 Ma and 322 Ma. The maximum deposition age is also defined by the crosscutting granite dated at 320 ± 3 Ma (Song et al., 2018).”

Line 549-550 it is not certain that the Central Tianshan Block is the source area for the early Paleozoic zircons of the meta-sediments in the Qincheng area. Line 570-572 the Central Tianshan Block is the most probable provenance area for the Precambrian detrital zircons in

the studied meta-sedimentary rocks. The zircons of Precambrian ages should be polycyclic.

How about the morphology of these zircons?

A: Thanks for this suggestion and question. We fully agree that the Precambrian zircons are polycyclic. The Precambrian zircons mostly belong to type 1 and type 2, displaying complex texture with cores and rims (Figs. 5 and S1). Some of them even show more than one rim, which is solid evidence for polycyclic reworking. In order to better explain our interpretations, we added several sentences to discuss this point in the new version.

In addition, Line590-595 the North Tianshan was likely connected with the northern margin of the Central Tianshan Block before the Late Carboniferous.... This discussion should indicate the Central Tianshan Block might have sourced the early Paleozoic zircons. So line 549-550 need more consideration.

A: Thanks for this suggestion. We reconsidered this sentence and rephrased it as “According to the studies on ophiolites of the North Tianshan Suture zone and Kangguer belt (Xu et al., 2006a, 2006b; Chen et al., 2019), the North Tianshan (or Kangguer) Ocean opened during the mid-late Carboniferous. Considering that the Precambrian zircons most likely came from the Central Tianshan Block (see discussion below), it is possible that the Central Tianshan Block have also provided certain early Paleozoic detritus for the sediments in the Qincheng area.”

3. Too many citations in some part, e.g. line 65, 128, 140.... Some representative references are enough.

A: You are right. We have checked and cited the most representative references only and deleted some references properly.

4. The English writing of this manuscript is fine, but small problems still exist. I am certain authors can correct after re-check the text.

A: Thanks a lot for this positive comment. We have re-checked the text and polished the English with the help of several colleagues good at English writing.

Reviewer #3: Comments on the paper by Xinghua Ni, Bo Wang et al.

This paper focuses on the Julideneng Formation of Carboniferous age in the Harlik Range of the North Tianshan Belt (NTB) in China. It includes plenty of U-Pb zircon age data conducted on the detrital zircons from the 4 parametamorphic rocks and igneous zircons from the 2 cross-cutting igneous (granitic) dikes. Based on the data obtained, the authors try to constrain the provenance, maximum and minimum depositional ages of the detrital zircons and then adapt a tectonic scenario for the evolution of the NTB (Harlik Range). Provenance of sediments is well constrained but depositional ages of detrital protoliths appear to need some more improvement. Also, a tectonic model can help understanding of the Pre-Carboniferous evolution of the Harlik region.

Thanks to Reviewer #3 for the encouraging opinion on our study. Yes, we tried to propose a cartoon model included in the revised manuscript to discuss the Paleozoic evolution of the study area and adjacent regions.

Comments keyed to the text

Line 23

I do not recommend using the term "Formation" for nomenclature of the metamorphic rocks, particularly those that lost their primary structures (e.g., bedding) during metamorphism. Instead, using of "Julideneng Metamorphic Complex" or "Julideneng Massif" is suggested.

A: Thank you so much for this meaningful suggestion. We agree that the use of “Julideneng Metamorphic Complex (JMC)” would be better on account of the high-grade yet relatively localized metamorphism. We have replaced it throughout the manuscript.

Except for the granitoids, the other units, which are shown in the legend of the map (Fig. 1c), are not defined clearly. It is noteworthy to identify whether they are metamorphic or sedimentary in origin.

A: According to references (e.g. XBMGR, 1993; Sun, 2007) and our own field investigations, most of rocks around the granitoids are sedimentary rocks and were locally deformed and metamorphosed up to greenschist facies. For example, middle Devonian strata that occur along the ridge of the Harlik Range were folded and locally reworked by shear zones, but the metamorphic grade of these rocks is very low.

We revised the text to clarify this point in the new version.

Lines 450-451

I recommend using "deposition of detrital protoliths of the meta-sedimentary rocks" instead "deposition of meta-sedimentary rocks".

A: Ok, it is rephrased as “the deposition of protoliths of the meta-sedimentary rocks”, and many thanks.

Lines 444-507

Based on the age data from a cutting granitoid at 320 Ma (Song et al., 2018), an inference reached is that 320 Ma is the minimum depositional age of the detrital protoliths of the metasedimentary rocks (line 451). This is not true. This age only provides a definite constraint on the minimum depositional age, not more. The minimum depositional age must be somewhat before the intrusion of the middle Carboniferous granitoids. Looking at the map

(Fig. 1c), it is shown that the post-collisional Carboniferous granitoids have the largest outcropping area totally after the other Carboniferous rocks. Such high-volumes of crustal melting in orogenic belts occur generally after delamination, which needs at least 30 Ma after the final closure of the Ocean (slab breakoff ~10-15 Ma, crustal thickening ~15 Ma and then delamination). Hence, it can be concluded that the deposition must be completed at least 30 Ma before the intrusion of the post-collisional granitoids, e.g., at 350 Ma (early Carboniferous) or somewhat before (late Devonian).

A: Thanks a lot for this very constructive comment and suggestion.

Yes, we strongly agree that the ages of crosscutting granitoids and migmatites only provide a minimum limit on the depositional age of protoliths of the meta-sedimentary rocks. The true depositional age should be older than the age of the metamorphism, migmatization and granitoids emplacement considering the processes of diagenesis of sediments, crustal thickening and uplifting related to orogeny, and large-scale crustal melting, such processes usually take several tens of million years, but it is difficult to precisely constrain up to now with the available methodologies.

Indeed, the post-collisional granitoids in some typical collisional orogenic belts, such as the Himalaya belt, formed 30 million years later after the collision began (e.g., Turner et al., 1996; Chung et al., 2005). However, in some accretionary orogenic belt, for example, the Newfoundland Appalachians, post-collisional magmatism occurred rapidly following arc-continent collision (<10 Ma; Whalen et al., 2006).

In adopting the reviewer's reasonable suggestion with great caution of un-constrainable time gap between the sedimentation and magmatic intrusion, we just use "Pre-late Carboniferous" (>322 Ma) as a minimum limit for the deposition timing of the protoliths of

meta-sedimentary rocks.

No clear distinction on the origin of migmatization has been presented (lines 468-497). One group of migmatites occur on a regional scale in the transition of high-grade metamorphism and anatexis at depths greater than 22-25 km where geothermal gradient is higher than 650 ° C. Other group of migmatites can form in metamorphic rocks near large intrusions when some of the magma is injected into the neighbouring metamorphic rocks. It is unclear which one of these processes is the cause of migmatization?

A: We are happy to learn from this very thoughtful comment and we totally agree with the reviewer's opinion. In section 6.3, we had some discussions about the origins of migmatization, and in the revise manuscript, we added some sentences to further discuss the possible different mechanisms of the migmatization and associated metamorphism and magmatism.

According to Sun (2007) and our field observations, the garnet-sillimanite-bearing meta-sedimentary rocks are likely the protoliths of the migmatites and associated felsic melts (anatexis). The generally N-dipping foliations bearing ~NW-SE stretching lineation likely resulted from sinistral transtension (Sun, 2007). In addition, the HT-LP metamorphism and migmatization are coeval with the emplacement of high-K calc-alkaline undeformed granites (320-316 Ma) with positive whole-rock $\epsilon_{Nd}(t)$ and zircon $\epsilon_{Hf}(t)$ values, probably related to the intrusion of neighboring granitoids, both of which are diagnostic of decompression melting in an extensional setting (Song et al., 2018). Similarly, in the nearby Bogda Belt, Carboniferous (350-315 Ma) volcanic rocks are thought to have formed in an intra-arc (Zhang et al., 2017; Wali et al., 2018) or back-arc extensional setting (Chen et al., 2013; Xie et al., 2016b). Therefore, we consider that the meta-sedimentary rocks and migmatites are likely

parts of the Harlik arc root, and the migmatization probably occurred due to decompression partial melting in an intra-arc or back-arc extensional setting and intrusion of large volume magma (Line 601-611).

If migmatization occurred at 320 Ma, coeval with large plutonism, re-metamorphism (overprinting) and partly igneous crystallization of the previous metamorphic rocks (schists) in areas near large intrusions of granite seems likely. However, cross-cutting relationship of granites with migmatites strongly argues against this and implies that migmatization should have been concerned with regional metamorphism (lines 479). Hence, granite migmatization at 320 Ma through regional metamorphism seems unreasonably as it involves swift burial to the depths > 22 km and then denudation.

A: As replied above, the metamorphism and migmatization likely occurred at an intra-arc or back-arc extensional setting. Such an extensional setting allows for heat flow from asthenosphere, resulting in high thermal gradients, and consequent HT-LP metamorphism and partial melting of the crust in a shallow depth (e.g. Zheng and Chen, 2017). According to Zhao et al. (1997) and Zhou (2004), the temperature of the metamorphism is as high as 680°C, while the pressure of the metamorphism is about 0.23-0.4 Gpa responding to 9-15 km depth. Therefore, the partial melting of the supra-crustal rocks (similar phenomenon with anatexis) in an extensional setting with significant addition of heat by magmatism may do not need to bury these sedimentary rocks to a depth of >22 km. In addition, it is not certain that 320 Ma zircons came from granites. Alternatively, small-scale mid-Carboniferous felsic dykes may have been remelted/assimilated. Moreover, the magmatism could be a long-term process over several tens of million years, and the later (younger) granitoids could crosscut the early ones and metamorphic rocks.

In order to avoid confusions, we revised the text here to better explain this point, and many thanks for this important comment.

Lines 509-581

This section presents clear estimations on possible provenances of the detrital zircons. However, paleogeographic position of the basin (NTB) relative to the source areas providing sediments are not sufficiently depicted. Early Paleozoic (Ordovician to Silurian) sediments are considered to have been derived from the Harlik-Dananhu arc in the NTB. What is the position of the basin in relation to this arc?

A: It is true that we just discussed the possible provenances of the detrital zircons and did not precisely point out possible paleogeographic position of the sedimentary basin. In fact, based on the previous studies, we have proposed that the study area might have been an intra-arc basin between the Harlik arc (to the north of the study area) and the Dananhu arc (to the south of the study area) to receive sediments during the deposition of protoliths of the meta-sedimentary rocks (line 599-604). In the revised manuscript, following the suggestion of the reviewer, we propose a cartoon model in which the relative position of this sedimentary basin is shown in Fig. 11A.

Was this arc occurred due to the southward subduction of the Kalamaili Ocean or northward subduction of the Kangguer Ocean?

A: As written in line 143-150, the generation of the Harlik and Dananhu arcs is still under debate. Some geologists considered these arcs were generated by southward subduction of the Kalamaili Ocean (Yuan et al., 2010; Xie et al., 2016c), while some others proposed that the Harlik and Dananhu arcs were produced by the northward subduction of the North Tianshan (or Kangguer) Ocean (Li et al., 2006; Zhang et al., 2017, 2018; Du et al., 2018a; Han and

Zhao, 2018; Chen et al., 2019) or by the both (Xiao et al., 2004; Ma et al., 2015).

According to the available data (XBGMR, 1993), the Harlik and Dananhu arcs were active since Silurian up to late Carboniferous. However, the existence of Kangguer Ocean in early Paleozoic is not documented up to now. Thus, the early Paleozoic magmatic activities in the Harlik and Dananhu arcs most likely resulted from southward subduction of the Kalamaili Ocean which existed at least since Ordovician to Silurian.

Carboniferous N-MORB-like ophiolitic basalts were considered as the relics of the oceanic plate of the Kangguer Ocean (e.g., Chen et al., 2019). Thus, the Kangguer Ocean could have existed in Carboniferous. In addition, arc magmatism in the Dananhu Arc shows a general southward younging tendency (Xiao et al., 2004; Li et al., 2006; Zhang et al., 2018). Moreover, the Kalamaili Ocean was likely already closed in mid-Carboniferous. Therefore, we consider that the northward subduction of the Kangguer Ocean played a significant role in the formation of Dananhu and Harlik arc magmatism during the Carboniferous.

In the revised version, we added sentences to further discuss this point and provide a cartoon model to illustrate the evolution scenario related to the subduction of Kalamaili and Kangguer oceanic plates.

Also, Kangguer Ocean is placed to the south between the NTB and CTB. If so, when was this ocean opened?

A: As have replied for the last comment above, according to studies on ophiolitic basalts in the Kangguer belt (e.g., Chen et al., 2019), the Kangguer Ocean was likely open in mid-late Carboniferous. But the Kangguer belt was intensively reworked by a strike-slip shear zone (Wang et al., 2008, 2014a), and it is now difficult to recognize the ophiolitic rocks related to the Kangguer Ocean, its existence and duration remain unclear, and further studies are in

need.

Furthermore, there is not an obvious description how and when the Mesoproterozoic and Neoproterozoic components (zircons) transported from their provenance (CTB) to the basin (NTB) lying to the north of the Kangguer Ocean.

A: Thanks a lot for this important comment.

As mentioned in the revised manuscript and replied above, although there is no direct evidence for the timing and mechanism of opening of the Kangguer Ocean, the existing geochemical data of ophiolitic basalts in the Kangguer belt show SSZ-like signatures (e.g., Chen et al., 2019), indicating that the Kuangger Ocean was likely a back-arc basin probably due to southward subduction of the Kalamaili Ocean. Before its opening, the study area (intra-arc basin between the Dananhu and Harlik arcs in the North Tianshan Belt (NTB) was connected with the Central Tianshan Block (CTB). Thus, the Mesoproterozoic to Neoproterozoic detritus (including zircons) could be transported from the source area (CTB) northward to the sedimentary basin (NTB); they may have deposited directly in the basin before Carboniferous or might be recycled again later.

In the revised manuscript, we added sentences to further explain this possibility as “The Precambrian zircons in the meta-sedimentary rocks are anhedral in shape and show complex core-rim textures (Figs. 5 and S1), indicating that they were multiple-cycled. Thus, these Precambrian zircons were probably transported from the Central Tianshan Block to the North Tianshan Belt (Dananhu Arc) before the opening of the North Tianshan (or Kangguer) Ocean, and thereafter re-transported into the Harlik area. This is in agreement with the fact that zircon populations of Devonian flyschs in the Dananhu Arc are comparable with that of the Central Tianshan Block (Wang et al., 2019). However, due to uncertainty on their deposition age,

these zircons could have been transported directly from the Central Tianshan Block as well.”

Line 596-599

If the granites cut the migmatites at 322 Ma, the migmatites should be older than this age.

Also, taking the intrusion depths of the granites into account (<7 km), such shallow depths are not convenient for the migmatization concerning with the regional metamorphism.

A: Yes, we totally understand and agree with the reviewer’s comment. However, in most migmatitic zone, only small-scale melts migrate along (sub-parallel to) the foliations of migmatite and/or restites. Once the melts aggregate to form larger magma body, they can ascend driven by buoyancy and crosscut the migmatite and country rocks (Sawyer, 1998). Logically, this kind of larger felsic magma form dykes and intrusion of which is certainly later than migmatization. But the processes of migration, aggregation and intrusion (crosscutting the migmatites) of a single pack of melts could occur in a relatively short period of time (Sawyer, 1994; Wang et al., 2014b) and the available zircon U-Pb method cannot recognize (within its errors) the relative different ages of migmatization (partial melting) and melt crystallization.

In addition, in a migmatization zone, granitic intrusions of different origins and different depths can co-exist, some granitic intrusions originated from great depths having nothing to do with the migmatization could intrude in the migmatites and country rocks, but this is not the topic of discussion in our manuscript.

Line 601-602

Regional migmatization and granitic magmatism can be coeval but do not display cross-cutting relationship due to the involvement of different depths for migmatization and granite emplacement.

A: As replied for the last comment above, according to the previous observations of Sayer (1998) and our studies in the migmatite zone (Wang et al., 2014b), granitic intrusions can crosscut the “coeval” migmatites, by saying that they are coeval because the available most reliable zircon U-Pb dating method cannot distinguish the ages of S-type granitic rocks from the timing of migmatization. Granitic magma can crosscut its source rocks (migmatites) via magma migration and associated cooling and crystallization.

Line 609-611

Above you mentioned that the Kangguer Ocean was closed in the Late Carboniferous. If so, this closure corresponds to the late orogenic extensional period.

A: Thanks for this comment. Yes, the closure of the Kangguer Ocean was usually supposed to occur at 320-300 Ma (Zhang et al., 2020). This period corresponds to the late (final) stage of orogenic processes of the Tianshan Belt. During the late Carboniferous, the Tianshan belt was located in an overall convergent regime, but due to the closure of the Kalamaili Ocean and the South Tianshan Ocean before ~320 Ma, the study area was also affected by post-orogenic extension while the Kangguer back-arc basin was in the process of closure. Thus, the migmatization at ~322 Ma could probably result from both the post-orogenic extension (related to the Kalamaili-East Junggar orogeny) and the back-arc or intra-arc extension during the closure of the Kangguer Ocean. We rephrased the sentences to better clarify this point.

A figure including cartoons on the tectonic evolution of the NTB and neighboring terranes can supply a substantial contribution to understanding of the early to middle Paleozoic events.

A: Thanks a lot for this thoughtful suggestion. We agree and tried to propose a cartoon model (Fig. 11) to show the tectonic evolution of the study area and adjacent regions on the basis of previous data and our own results.

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1 **Late Paleozoic tectonic evolution of the North Tianshan Belt: New**
2 **structural and geochronological constraints from meta-sedimentary**
3 **rocks and migmatites in the Harlik Range**

4
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17
18 **Abstract**

19 The North Tianshan Belt (NTB) formed by the subduction and accretion of the
20 Junggar Ocean is a key area for reconstructing the Paleozoic tectonic evolution of the

21 southern Central Asian Orogenic Belt (CAOB). Despite numerous studies, the
22 interpretation of the late Paleozoic tectonic evolution of the NTB meets no consensus
23 yet. We conducted field investigations and LA-ICP-MS zircon U-Pb dating on
24 metamorphic rocks from the Julideneng Metamorphic Complex (JMC) in the Harlik
25 Range, which is located between the Turpan-Hami Basin to the south and the East
26 Junggar Belt to the north. The metamorphic rocks are exposed in a NW-SE striking,
27 ~10 km-wide belt and mainly composed of migmatites, garnet-sillimanite mica
28 schists, andalusite schists, and low-grade meta-sandstones. Detrital zircons from the
29 low-grade meta-sandstone yielded ages of 1400-1250, 1000-850, ~780, ~580, ~490,
30 ~445 and ~425 Ma. Three micaschists contain zircon populations of 2500-2175,
31 1800-1600, 1500-1100, 1000-850, 800-500, ~475, ~425, 420-380, ~346 Ma, and a
32 youngest age peak at ~322 Ma. Two samples of leucocratic dykes in migmatites
33 yielded comparable age populations with two major peaks at 322 Ma and 297 Ma,
34 which are interpreted as two stages of successive partial melting and anatectic melts
35 crystallization. On the basis of structural features, zircon textures and U-Pb ages,
36 combined with already published data, we propose that: (1) the meta-sedimentary
37 rocks of the JMC were deposited after 425 Ma and before 322 Ma (latest Silurian to
38 late Carboniferous); (2) the Precambrian detrital zircons in the meta-sedimentary
39 rocks were probably derived from the Central Tianshan Block, which was once
40 connected with the NTB; and (3) the migmatization and coeval granitic plutonism
41 occurred at ~322-297 Ma (late Carboniferous), most likely associated with crustal

42 thinning resulted from continent-based intra-arc or back-arc or post-orogenic
43 extension.

44

45 **Keywords:** Central Asian Orogenic Belt; East Junggar; North Tianshan (Tien Shan);
46 accretionary orogeny; post-orogenic crustal thinning; migmatization

47

48 **1. Introduction**

49 The Tianshan Orogen is located in the southernmost part of the Central Asia
50 Orogenic Belt (CAOB), which is one of the largest Phanerozoic orogenic systems on
51 the Earth (Şengör et al., 1993; Windley et al., 2007; Xiao et al., 2013; Safonova,
52 2017). It recorded the Paleozoic consumption of the southern Paleo-Asian Ocean
53 domains (i.e., the Junggar-North Tianshan Ocean and Paleo-Tianshan Ocean or
54 Turkestan Ocean), successive accretion of island arcs, accretionary wedges and
55 microcontinents, as well as the final amalgamation/collision between the Kazakhstan
56 and Tarim blocks (e.g., Gao et al., 1998, 2009; Li, 2004; Xiao et al., 2004, 2013;
57 Charvet et al., 2007, 2011; Han et al., 2011; Wang et al., 2011a, 2018a). Deciphering
58 the subduction-accretion processes of this belt is therefore helpful for a better
59 understanding of the Paleozoic evolution of the southwestern CAOB and Phanerozoic
60 Asia crustal growth (Han and Zhao, 2018; Huang et al., 2020).

61 Numerous studies on the Tianshan Orogen were conducted focusing on

62 kinematic analysis (e.g., Charvet et al., 2007, 2011; Lin et al., 2009; Wang et al.,
63 2010), characteristics of ophiolites (e.g., Shu and Wang, 2003; Dong et al., 2006; Xu
64 et al., 2006a, 2015a; Wang et al., 2011a, 2018a; Jiang et al., 2014), geochemistry of
65 arc-related magmatic rocks (e.g., Chen et al., 2013; Xie et al., 2016a; Zhang et al.,
66 2017; Wali et al., 2018) and post-collisional magmatism (e.g., Gu et al., 1999; Wang
67 et al., 2009a, 2014a; Yuan et al., 2010; Chen et al., 2011; Muhtar et al., 2020). Based
68 on these results, various tectonic models were proposed but no consensus has been
69 achieved (e.g., Gao et al., 2009; Charvet et al., 2011; Xiao et al., 2013; Han and Zhao,
70 2018). The controversy arises over (1) the regional correlation of various magmatic
71 arcs, and (2) the timing of the final amalgamation of the Tianshan Orogen. Late
72 Paleozoic magmatic arcs were diversely correlated with the subduction of the South
73 Tianshan Ocean, the Junggar-North Tianshan Ocean and the Kalamaili Ocean (e.g.,
74 Xiao et al., 2004, 2013; Charvet et al., 2007, 2011; Han and Zhao, 2018). The
75 termination of accretion was controversially estimated to be Devonian-early
76 Carboniferous (Xia et al., 2002, 2012; Ma et al., 2015), late Carboniferous-early
77 Permian (Gao et al., 1998, 2009; Charvet et al., 2007, 2011; Han et al., 2010, 2011;
78 Wang et al., 2014a; Han and Zhao, 2018), or end-Permian to mid-Triassic (Xiao et al.,
79 2009; Chen et al., 2020).

80 The Harlik Range is the northeastern part of the Tianshan Orogen where the
81 latter connects with the East Junggar Belt. It is a key area for unraveling the tectonic
82 evolution of the Tianshan Orogen (Xiao et al., 2004; Huang et al., 2018). The tectonic

83 setting and evolution of the Harlik Range remain a matter of debate. Xia et al. (2002,
84 2012) proposed that it underwent intra-continental rifting in Carboniferous to Permian
85 time; while some other authors suggested a volcanic arc setting during the
86 Ordovician-Carboniferous (Xiao et al., 2004; Han and Zhao, 2018). Additionally, Sun
87 (2007) proposed that it experienced an Ordovician-Silurian arc and a
88 Devonian-Carboniferous back-arc extension.

89 Meta-sedimentary rocks and migmatites are well exposed in the southern Harlik
90 Range (Fig. 2b), they may provide key evidence for the Paleozoic tectonic evolution
91 of the North Tianshan Belt. However, these metamorphic rocks were poorly studied.
92 They were ever considered as late Carboniferous in age (XBGMR, 1966; Sun et al.,
93 2007a), but the depositional ages of their protoliths were not well constrained (Cao et
94 al., 2009). Furthermore, the timing and tectonic setting of the metamorphism were
95 diversely interpreted as (i) two-stage regional metamorphism associated with
96 Carboniferous intra-arc rifting and Permian collision (Zhao et al., 1997); (ii) contact
97 metamorphism during the Carboniferous and Permian magmatism (Zhou et al., 2004);
98 or (iii) Permian dynamic metamorphism during post-collisional extension (Sun,
99 2007).

100 In this study, we present new field structural observations and zircon
101 LA-ICP-MS U-Pb ages of the meta-sedimentary rocks and migmatites from the
102 Harlik Range. These new results combined with previously published data allow us to
103 better constrain the timing of protoliths deposition and metamorphism of these

104 meta-sedimentary rocks, to discuss the provenances of the sediments, and to
105 tentatively replace the high-temperature metamorphism and anatexis in the framework
106 of the late Paleozoic tectonic evolution of the North Tianshan Belt.

107 **2. Geological background**

108 *2.1. Regional tectonic framework*

109 The Chinese segment of the Tianshan Orogen is geographically divided into
110 eastern and western parts along the Urumqi-Korla line. The eastern Chinese Tianshan
111 is further divided into three tectonic units as the South Tianshan, Central Tianshan and
112 North Tianshan belts (Fig. 1b; Xiao et al., 2004; Li et al., 2006; Charvet et al., 2007).

113 These units are separated from each other by two major faults (namely the Main
114 Tianshan Shear Zone and Baluntai-Xingxingxia Fault), which are dextral strike-slip
115 faults active mainly during the Permian along reactivated older suture zones
116 (Laurent-Charvet et al., 2003; Charvet et al., 2007; Wang et al., 2008, 2014a; de Jong
117 et al., 2009; He et al., 2021).

118 The South Tianshan Belt (STB) is connected with the northern margin of the
119 Tarim Block and mainly consists of ophiolitic mélanges and Cambrian to
120 Carboniferous sedimentary and volcanic rocks (XBGMR, 1993). These rocks are
121 locally metamorphosed and imbricated within several thrust-and-fault belts (Charvet
122 et al., 2011). The western STB was formed by the amalgamation of the Tarim Block

123 and the Central Tianshan Belt following the closure of the South Tianshan Ocean and
124 several back-arc basins (Gao et al., 1998, 2009; Xiao et al., 2004; Han et al., 2011;
125 Wang et al., 2011a, 2018a; Huang et al., 2018; Zhong et al., 2019). In contrast, the
126 eastern STB (also named the Beishan Belt) was formed by the accretion of several
127 Precambrian-based magmatic-arc terranes (Yuan et al., 2015; Yu et al., 2016; Zong et
128 al., 2017; He et al., 2018a) and ophiolitic mélanges during the Paleozoic (Xiao et al.,
129 2010; Ao et al., 2012; Song et al., 2015; Shi et al., 2018).

130 The Central Tianshan Belt (CTB) is composed of a Precambrian basement (Hu et
131 al., 2000, 2010; Liu et al., 2004; Ma et al., 2012b; He et al., 2014; Wang et al., 2017;
132 Han and Zhao, 2018; Huang et al., 2019), Ordovician to early Devonian arc-related
133 volcanic and sedimentary sequences, and Paleozoic intrusive rocks (Xiao et al., 2004,
134 2013; Shi et al., 2007; Lei et al., 2011; Ma et al., 2013; Zhong et al., 2015; Han and
135 Zhao, 2018; He et al., 2018b). Both the basement and arc-type rocks are
136 unconformably overlain by unmetamorphosed Carboniferous to Permian sediments
137 (XBGMR, 1993). The CTB is considered either as an independent Precambrian
138 micro-continent involved in the accretion of the Tianshan Orogen (Hu et al., 2000;
139 Huang et al., 2015, 2017) or as a part of the northern Tarim, which was drifted off and
140 then re-amalgamated with Tarim due to the opening and closure of the South Tianshan
141 back-arc basins (Charvet et al., 2007; Lei et al., 2011; Ma et al., 2014; Gao et al., 2015;
142 Zhong et al., 2017).

143 The North Tianshan Belt (NTB) refers to the domain between the CTB to the

144 south and the East Junggar Belt to the north (Fig. 1b). This belt is predominantly
145 composed of Ordovician to Carboniferous volcano-sedimentary sequences **crosscut by**
146 **Paleozoic granitoids** (XBGMR, 1993). It is considered as a Paleozoic arc system
147 formed by southward subduction of the Kalamaili Ocean (Xiao et al., 2004; Yuan et
148 al., 2010; Xie et al., 2016c), and/or by northward subduction of the North Tianshan
149 Ocean (Ma et al., 2015; Zhang et al., 2018; Du et al., 2018a; Han and Zhao, 2018;
150 Chen et al., 2019). The NTB is further divided into three sub-units, i.e., the
151 Harlik-Dananhu Arc, Bogda Arc and Kangguer-Yamansu Arc (e.g., Xiao et al., 2004)
152 unconformably covered by the Mesozoic-Cenozoic Turpan-Hami Basin (Fig. 1b;
153 XBGMR, 1993).

154 The Harlik-Dananhu Arc occurs on both north and south sides of the
155 Turpan-Hami Basin, either formed by the breakup of a single arc due to intra-arc
156 rifting (Xiao et al., 2004; Ma et al., 2015) or resulted from southward migration of the
157 magmatic front **that generated the Harlik and Dananhu arcs successively** (Sun, 2007).
158 The Bogda Arc is generally interpreted as a Carboniferous magmatic arc and Permian
159 post-collisional magmatic belt (Shu et al., 2011; Chen et al., 2011; Xie et al., 2016a;
160 Wali et al., 2018), although some authors suggested **a Carboniferous to Permian rift**
161 (Gu et al., 2000, 2001; Xia et al., 2008, 2012). The Kangguer-Yamansu Arc is a late
162 Paleozoic arc/fore-arc system (Xiao et al., 2004; Han and Zhao, 2018) **reworked by**
163 **Permian intracontinental dextral ductile shear zone** (Wang et al., 2008, 2014a;
164 Branquet et al., 2012; Zhu et al., 2019).

165 2.2. Geological background of the Harlik Range

166 The Harlik Range (or Harlik Arc) is situated between the Turpan-Hami Basin to
167 the south and the East Junggar Belt to the north (Fig. 1b). The oldest stratigraphic unit
168 is the Ordovician Huangcaopo Group, which occurs along the northern foot of the
169 Harlik Range. It mainly consists of weakly metamorphosed marine clastic rocks and
170 tuffs (Ma et al., 1997; Chen et al., 2014). The Silurian strata are barely exposed in the
171 Harlik Range (XBMGR, 1993; Sun, 2007). Ordovician-Silurian (470-420 Ma)
172 intrusions in the Harlik Range mostly belong to calc-alkaline or tholeiitic series and
173 show typical subduction-related geochemical features associated with mantle-like
174 whole-rock $\epsilon_{\text{Nd}}(t)$ and zircon $\epsilon_{\text{Hf}}(t)$ values (Ma et al., 2015; Wang et al., 2016, 2018b;
175 Du et al., 2018a; Han and Zhao, 2018).

176 The Devonian strata, according to regional facies correlation, are mainly
177 composed of volcanic rocks, carbonates and siliciclastic rocks (XBGMR, 1993). The
178 Lower Devonian Dananhu Formation is distributed along the southern Harlik Range
179 and the southern margin of the Turpan-Hami Basin (Fig. 1c). The Middle Devonian
180 Tousuquan Formation is recognized along the ridge of the Harlik Range. Some
181 rhyolites from this formation, however, yielded zircon U-Pb ages of 469 ± 9 Ma (Li et
182 al., 2017) and were intruded by granitoids dated at 446 ± 3 Ma to 448 ± 7 Ma (Cao et
183 al., 2006; Liu et al., 2017), indicating that some rocks in the Tousuquan Formation
184 should be assigned to the Ordovician. Meanwhile, Upper Devonian sediments are rare

185 in the Harlik Range and thus were poorly investigated.

186 The Carboniferous strata can be divided into lower and upper units. The lower
187 unit includes the Jiangbasitao and Xiaorequanzi formations, which mainly consist of
188 volcanoclastic and volcanic rocks (XBMGR, 1993). The upper unit, previously named
189 as Julideneng Formation, is distributed along the southern foot of the Harlik Range
190 and is mainly composed of tuffs, sandstones and tuffaceous sandstones (Sun, 2007).
191 However, to the north of the Qincheng Town, some of these rocks were
192 metamorphosed into greenschist to amphibolite facies (Zhao et al., 1997; Zhou, 2004;
193 Sun, 2007) and their protoliths ages and timing of metamorphism remain unclear. In
194 this study, we separate these metamorphic rocks from the Julideneng Formation and
195 call them as the Julideneng metamorphic complex (JMC). The Carboniferous
196 calc-alkaline diorites and granites from the Harlik Range were formed at 320-300 Ma.
197 These granitoids were likely emplaced during the tectonic transition from
198 convergence to extension (Sun et al., 2005; Song et al., 2018; Zhu et al., 2018).

199 The Lower Permian strata, unconformably overlying the pre-Permian rocks, are
200 mainly composed of terrestrial conglomerates, sandstones and siltstones intercalated
201 with volcanic rocks (Sun, 2007; Shu et al., 2011; Chen et al., 2014). The Permian
202 granitoids are transitional from calc-alkaline to alkaline and yielded zircon U-Pb ages
203 of 298-280 Ma (Wang et al., 2009c; Yuan et al., 2010; Chen et al., 2016). They are
204 usually associated with coeval mafic dykes, both were formed in an extensional or
205 transtensional setting (Gu et al., 1999; Wang et al., 2009c; Yuan et al., 2010; Chen et

206 al., 2016).

207 **3. Field geology and sample descriptions**

208 Our field investigations were conducted along a section from Qincheng Town to
209 Xiaopu Village, southern Harlik Range (Fig. 2a-b). The southern part of the section is
210 dominated by schistose tuffs, sandstones and tuffaceous sandstones belonging to the
211 Upper Carboniferous Julideneng Formation. The northern part of this section consists
212 of middle Devonian sandstones, tuffaceous sandstones and limestones, which were
213 silicified and crosscut by numerous diabase dykes showing NE-SW or nearly E-W
214 strikes (Fig. 2b; XBGMR, 1966; Sun, 2007). The central part is a NW-SE-striking belt
215 of >30 km long and ~10 km wide (Fig. 2a-b; Zhao et al., 1997, 2002; Sun, 2007), this
216 belt is made of metamorphic rocks of the Julideneng metamorphic complex (JMC),
217 including low-grade meta-sandstones, andalusite schists, garnet-sillimanite
218 micaschists and migmatites (Zhao et al., 1997; Zhou, 2004; Sun, 2007).

219 In the southern part of the JMC, the sedimentary rocks were weakly deformed
220 and slightly metamorphosed. The bedding (S0) can be easily recognized and cleavage
221 (S1) is well developed, both dip to the northeast with S1 steeper than S0 (Figs. 2b-c
222 and 3a), indicating a normal sequence. Further northwards, S0 is gradually transposed
223 into sub-vertical schistosity with increasing metamorphic grade (Sun, 2007). A
224 migmatite zone of ~1 km wide occurs in the northern part of the JMC. Migmatites are
225 typically flow-folded (Sawyer, 2008) and contain centimeter-thick, garnet-bearing

226 leucocratic dykes. They display all the intermediates between folded and boudinaged
227 leucosome ribbons, foliated (orthogneissic) sills and slightly foliated crosscutting
228 dykes. Leucosomes are surrounded by melanosomes with biotite-rich boundaries and
229 restites of meta-sandstone (Fig. 3b). Foliation in the migmatites is roughly in
230 accordance with that in the surrounding meta-sedimentary rocks (Fig. 3c).
231 Flow-folded migmatites and slightly folded small-scale garnet-bearing leucocratic
232 dykes (Fig. 3b and 3d) indicate a continuum from pre- to late-tectonic in situ partial
233 melting and short-distance transport of anatectic melts. A progressive lateral change
234 from quartzites, schists and crinoidal limestone into migmatites can be observed to the
235 west of the main road, and restites of quartzite and limestone (changed into
236 calc-silicate) locally occur in migmatites.

237 The southwestern border of the migmatite zone is in fault contact with weakly
238 deformed meta-sandstones (Figs. 2c and 3e). The fault zone, ~5-10 meters in width,
239 was strongly sheared with schistosity/cleavage dipping 70-75° to the south.
240 Considering the difference in metamorphic grade, there was probably a bulk
241 normal-fault motion (Fig. 2c). In addition, the complex deformation of the fault zone
242 likely suggests a polyphase motion. The northern side of the migmatite zone was
243 crosscut by a coarse-grained K-feldspar granite dated at 297 ± 2 Ma (zircon U-Pb age;
244 Chen and Shu, 2010). To the north, the granite is in fault contact with low-grade
245 meta-sedimentary rocks of the Middle Devonian Tousuquan Formation (Fig. 2b-c).
246 The boundary is an E-W-striking mylonite zone dipping steeply to the north, which

247 bears a down-dip stretching lineation. Kinematic indicators in ductilely deformed
248 granites are consistent with a normal-fault motion. Therefore, the high-grade
249 migmatite zone appears in a kind of horst or pop-up structure surrounded by
250 lower-grade meta-sedimentary rocks. Late Carboniferous-early Permian (zircon U-Pb
251 ages of 316-295 Ma) undeformed granodiorite, biotite granite, leucogranite as well as
252 numerous NE-striking pegmatite and mafic dykes crosscut and thus post-date the
253 metamorphic belt (Wang et al., 2009c; Chen and Shu., 2010; Song et al., 2018; Zhu et
254 al., 2018). In addition, the meta-sedimentary rocks yielded Early Permian muscovite
255 and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages ranging from 301 to 277 Ma (Sun, 2007).

256 In order to constrain the age and provenance of the meta-sedimentary rocks,
257 and the timing of the migmatization, six representative samples were collected from
258 the JMC. Three micaschist samples (12TS119A, B, E) were taken from the migmatite
259 zone (Fig. 2c). The sample 12TS119A is composed of quartz (45-50 vol. %), biotite
260 (20-25 vol. %), plagioclase (10-15 vol. %), muscovite (5-10 vol. %) and a small
261 amount of sillimanite. The sample 12TS119B is a mylonitized micaschist and mainly
262 consists of quartz (30-35 vol. %), biotite (20-25 vol. %), muscovite (30-35 vol. %)
263 and plagioclase (5-10 vol. %). Another slightly altered sample 12TS119E is composed
264 of quartz (30-35 vol. %), chloritized biotite (20-25 vol. %), muscovite (10-15 vol. %),
265 sericite (20-25 vol. %) and minor sillimanite (< 5 vol. %). In these micaschists, the
266 preferred orientation of biotite and/or muscovite and elongated quartz grains define
267 well-developed foliations (Fig. 4a-c).

268 One sample (12TS119F; Fig. 2c) was collected from the meta-sandstones that
269 are in fault contact with the migmatites (Fig. 3e). This meta-sandstone is mainly
270 composed of quartz (60-70 vol. %), chloritized mica (10-15 vol. %) and plagioclase
271 (15-20 vol. %). The chloritized micas are weakly oriented and define an almost
272 unnoticeable foliation due to the fine-grain and equidimensional shape of quartz and
273 plagioclase (Fig. 4d). Undulose extinction and bulging dynamic recrystallization of
274 quartz (Fig. 4a-d) indicate ductile deformation of these meta-sedimentary rocks under
275 moderate temperature conditions.

276 Two samples were taken from migmatitic gneissic-granite (12TS119G) and
277 migmatite leucosome (12TS119H) (Fig. 3d). Both of them are mainly composed of
278 quartz (40-45 vol. %), K-feldspar (25-30 vol. %), plagioclase (20-25 vol. %) and
279 minor muscovite and biotite (Fig. 4e-f). The migmatitic gneissic-granite shows a clear
280 foliation defined by the preferred orientation of micas and elongated quartz ribbons
281 (Fig. 3c). The feldspar and quartz exhibit lattice bending, subgrains, undulose
282 extinction and deformation bands, suggesting that these grains accommodated
283 intracrystalline plastic deformation by dislocation creep (Fig. 4e; Gower and Simpson,
284 1992; Hirth and Tullis, 1992; Passchier and Trouw, 2005). In addition, typical
285 chessboard subgrains in quartz and lobate grain boundaries between quartz and
286 feldspar indicate high-temperature ductile deformation (Gower and Simpson, 1992;
287 Kruhl, 1996; Stipp et al., 2002). By contrast, the migmatite leucosome (12TS119H)
288 shows nearly equant and diamond-shaped quartz crystals enclosed by optically

289 continuous K-feldspar (Fig. 4f), indicating that quartz crystallized from anatectic
290 melts before K-feldspar crystallized from the remaining melts (Sawyer, 2008).
291 Undulose extinction and recrystallization by grain boundary migration of quartz (Fig.
292 4f) suggest localized high-temperature ductile deformation.

293 4. Analytical methods

294 All samples were crushed and milled into powders, from which zircon grains
295 were separated by heavy liquid and magnetic separation, and finally handpicked under
296 a binocular microscope fitted with a UV light. Selected zircon grains were mounted in
297 epoxy, polished to about half of their thickness, and then coated with gold.
298 Cathodoluminescence (CL) images of zircons were obtained at the State Key
299 Laboratory for Mineral Deposits Research (SKL-MDR), Nanjing University, using a
300 Quanta 400 FEG scanning electron microscope equipped with a Gatan mini-CL
301 detector (Mono CL3+).

302 U-Pb dating and trace elements analysis of representative zircons were
303 conducted in two laboratories. The samples 12TS119A and 12TS119B were dated at
304 the SKL-MDR of Nanjing University using Agilent 7500a inductively coupled plasma
305 mass spectrometry (ICP-MS) coupled to a New Wave 193 nm laser ablation system
306 with an in-house sample cell. The detailed analytical procedures are similar to those
307 described in Jackson et al. (2004) and Liu et al. (2014). The U-Pb dating and trace
308 elements analyses of zircons from samples 12TS119E, 12TS119F, 12TS119G and

309 12TS119H were carried out at the State Key Laboratory of Geological Processes and
310 Mineral Resources, China University of Geosciences (Wuhan), where laser sampling
311 was performed using a GeoLas 2005 System and an Agilent 7500a ICP-MS
312 instrument was used to acquire ion-signal intensities. The detailed operating
313 conditions and analytical procedures are described in Liu et al. (2008, 2010a, 2010b).

314 For zircon crystals older than 1000 Ma, $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages were used to
315 plot relative probability diagrams considering large amounts of radiogenic Pb. For
316 zircon grains younger than 1000 Ma, $^{206}\text{Pb}/^{238}\text{U}$ apparent ages are more reliable due to
317 the low content of radiogenic Pb and low uncertainty of common Pb correction.
318 Uncertainties are quoted at 1σ for individual analysis and 2σ (with 95% confidence
319 level) for weighted mean ages, respectively. The results of U-Pb isotopic dating and
320 trace element compositions are listed in Supplementary Table S1 and Table S2,
321 respectively.

322 **5. Results**

323 *5.1. Meta-sandstone*

324 A total of 55 zircon grains were chosen for U-Pb dating from the weakly
325 metamorphosed sandstone sample 12TS119F. The CL images of all dated zircons
326 together with their ages are shown in Supplementary Fig. S1 and those of the
327 representative grains are presented in Fig. 5a. Most zircons have euhedral to

328 sub-euhedral shapes and show clear oscillatory zoning without or with narrow dark
329 rims, indicating original magmatic sources (Connelly, 2000; Corfu et al., 2003;
330 Hoskin and Schaltegger, 2003). A small group of zircons show stubby or sub-rounded
331 shapes and have complex core-rim textures, comprising irregular cores with blurry or
332 patchy zoning and structureless rims. This kind of zircons may have been produced by
333 modification of primary igneous zircons in response to metamorphism (Corfu et al.,
334 2003; Hoskin and Schaltegger, 2003; Rubatto, 2017). **The rest few zircons are**
335 **rounded and sector zoned or without zoning**, indicative of metamorphic origin (Figs.
336 5a and S1; Corfu et al., 2003; Hoskin and Schaltegger, 2003).

337 Forty-five out of fifty-five grains yielded concordant ages, a large majority of
338 which have ages < 540 Ma, with two major age peaks at 425 Ma (n = 14; 31.1%) and
339 445 Ma (n = 10; 22.2%), as well as a minor age peak at ca. 490 Ma. The Precambrian
340 zircons show sub-peaks at ~580 Ma, ~780 Ma, and in a range of 850-1000 Ma; only
341 two Mesoproterozoic grains (1280 Ma and 1372 Ma) **were identified (Fig. 6a-b; Table**
342 **S1)**. The remaining ten analyses yielded discordant ages (Fig. 6a) probably due to Pb
343 loss or disequilibrium of their isotopic systems (Connelly, 2000).

344 Twenty-three zircons with ages around 445-425 Ma were analyzed for rare earth
345 element (REE) compositions. Most grains are characterized by steeply-rising REE
346 patterns with remarkable positive Ce and negative Eu anomalies (Fig. 7a), together
347 with high Th/U ratios (mostly > 0.4) (Fig. 6b; Table S1), generally consistent with
348 typical magmatic zircons (Hoskin and Schaltegger, 2003; Rubatto, 2017). Only two

349 zircons (Nos. 38 and 51) display relatively higher LREE values and weaker Ce
350 anomalies in comparison to the other zircons, and their REE patterns (Fig. 7a) are
351 similar to those of **hydrothermal zircons** (Hoskin, 2005).

352 5.2. *Micaschists*

353 From three micaschist samples, a total of 192 zircon grains were analyzed, which
354 show various sizes, sub-rounded to sub-euhedral shapes and complicated internal
355 textures (Figs. 5 and S1). According to their CL images, four types of zircons can be
356 recognized. (1) Type 1 zircons have core-rim textures in which the cores are bright
357 with oscillatory zoning and the rims are relatively dark and un-zoned, corresponding
358 to originally magmatic zircons surrounded by metamorphic overgrowths (Hoskin and
359 Schaltegger, 2003). (2) Type 2 zircons also show core-rim textures with bright
360 un-zoned cores, **which could be originally metamorphic then subjected to secondary**
361 **metamorphic or hydrothermal overgrowth**. Alternatively, they could also be originally
362 magmatic but were intensively “reworked” (via solid-state recrystallization or local
363 dissolution-reprecipitation) by the subsequent metamorphism or alteration so that the
364 original magmatic oscillatory zoning was totally erased. In the latter case, the
365 overgrowth rims may have formed synchronously with the reworking of the cores or
366 even reflect a later metamorphic and/or hydrothermal event (Hoskin and Schaltegger,
367 2003). (3) Type 3 zircons have homogeneous dark to black CL images without visible
368 oscillatory zoning, likely formed by metamorphism or hydrothermal activities

369 (Connelly, 2000; Corfu et al., 2003; Hoskin and Schaltegger, 2003). (4) Type 4
370 zircons are characterized by prismatic shapes and moderately bright CL images with
371 clearly concentric magmatic oscillatory zoning, without visible overgrowths.

372 In order to obtain sufficiently representative zircon populations, all four types of
373 zircons from each sample were analyzed. Most analyses plot on or close to the
374 Concordia, but a few zircons show remarkable discordance, especially for the sample
375 12TS119E (Fig. 6c, e and g). One reason for discordant ages can be Pb loss due to
376 metamorphic or hydrothermal alteration. In addition, analytical mixing between two
377 parts of zircons with different origins (e.g., older cores and younger rims) is also
378 highly possible as some of the discordant zircons with core-rim texture are quite small
379 (Fig. S1). The geological meaning of the discordant ages is ambiguous; therefore,
380 they are excluded from further discussion and only concordant ages (concordance >
381 90%) are considered.

382 For the micaschist sample 12TS119A, fifty-eight out of sixty dated zircons
383 yielded concordant ages (Fig. 6c) ranging from 313 to 2175 Ma. They show a
384 dominant age peak at 477 Ma (n = 19; 32.8%), two younger age peaks at 322 Ma (n =
385 4; 6.9%) and 414 Ma (n = 4; 6.9%), and other populations of 500-550, 600-750,
386 850-1000, 1100-1500, 1600-1800 and 2175 Ma (Fig. 6d). The youngest nine ages
387 (peaked at 322 and 414 Ma) (Fig. 6d; Table S1) are obtained exclusively from type 2
388 zircons with Th/U ratios mostly lower than or near 0.4 (Table S1; Fig. 6d), showing
389 bright or dark cores characterized by surface-controlled alteration (Corfu et al., 2003)

390 and encircled by thin and dark rims (Figs. 5b and S1). Zircons defining the major age
391 peak of 477 Ma mainly belong to the **type 1 and type 2**, and show Th/U ratios higher
392 than 0.4 (Table S1; Figs. 5b, 6d and S1). The other older zircons cover **types 1 and 2**,
393 and have variable Th/U ratios mostly higher than 0.4 (Figs. 6d and S1).

394 Sixty zircons were dated for the micaschist sample 12TS119B and all of them
395 yielded concordant ages (Fig. 6e). **Their age populations** are very similar to those of
396 the sample 12TS119A (Fig. 6f). Therein, three youngest zircons (380-413 Ma) belong
397 to the type 3 displaying homogeneous dark to black CL images (Figs. 5c and S1) and
398 Th/U ratios around 0.4 (Table S1; Fig. 6f). Twenty zircons (33.3%) of type 1 and
399 minor **type 2 and type 4** (Figs. 5c and S1) define an age peak at 477 Ma and show
400 Th/U ratios mostly higher than 0.4 (Fig. 6f; Table S1). Other ages around 500-550,
401 600-750, 850-1000, 1100-1500, 1600-1800 and 2200-2500 Ma (Fig. 6f) were
402 obtained from zircons of all four types, most of which show Th/U ratios higher than
403 0.4 (Table S1).

404 As for the sample 12TS119E, sixty-one out of seventy-two zircons provided
405 concordant ages ranging from 346 to 1765 Ma (Fig. 6g-6h). A major age peak at 475
406 Ma (n = 11; 18.0%) and a minor age peak at 425 Ma (n = 5; 8.2%) are mainly defined
407 by types 1 and 2 zircons (Figs. 5d and S1), which mostly show Th/U ratios higher
408 than 0.4 (Fig. 6h; Table S1). These zircons show steeply-rising REE patterns,
409 remarkable positive Ce anomalies and negative Eu anomalies (Fig. 7b). Thus, these
410 ages are indicative of magmatic events (Hoskin and Schaltegger, 2003; Hoskin, 2005).

411 One exceptional zircon (No. 57; ~424 Ma) shows a quite high Th/U ratio (2.93; Table
412 S1). For some unclear reasons, a **V-shaped REE pattern** due to its high LREE content
413 is similar to that of some “hydrothermal” zircons (Fig. 7b). Five zircons of types 2
414 and 3 with dark, homogenous CL images (Figs. 5d and S1) yielded ages from 346 to
415 402 Ma, they display gently-rising REE patterns with weak Ce anomalies and Th/U
416 ratios mostly lower than 0.4 (Figs. 6h and 7b), similar to zircons of hydrothermal
417 origin (Fig. 7b). With only a few exceptions, the other age populations (500-550,
418 600-800, 850-1000, 1100-1400 and 1600-1800 Ma) correspond to all four zircon
419 types (Fig. 6g-6h) with Th/U ratios mostly higher than 0.4 (Fig. 6h; Table S1).

420 5.3. Migmatites

421 For two migmatite samples, a total of 38 analyses were conducted on 36 zircons.
422 Their CL images and ages are shown in **Fig. 8**. Almost all the dated zircons are
423 euhedral to sub-euhedral with prismatic shapes, they have clear oscillatory zoning
424 (Fig. 8) and their Th/U ratios are mostly higher than or close to 0.4 (Table S1),
425 suggesting a magmatic origin.

426 Out of twenty analyses on zircons from the migmatitic gneissic-granite
427 12TS119G, thirteen concordant ages form **two age peaks** at 297.4 ± 2.1 Ma ($n = 8$;
428 61.5%; MSWD = 0.26) and 322.2 ± 2.3 Ma ($n = 5$; 38.5%; MSWD = 0.066) (Fig. 8c
429 and 8e). Seven zircons yielded discordant ages (Fig. 8c; Table S1) **that are not**
430 **considered in the following discussion.**

431 Eighteen zircons were dated for the migmatite leucosome sample 12TS119H and
432 fifteen analyses yielded concordant ages (Fig. 8d), **defining comparable two age**
433 **groups** of 297.1 ± 2.7 Ma ($n = 4$; 26.7%; MSWD = 0.13) and 322.5 ± 2.1 Ma ($n = 8$;
434 53.3%; MSWD = 0.13) (Fig. 8f). Three zircons (Nos. 6, 10 and 16) yielded older and
435 probably inherited ages of 338-365 Ma (Fig. 8d). The remaining three zircons (Nos. 2,
436 5 and 15) with discordant ages have been rejected.

437 The dated concordant zircons from these two samples were further analyzed for
438 REE compositions. The results show steeply-rising Chondrite-normalized REE
439 patterns characterized by enrichment of HREE relative to LREE, mostly positive Ce
440 anomalies and negative Eu anomalies (Fig. 7c and 7d), in accord with an igneous
441 origin. Only two zircons (Nos. 15 and 16) in sample 12TS119G have slightly different
442 REE patterns with relatively higher LREE values and weaker Ce anomalies than
443 typical magmatic zircons (Fig. 7c).

444 **6. Discussion**

445 *6.1. Protoliths depositional and metamorphic ages of the meta-sedimentary rocks*

446 The most remarkable age population of detrital zircons from the meta-sandstone
447 and micaschists lies in the 540-420 Ma interval. The micaschists have dominant peaks
448 of 477-475 Ma, while the meta-sandstone shows a peak at 425 Ma that resembles a
449 minor peak of the micaschist 12TS119E (Fig. 6). Since these detrital zircons are

450 mostly of magmatic origins, their ages constrain the maximum depositional ages for
451 the protoliths of meta-sedimentary rocks. The metamorphic ages at 322 Ma and 297
452 Ma provide a constraint on the minimum sedimentary age (see discussion below).
453 Thus, the deposition of protoliths of the meta-sedimentary rocks may have occurred
454 between 425 Ma and 322 Ma. The maximum deposition age is also defined as >320
455 Ma by the crosscutting granite dated at 320 ± 3 Ma (Song et al., 2018).

456 Zircons of ~480-420 Ma from sillimanite micaschists generally exhibit dark rims,
457 whereas detrital zircons of ~425 Ma from the meta-sandstone usually show no
458 overgrowth (Figs. 5 and S1). This indicates that zircons from high-grade micaschists
459 were significantly reworked by metamorphism, in contrast to the low-grade
460 meta-sandstone. Such reworking may also account for the occurrence of discordant
461 detrital zircons in the meta-sedimentary rocks (Fig. 6), most likely due to incomplete
462 metamorphic reset.

463 The youngest zircon group (~420-320 Ma) from the micaschists, displaying
464 diagnostic features of metamorphic and/or hydrothermal zircons, has no equivalent in
465 the meta-sandstone. Therefore, the younger ages suggest partial or total overprint
466 during amphibolite facies metamorphism, although it cannot be excluded that some of
467 them were originally (pre-sedimentation) metamorphic. The metamorphism likely
468 occurred at ~322 Ma, which is the youngest age peak of metamorphic zircons. The
469 older ages (420-322 Ma) possibly resulted from age mixing between primary cores
470 and recrystallized areas or overgrowths (Corfu et al., 2003).

471 The two migmatite samples yielded exactly identical age peaks at 322 Ma and
472 297 Ma (Fig. 8). Both **zircon groups** show clear concentric oscillatory zonings, high
473 Th/U ratios and steeply-rising REE patterns, **indicative of magmatic origin** (Fig. 8;
474 Table S1). Thus, these two ages represent two distinct episodes of zircon
475 crystallization. **Although zircons from both groups generally show similar**
476 **morphologies and internal textures, some 322 Ma grains have thin dark rims (Fig.**
477 **8a-b), which may correspond to overgrowth during the second episode of**
478 **crystallization at ~297 Ma.** This is also confirmed by (1) the occurrence of thin dark
479 rims surrounding the **inherited zircons** of 338 Ma, 342 Ma and 365 Ma (Fig. 8a-8b),
480 and (2) **conspicuous dark rims** and zoning-controlled alteration developed in
481 discordant zircons (Fig. 8a-b).

482 **Regional tectonics, metamorphism, and migmatization have close spatial and**
483 **temporal relationships with peraluminous leucogranite genesis (e.g., Barrow, 1893;**
484 **Vernon, 1982; Barton and Hanson, 1989; Okay et al., 2014). Late Paleozoic granite**
485 **plutons (Figs. 2b and 9) occurred in two episodes at 330-310 Ma and 305-290 Ma**
486 **(Sun et al., 2007b; Wang et al., 2009c; Chen and Shu, 2010; Chen et al., 2016; Song et**
487 **al., 2018), which fit the two zircon age peaks of zircons from migmatites (322 Ma and**
488 **297 Ma) (Figs. 8 and 9). Moreover, the age of the first episode of granitic magmatism**
489 **is also consistent with the youngest age peak (322 Ma) of “metamorphic” zircons of**
490 **the micaschists (Fig. 9b). Therefore, ~322 Ma can be reasonably interpreted as the**
491 **timing of amphibolite facies metamorphism, migmatization and the first episode of**

492 magmatism. As the migmatites also contain zircons of ~297 Ma, it is likely that
493 anatectic melts were not totally crystallized at ~322 Ma probably due to high thermal
494 gradient or continuous addition of melts until ~297 Ma in connection with the second
495 episode of granitic magmatism, giving birth to the crystallization of the younger
496 zircons, while some zircons of ~322 Ma were preserved. Finally, leucogranite dykes
497 of ~308 Ma contain a few inherited zircons with 320-330 Ma ages (Zhu et al., 2018).
498 Such a genetic relationship between migmatites and granites is likely but needs to be
499 confirmed through detailed geochemical investigations.

500 It is also worth noting that mica $^{40}\text{Ar}/^{39}\text{Ar}$ apparent ages of the metamorphic
501 rocks range from 301 to 277 Ma and were considered as the timing of the
502 metamorphism in the Harlik domain (Sun, 2007). However, considering: (1) the
503 relatively low closure temperature of argon isotopic system of micas (Harrison et al.,
504 1985, 2009), (2) the occurrence of extensive Permian granitic plutons and their close
505 spatial relationships with meta-sedimentary rocks and migmatites, and (3) the good
506 match between mica $^{40}\text{Ar}/^{39}\text{Ar}$ apparent ages (301-277 Ma) and zircon U-Pb ages of
507 granites (305-290 Ma), we consider that mica $^{40}\text{Ar}/^{39}\text{Ar}$ apparent ages of
508 meta-sedimentary rocks most likely correspond to the timing of thermal reset and
509 final cooling event related to the second episode of magmatism.

510 6.2. Provenances of the meta-sedimentary rocks

511 The studied meta-sedimentary rocks contain both Paleozoic and Proterozoic

512 detrital zircons (Fig. 6). Among overall 224 concordant detrital zircons, 126 grains
513 (56%) yielded Paleozoic ages and 98 zircons (44%) yielded Proterozoic ages. For the
514 Paleozoic ages, as aforementioned, the U-Pb system of detrital zircons younger than
515 420 Ma was likely affected by post-depositional metamorphism. Thus, these zircons
516 and their ages should be rejected for provenance investigation. The Ordovician to
517 Silurian detrital zircons (~480-420 Ma with peaks at ~475, ~445 and ~425 Ma) are
518 dominant constituents in the meta-sedimentary rocks (Fig. 9b). **This is consistent with**
519 **the study of Sun et al. (2007a)** who found a predominant Ordovician to Silurian zircon
520 population (482-418 Ma) in low-grade sandstones from the study area.

521 As discussed above, the early Paleozoic zircons are mainly derived from
522 magmatic rocks. **Numerous early Paleozoic magmatic rocks of 440-450 Ma were**
523 **previously reported both in the Harlik and Dananhu arcs, while magmatic rocks of**
524 **420-430 Ma crop out in the Dananhu area only** (Cao et al., 2006; Ma et al., 2015;
525 Wang et al., 2016; Zhang et al., 2016a; Chen et al., 2017; Liu et al., 2017; Deng et al.,
526 2018; Du et al., 2018a; Wang et al., 2018b; Zheng et al., 2018; Chai et al., 2019). In
527 addition, very few **~475 Ma magmatic rocks** have been reported so far in the North
528 Tianshan, and only rhyolites of 469 ± 9 Ma were documented in the Harlik area (Li et
529 al., 2017). The angular to sub-angular early Paleozoic detrital zircons indicate short
530 distances of transportation (Sun et al., 2007a), while these samples are from the
531 Qincheng area that is situated between the Harlik Arc and Dananhu Arc; thus, it is
532 suggested that these early Paleozoic detrital zircons (~480-420 Ma) came from

533 magmatic rocks of the Harlik and Dananhu arcs.

534 Ordovician to Silurian arc-type magmatic rocks are also exposed in the Central
535 Tianshan and East Junggar-Altai belts (Fig. 10), which are potential sources for the
536 meta-sedimentary rocks. However, the North Tianshan was separated from East
537 Junggar-Altai belts before the early Carboniferous (>340 Ma) by the Kalamaili
538 oceanic basin (Li et al., 2009; Wang et al., 2009b; Huang et al., 2012; Zhang et al.,
539 2013; Xu et al., 2015a; Du et al., 2018b; Han and Zhao, 2018; Wang et al., 2019),
540 while the depositional age of protoliths of the meta-sedimentary rocks is roughly
541 constrained between ~425 to ~322 Ma. Therefore, the available data cannot
542 sufficiently prove or disprove that the East Junggar-Altai magmatic arcs might be
543 possible sources for the Ordovician to Silurian detrital zircons of the
544 meta-sedimentary rocks in the Qincheng area.

545 In addition, it is suggested that the North Tianshan (Harlik-Dananhu arcs) was
546 amalgamated with the Yamansu Arc and Central Tianshan Block at ~320-300 Ma
547 along the Kangguer shear zone after the closure of the Kangguer Ocean (e.g., Li, 2004;
548 Li et al., 2006; Zhang et al., 2020; Zhao et al., 2019). However, the rock sequences on
549 both sides of this shear zone are comparable and it might have been located within the
550 North Tianshan belt (Wang et al., 2008, 2014a; Branquet et al., 2012). According to
551 the studies on ophiolites of the North Tianshan Suture zone and Kangguer belt (Xu et
552 al., 2006a, 2006b; Chen et al., 2019), the North Tianshan (or Kangguer) Ocean
553 opened during the mid-late Carboniferous. Considering that the Precambrian zircons

554 most likely came from the Central Tianshan Block (see discussion below), it is
555 possible that the Central Tianshan Block also provided certain early Paleozoic detritus
556 for the sediments in the Qincheng area.

557 The main population of Proterozoic zircons in the meta-sedimentary rocks is the
558 Neoproterozoic group (550-1000 Ma) showing a peak at ~870 Ma and a subordinate
559 peak at ~780 Ma. Minor zircon populations of 1.1-1.5 Ga, 1.6-2.0 Ga, 2.1-2.3 Ga and
560 ~2.5 Ga with peaks at ~1.45 Ga and ~1.7 Ga are also recognized (Fig. 10a). However,
561 there is no Precambrian basement exposed in the NTB (Xiao et al., 2004; Zhang et al.,
562 2016b). These Proterozoic zircons were thus most likely transported from nearby
563 Precambrian-based continental blocks. Chen et al. (2014) suggested that the Harlik
564 Range is a part of the Tuva-Mongol-Altai Arc. Nevertheless, the available data
565 indicate that the Tuva-Mongol-Altai Arc and the East Junggar Belt both lack
566 magmatic events and detrital records in the ~1.35-1.45 Ga interval (Fig. 10d-e; Jiang
567 et al., 2011), which are common in the North Tianshan (Fig. 10a-b; Chen et al., 2014).
568 In contrast, a large quantity of Mesoproterozoic granitic rocks of ~1.40-1.45 Ga have
569 been documented in the Central Tianshan Block (Fig. 10c; Ma et al., 2012a; He et al.,
570 2014, 2015; Wang et al., 2014b, 2017; Huang et al., 2015). Moreover, the Central
571 Tianshan Block has a detrital zircon age spectrum similar to that of the Harlik Range
572 and the entire North Tianshan, they all display zircon populations of 750-800 Ma,
573 850-1000 Ma, ~1.45 Ga, 1.6-1.8 Ga and ~2.5 Ga. More importantly, the igneous rocks
574 in the Central Tianshan Block formed during ~800, ~900 Ma and ~1.45 Ga episodes,

575 identical with the **detrital zircon age peaks** of the meta-sedimentary rocks from the
576 Harlik Range, which are **absent** in the other neighboring units (Fig. 10). Therefore, the
577 Central Tianshan Block is the most probable provenance area for the Precambrian
578 detrital zircons in the studied meta-sedimentary rocks.

579 **The Precambrian zircons in the meta-sedimentary rocks are anhedral in shape and**
580 **show complex core-rim textures (Figs. 5 and S1), indicating that they were**
581 **multiple-cycled. Thus, these Precambrian zircons were probably transported from the**
582 **Central Tianshan Block to the North Tianshan Belt (Dananhu Arc) before the opening**
583 **of the North Tianshan (or Kangguer) Ocean, and thereafter re-transported into the**
584 **Harlik area. This is in agreement with the fact that zircon populations of Devonian**
585 **flyschs in the Dananhu Arc are comparable with that of the Central Tianshan Block**
586 **(Wang et al., 2019). However, due to uncertainty on their deposition age, these zircons**
587 **could have been transported directly from the Central Tianshan Block as well.**

588 Clastic sediments derived from orogens are generally a mixture of multifarious
589 detritus from metamorphic, sedimentary and igneous rocks (e.g., Han et al., 2017).
590 Mixing and preferential elimination of certain zircons during transport can
591 significantly modify zircon populations in sediments, especially in old
592 multiple-cycled populations (Hay and Dempster, 2009; Han et al., 2017). Therefore,
593 comparison of detrital zircon populations must be undertaken with much care. In the
594 present case, provenance from the Central Tianshan Block is most likely, but
595 considering the limited size of the database, other provenances cannot be completely

596 excluded.

597 *6.3. Implications for the late Paleozoic tectonic evolution of the North Tianshan belt*

598 Our new zircon U-Pb data indicate that the meta-sediments from the JMC were
599 deposited in the interval between late Silurian and late Carboniferous. The
600 predominant early Paleozoic detrital zircons were potentially derived from both the
601 Harlik and Dananhu arcs. In combination with the low maturity of the meta-sandstone
602 that suggests a near-source deposition (Sun et al., 2007a), an intra-arc basin
603 (Qincheng or Xiaopu basin; Zhao et al., 1997) located between these arcs can be
604 suggested (Fig. 11A). In addition, the Precambrian zircons in the meta-sedimentary
605 rocks were probably derived from the Central Tianshan Block. As a result, the North
606 Tianshan was likely connected with the northern margin of the Central Tianshan
607 Block before the Carboniferous. The North Tianshan was rifted from the Central
608 Tianshan Block in the mid-late Carboniferous (Xu et al., 2006a, 2006b; Chen et al.,
609 2019) due to the opening of the North Tianshan (or Kangguer) Ocean, and was
610 thereafter re-amalgamated to the Central Tianshan Block during the latest
611 Carboniferous (Han et al., 2010; Zhang et al., 2015b, 2020) (Fig. 11B-D).

612 As discussed above, the amphibolite-facies metamorphism and migmatization
613 occurred at ~322 Ma. According to Sun (2007) and our field observations, the
614 garnet-sillimanite-bearing meta-sedimentary rocks are most likely the source rocks of
615 the migmatites and associated felsic dykes. The N-dipping foliations that bear

616 ~NW-SE stretching lineation resulted from sinistral transtension (Sun, 2007). In
617 addition, the HT-LP metamorphism (Zhao et al., 1997) and migmatization are coeval
618 with the co-emplacement of undeformed high-K calc-alkaline I- and A-type granites
619 (320-316 Ma) that formed probably in an extensional setting (Song et al., 2018).
620 Similarly, in the nearby Bogda area, Carboniferous (350-315 Ma) volcanic rocks are
621 thought to have formed in an intra-arc (Zhang et al., 2017; Wali et al., 2018) or
622 back-arc extensional setting (Chen et al., 2013; Xie et al., 2016b). Taking all these
623 arguments into consideration, we suggest that the meta-sedimentary rocks and
624 migmatites are likely parts of the Harlik arc root, and the migmatization probably
625 occurred due to decompression partial melting in a continent-based intra-arc or
626 back-arc extensional setting (Fig. 11C).

627 The migmatites in the Harlik Range also recorded an event at ~297 Ma, which is
628 coeval with the widespread emplacement of undeformed post-orogenic K-feldspar
629 granites and leucocratic two-mica granites at 298-295 Ma (Wang et al., 2009c; Chen
630 and Shu, 2010). The occurrence of ductilely deformed granites along the northern
631 boundary of the metamorphic belt (Fig. 2b-c), and dip-slip (normal) stretching
632 lineation along the north-dipping mylonite zone (see section 3) indicate syn-kinematic
633 emplacement of granites. Therefore, the development of a large volume of latest
634 Carboniferous to earliest Permian post-orogenic granitoids (Wang et al., 2009c, 2009d;
635 Chen and Shu, 2010; Yuan et al., 2010; Chen et al., 2016), bimodal dyke swarms (Gu
636 et al., 1999) and nearly synchronous ductile normal faults correspond to the

637 exhumation of the metamorphic units under a regional post-orogenic extensional
638 regime and thus prominent crustal thinning (Fig. 11D). Final cooling at 301-277 Ma
639 revealed by mica $^{40}\text{Ar}/^{39}\text{Ar}$ apparent ages (Sun, 2007) indicates that these events
640 terminated during the Early Permian.

641 7. Conclusions

642 (1) Protoliths of the meta-sedimentary rocks from the Julideneng Metamorphic
643 Complex in the southern Harlik Range were originally deposited between the
644 latest Silurian and late Carboniferous (425-322 Ma).

645 (2) The Harlik-Dananhu magmatic arcs were likely the major sources for the
646 Ordovician to Silurian detrital zircons in the meta-sedimentary rocks, while the
647 Precambrian detrital zircons were most likely derived from the Central Tianshan
648 Block, although possible provenances from the East Junggar and Chinese Altai
649 cannot be excluded.

650 (3) High-grade metamorphism and migmatization occurred at ~322 Ma in the
651 southern Harlik Range probably related to continent-based intra-arc or back-arc
652 crust thinning. The orogenic events in the Harlik Range terminated before the
653 Early Permian.

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1336 **Figure and Table captions:**

1337 Fig. 1. (a) Tectonic sketch map of Eurasia showing the location of the Central Asian
1338 Orogenic Belt (modified from Sengör et al., 1993). (b) Sketch map of the northern
1339 Xinjiang area, NW China, showing tectonic subdivisions of the Chinese Tianshan
1340 (modified from Wang et al., 2014a). Abbreviations: NTB = North Tianshan Belt, CTB
1341 = Central Tianshan Belt, STB = South Tianshan Belt. (c) Geological map of the
1342 northeastern Tianshan Belt (modified from 1:1,000,000 scale geological map of the
1343 Chinese Tianshan and surrounding regions, after XGSC, 2007).

1344

1345 Fig. 2. (a) Geological map of the Harlik Range, North Tianshan (modified from
1346 1:200,000 scale geological map No. K-46-XI by XBGMR, 1966). (b) Detailed

1347 geological map of the Qincheng area, North Tianshan showing the metamorphic zone
1348 and sampling sites (modified from Sun, 2007). Dating results are from Sun, 2007;
1349 Chen and Shu, 2010. Abbreviations: Bt = Biotite Ar-Ar age, Mus = Muscovite Ar-Ar
1350 age, Zr = Zircon U-Pb age. (c) Cross-section of **the Julideneng Metamorphic Complex**
1351 **(JMC)** in the Qincheng area showing the occurrence of migmatites and sampling sites.
1352 Stereograms of the bedding and foliation are equal-area Schmidt net, lower
1353 hemisphere.

1354

1355 Fig. 3. Representative field photographs of meta-sedimentary rocks and migmatites in
1356 the Qincheng area, North Tianshan. (a) Weakly deformed and metamorphosed
1357 sandstone and siltstone. The cleavage S1 is steeper than the bedding S0 indicating a
1358 normal sequence. (b) Migmatite with leucosome (Leu), melanosome (Mel) and
1359 mesosome (Mes). (c) Parallel and consistent foliations in gneissic-granite and schist.
1360 (d) Migmatite with **irregular transition** between leucosome and melanosome. (e)
1361 **Faulted contact** between meta-sandstones and migmatites.

1362

1363 Fig. 4. Photomicrographs of metamorphic rocks and migmatites from the Qincheng
1364 area, North Tianshan. (a-c) Micaschists (12TS119A, B and E) showing preferred
1365 orientations of mica and sillimanite. (d) Meta-sandstone (12TS119F) with weak
1366 orientation of chloritized mica and tabular feldspar grains. (e) Cuspate and lobate
1367 grain boundaries between plagioclase and quartz with chessboard subgrains

1368 (12TS119G). (f) Optically continuous K-feldspar enclosing diamond-shaped quartz
1369 crystals in leucosome (12TS119H). Mineral abbreviations: Kf = K-feldspar; Bt =
1370 biotite; Chl = chlorite; Mus = muscovite; Pl = plagioclase; Qz = quartz; Sil =
1371 sillimanite.

1372

1373 Fig. 5. Cathodoluminescence images for representative zircons from meta-sandstone
1374 (12TS119F) and mica schists (12TS119A, B and E) showing their apparent $^{206}\text{Pb}/^{238}\text{U}$
1375 ages (<1000 Ma) or $^{207}\text{Pb}/^{206}\text{Pb}$ ages (>1000 Ma). **Four types of zircons can be**
1376 **recognized. See text for more explanations.** The CL images of all the dated zircons
1377 can be found in Supplementary Fig. S1.

1378

1379 Fig. 6. Concordia diagrams (a, c, e and g) and U-Pb age probability diagrams (b, d, f
1380 and h), and insets are plots of Th/U ratios vs. U-Pb age for detrital zircons from the
1381 meta-sedimentary rocks, southern Harlik Range.

1382

1383 Fig. 7. Chondrite-normalized REE patterns for detrital zircons from meta-sandstone
1384 12TS119F (a), mica schist 12TS119E (b), and two migmatites 12TS119G and
1385 12TS119H (c-d). Only the Paleozoic detrital zircons with $^{206}\text{Pb}/^{238}\text{U}$ ages between 425
1386 Ma and 475 Ma were analyzed for REE abundances. The grey shaded area is the REE
1387 composition of hydrothermal zircons (after Hoskin, 2005; Yang et al., 2014) and
1388 magmatic zircons of various igneous rocks (Belousova et al., 2002; Hoskin, 2005;

1389 Long et al., 2012a; Yang et al., 2014). Insets are plots of Th/U ratios against U-Pb age.

1390 Chondrite normalization values are from Sun and McDonough (1989).

1391

1392 Fig. 8. (a-b) Cathodoluminescence images showing $^{206}\text{Pb}/^{238}\text{U}$ apparent ages, (c-d)

1393 Concordia diagrams, and (e-f) U-Pb age probability diagrams for the zircons from the

1394 migmatites, Qincheng area, North Tianshan.

1395

1396 Fig. 9. (a) Compilation of zircon U-Pb ages for granites **crosscutting** the

1397 meta-sedimentary rocks of the Harlik area (data from Sun et al., 2007b; Wang et al.,

1398 2009c; Chen and Shu, 2010; Chen et al., 2016; Song et al., 2018). (b) U-Pb age

1399 spectra of Paleozoic zircons from the migmatites and meta-sedimentary rocks of the

1400 Qincheng area (this study), North Tianshan.

1401

1402 Fig. 10. Compilation of zircon U-Pb ages from the Qincheng area and neighboring

1403 tectonic units. The right columns show the age distributions of Precambrian zircons

1404 only. DZ: Detrital zircons from sedimentary rocks; IZ: Zircons from igneous rocks

1405 (Inherited zircons were excluded). All the reference data and corresponding literature

1406 are listed in Supplementary Table S2.

1407

1408 **Fig. 11. Tentative cartoon model for the Paleozoic tectonic evolution of the North**

1409 **Tianshan Belt and adjacent areas.**

1410

1411 Table 1. Sample description and analytical data summary.

1412

1413 Supplementary Fig. S1. Cathodoluminescence images for all the dated detrital zircons
1414 from the meta-sedimentary rocks, Qincheng area, North Tianshan.

1415

1416 Supplementary Fig. S2. Discrimination diagrams for magmatic and hydrothermal
1417 zircons of the meta-sedimentary rocks and migmatites (after Hoskin, 2005). (a, c, e
1418 and g) $(\text{Sm}/\text{La})_N$ (chondrite-normalized Sm/La ratio) vs. La (ppm) plots. (b, d, f and h)
1419 Ce/Ce^* (Ce anomaly) vs. $(\text{Sm}/\text{La})_N$ plots. Chondrite normalization values are from
1420 Sun and McDonough (1989).

1421

1422 Supplementary Table S1. LA-ICP-MS zircon U-Pb analytical results of the
1423 meta-sedimentary rocks and migmatites from the Qincheng area, North Tianshan.

1424

1425 Supplementary Table S2. REE abundances of representative zircons of
1426 meta-sedimentary rocks and migmatites from the Qincheng area, North Tianshan.

1427

1428 Supplementary Table S3. Compilations of zircon U-Pb ages from the Qincheng area,
1429 North Tianshan and the neighboring Central Tianshan, East Junggar, and Chinese
1430 Altai.

1 **Late Paleozoic tectonic evolution of the North Tianshan Belt: New**
2 **structural and geochronological constraints from meta-sedimentary**
3 **rocks and migmatites in the Harlik Range**

4
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18
19 **Abstract**

20 The North Tianshan Belt (NTB) formed by the subduction and accretion of the

21 Junggar Ocean is a key area for reconstructing the Paleozoic tectonic evolution of the
22 southern Central Asian Orogenic Belt (CAOB). Despite numerous studies ~~have been~~
23 ~~done~~, the interpretation of the late Paleozoic tectonic evolution of the NTB meets no
24 consensus yet. We conducted field investigations and LA-ICP-MS zircon U-Pb dating
25 on ~~the~~ metamorphic rocks ~~offrom~~ the ~~Upper Carboniferous Julideneng Formation~~
26 Julideneng Metamorphic Complex (JMC) in the Harlik Range, which is located
27 between the Turpan-Hami Basin to the south and the East Junggar Belt to the
28 north~~west~~. The metamorphic rocks are exposed in a NW-SE striking, ~10 km-wide
29 belt and mainly composed of migmatites, garnet-sillimanite mica schists, andalusite
30 schists, and low-grade meta-sandstones. Detrital zircons from the low-grade
31 meta-sandstone yielded ages of 1400-1250, 1000-850, ~780, ~580, ~490, ~445 and
32 ~425 Ma. Three mica ~~schists~~ contain zircon populations of 2500-2175, 1800-1600,
33 1500-1100, 1000-850, 800-500, ~475, ~425, 420-380, ~346 Ma, and a youngest age
34 peak at ~322 Ma. Two samples of leucocratic dykes in migmatites yielded comparable
35 age populations with two major peaks at 322 Ma and 297 Ma, which ~~may beare~~
36 interpreted as ~~the minimum age of youngest protolith~~ two stages of successive partial
37 melting and anatectic-anatexic magma melts crystallization ~~respectively~~. On the basis
38 of structural features, zircon textures and U-Pb ages, combined ed with ~~the already~~
39 published data, we propose that: (1) the meta-sedimentary rocks of the ~~Julideneng~~
40 FormationJMC were deposited ~~between~~ after 425 Ma and before 322 Ma (latest
41 Silurian to ~~early~~ Late Carboniferous); (2) the Precambrian detrital zircons in the

42 meta-sedimentary rocks were probably derived from the Central Tianshan Block,
43 which was once connected with the NTB; and (3) the ~~migmatisation~~ migmatization
44 and coeval granitic plutonism occurred at ~322-297 Ma (~~L~~ate Carboniferous), most
45 likely associated with crustal thinning ~~resulted from a continent-based~~ intra-arc or
46 back-arc setting ~~to or post-orogenic extension setting, a late to post-orogenic setting.~~

47

48 **Keywords:** Central Asian Orogenic Belt; East Junggar ~~Balkash Ocean~~; North
49 Tianshan (Tien Shan); accretionary orogeny; post-orogenic crustal thinning;
50 migmatization

51

52 1. Introduction

53 The Tianshan Orogen is located in the southernmost part of the Central Asia
54 Orogenic Belt (CAOB), which is one of the largest Phanerozoic orogenic systems on
55 the Earth (Şengör et al., 1993; Windley et al., 2007; Xiao et al., 2013; Safonova,
56 2017). It recorded the Paleozoic ~~subduction~~ consumption of the southern ~~domains of~~
57 ~~the~~ Paleo-Asian Ocean domains (i.e., the Junggar-~~Balkash~~ North Tianshan Ocean and
58 Paleo-Tianshan Ocean or Turkestan Ocean), successive accretion of ~~various tectonic~~
59 ~~units including~~ island arcs, accretionary wedges and microcontinents, ~~and~~ as well as
60 the final amalgamation/collision ~~of~~ between the Kazakhstan and Tarim blocks (e.g.,
61 Gao et al., 1998, 2009; Li ~~et al.~~, 2004, ~~2006, 2009~~; Xiao et al., 2004, 2013; Charvet et

62 al., 2007, 2011; [Han et al., 2011](#); ~~Wang et al., 2008, 2011a, 2018a; Han et al., 2014~~).
63 Deciphering the subduction-accretion processes ~~eses~~ of this belt is therefore helpful for a
64 better understanding of the Paleozoic evolution of the southwestern CAOB and
65 Phanerozoic Asia crustal growth (Han and Zhao, 2018; Huang et al., 2020).

66 Numerous studies on the Tianshan Orogen were conducted ~~through~~ focusing on
67 kinematic analysis (e.g., Charvet et al., 2007, 2011; Lin et al., 2009; Wang et al., 2010;
68 ~~2018a~~), characteristics of ophiolites geochemistry (e.g., Shu and Wang, 2003; Dong
69 et al., 2006; Xu et al., 2006a, ~~2006b~~, 2015a; ~~Shu et al., 2007~~; Wang et al., ~~2009b~~,
70 2011a, 2018a; Huang et al., 2012; Jiang et al., 2014), geochemistry of arc-related
71 magmatic rocks (e.g., Chen et al., 2013; Xie et al., 2016a, ~~2016b, 2016c~~; Zhang et al.,
72 2017; Wali et al., 2018) and post-collisional magmatism (e.g., Gu et al., 1999; ~~Shu et~~
73 ~~al., 2005, 2011~~; Wang et al., 2009a, 2014a; ~~Chen and Shu, 2010~~; Yuan et al., 2010;
74 Chen et al., 2011; Muhtar et al., 2020). Based on these results, various tectonic
75 models ~~have been~~ were proposed but no consensus ~~was~~ has been achieved (e.g., Gao et
76 al., 2009; Charvet et al., 2011; Xiao et al., 2013; ~~Wang et al., 2018a~~; Han and Zhao,
77 2018). The controversy arises ~~mainly about~~ over (1) the regional correlation of various
78 magmatic arcs, and (2) the timing of the final amalgamation of the Tianshan Orogen.
79 Late Paleozoic magmatic arcs were diversely correlated with the subduction of the
80 South Tianshan Ocean, the Junggar-North Tianshan Ocean and the Kalamaili Ocean
81 (e.g., Xiao et al., 2004, 2013; Charvet et al., 2007, 2013; Han and Zhao, 2018). The
82 ~~end~~ termination of accretion was controversially estimated to be Devonian-early

83 Carboniferous (Xia et al., 2002, 2012; Ma et al., 2015), late Carboniferous-early
84 Permian (Gao et al., 1998, 2009; Charvet et al., 2007, 2011; [Han et al., 2010, 2011;](#)
85 [Wang et al., 2010, 2014a, 2018a;](#) [Han et al., 2010, 2011;](#) Han and Zhao, 2018), or
86 end-Permian to mid-Triassic (Xiao et al., 2009; Chen et al., 2020).

87 The Harlik Range is ~~located in~~ the northeastern part of the Tianshan Orogen ~~and~~
88 [where the latter](#) connects with the East Junggar Belt ~~to the northeast;~~ ~~thus,~~ ~~it~~ It is a key
89 area for unraveling the tectonic evolution of the Tianshan Orogen (Xiao et al., 2004;
90 Huang et al., 2018). The tectonic setting and evolution of the Harlik Range remain a
91 matter of debate. Xia et al. (2002, 2012) proposed that it underwent intra-continental
92 rifting in Carboniferous to Permian time; while some other authors suggested a
93 volcanic arc setting during the Ordovician-Carboniferous (Xiao et al., 2004; [Ma et al.,](#)
94 [2015;](#) [Du et al., 2018a](#) [Han and Zhao, 2018](#)). Additionally, Sun (2007) proposed that it
95 experienced an Ordovician-Silurian arc and a Devonian-Carboniferous back-arc
96 extension.

97 Meta-sedimentary rocks and migmatites are well exposed in the southern Harlik
98 Range (Fig. 2b), they may provide key evidence for the Paleozoic tectonic evolution
99 of the North Tianshan Belt. However, these metamorphic rocks were poorly studied.
100 They were ever considered as late Carboniferous in age (XBGMR, 1966; Sun et al.,
101 2007a), but the depositional ages of their protoliths were not well constrained (Cao et
102 al., 2009). Furthermore, the timing and tectonic setting of the metamorphism were
103 diversely interpreted as ~~(+i)~~ two-stage regional metamorphism associated with

104 Carboniferous intra-arc rifting and Permian collision, ~~respectively~~ (Zhao et al., 1997);
105 (~~iii~~) contact metamorphism during the Carboniferous and Permian magmatism (Zhou
106 et al., 2004); or (~~iiii~~) Permian dynamic metamorphism ~~under~~ during post-collisional
107 extension ~~_setting_~~ (Sun, 2007).

108 In this study, we present new field structural observations and zircon
109 LA-ICP-MS U-Pb ages ~~for~~ of the meta-sedimentary rocks and migmatites from the
110 Harlik Range. These new results combined with ~~the~~ already previously ~~previous~~
111 studies published data allow us to better constrain the ~~depositional and metamorphic~~
112 age timing of of protoliths deposition and metamorphism of these ~~metamorphic~~
113 meta-sedimentary rocks, to discuss the provenance ~~s~~ of the ~~meta-sedimentary~~
114 ~~rocks~~ sediments, and to ~~decipher the significance of the~~ tentatively replace the
115 high-temperature metamorphism and anatexis and regarding in the framework of the
116 late Paleozoic tectonic evolution of the North Tianshan Belt.

117 **2. Geological background**

118 *2.1. Regional tectonic framework*

119 The Chinese segment of the Tianshan Orogen is geographically divided into
120 eastern and western parts along the Urumqi-Korla roadline. The eastern Chinese
121 Tianshan is further divided into three tectonic units as: the South Tianshan, Central
122 Tianshan and North Tianshan belts ~~belts~~ (Fig. 1b; Xiao et al., 2004; Li et al., 2006;

123 [Charvet et al., 2007, 2009](#)). These units are separated from each other by two major
124 faults; ([namely](#) the Main Tianshan Shear Zone and Baluntai-Xingxingxia Fault),
125 which are dextral strike-slip faults active mainly during the Permian along reactivated
126 older suture zones ~~represented by ophiolitic mélanges~~ (Laurent-Charvet et al., [2002,](#)
127 [2003;](#) ~~Shu et al., 2002;~~ Charvet et al., 2007; Wang et al., 2008, 2009, 2014a; de Jong
128 et al., 2009; [He et al., 2021](#)).

129 The South Tianshan Belt (STB) is connected with the northern margin of the
130 Tarim Block and mainly consists of ophiolitic mélanges and Cambrian to
131 Carboniferous sedimentary and volcanic rocks ([XBGMR, 1993](#)). These rocks are
132 locally metamorphosed and imbricated within several thrust-and-fault belts (Charvet
133 et al., [2007, 2011](#)). The western STB was formed by the amalgamation of the Tarim
134 Block and the Central Tianshan Belt following the closure of the South Tianshan
135 Ocean and [several](#) back-arc basins (Gao et al., 1998, 2009; Xiao et al., 2004; Han et
136 al., 2011; Wang et al., 2011a, 2018a; Huang et al., 2018; Zhong et al., 2019). In
137 contrast, the eastern STB (~~now corresponds to also named~~ the Beishan Belt) ~~was,~~
138 formed by the accretion of several ~~Precambrian-Precambrian~~-based magmatic-arc
139 terranes (Yuan et al., 2015; Yu et al., 2016; Zong et al., 2017; He et al., 2018a) and
140 ophiolitic mélanges during the Paleozoic (Xiao et al., 2010; Ao et al., 2012; Song et
141 al., [2013, 2015;](#) Shi et al., 2018).

142 The Central Tianshan Belt (CTB) is composed of a Precambrian basement (Liu
143 et al., 2004; Hu et al., 2010; Ma et al., [2012a, 2012b;](#) He et al., 2014, [2018b;](#) Wang et

144 al., ~~2014b, 2014d~~, 2017; Han and Zhao, 2018; Huang et al., 2019), Ordovician to
145 early Devonian arc-related volcanic and sedimentary sequences, and ~~early~~ Paleozoic
146 ~~to early Mesozoic~~ intrusive rocks (Xiao et al., 2004, 2013; Shi et al., 2007; ~~Dong et al.,~~
147 ~~2011~~; Lei et al., 2011; Ma et al., 2013, ~~2014~~; Zhong et al., 2015; ~~Du et al., 2018a~~; Han
148 and Zhao, 2018; He et al., 2018b). Both the basement and arc-type rocks are
149 unconformably overlain by unmetamorphosed Carboniferous to Permian ~~sedimentary~~
150 ~~cover~~ sediments (XBGMR, 1993; ~~Xiao et al., 2013~~). The CTB is considered either as
151 an independent Precambrian micro-continent involved in the accretion of the Tianshan
152 Orogen (Hu et al., 2000; Huang et al., 2015b, 2017) or as a part of the northern Tarim,
153 which was drifted off and then re-amalgamated with Tarim due to the opening and
154 closure of the South Tianshan back-arc basins (Charvet et al., 2007, ~~2011~~; ~~Wang et al.,~~
155 ~~2008, 2011a, 2018a~~; Lei et al., 2011; Ma et al., ~~2012a, 2012b~~, 2014; Huang et al.,
156 2015a; Gao et al., 2015; Zhong et al., ~~2015, 2017~~, 2019, 2019).

157 The North Tianshan Belt (NTB) refers to the domain between the CTB to the
158 south and the East Junggar Belt to the north (Fig. 1b). This belt is predominantly
159 composed of Ordovician to Carboniferous volcano-sedimentary sequences ~~and~~
160 crosscut by Paleozoic granitoids ~~associated granitic intrusions~~ (XBGMR, 1993). It is
161 considered as a Paleozoic arc system formed by southward subduction of the
162 Kalamaili Ocean (~~Zhao et al., 2002~~; Xiao et al., 2004; Yuan et al., 2010; Xie et al.,
163 ~~2016a, 2016b~~, 2016c), and/or by northward subduction of the North Tianshan Ocean
164 (Sun, 2007; Ma et al., 2015; Zhang et al., 2017, 2018; Du et al., 2018a; Han and Zhao,

165 2018; Chen et al., 2019). The NTB is further divided into three sub-units, i.e., the
166 Harlik-Dananhu Arc, Bogda ~~Belt-Arc~~ and Kangguer-Yamansu ~~Belt-Arc~~ (e.g., Xiao et
167 al., 2004) ~~covering unconformably covered by the Mesozoic-Cenozoic~~ Turpan-Hami
168 Basin ~~which that is now filled by with Mesozoic-Cenozoic sedimentary rocks~~ (Fig. 1b;
169 XBGMR, 1993).

170 The Harlik-Dananhu Arc occurs on both north and south sides of the
171 Turpan-Hami Basin, either formed by the breakup of a single arc due to intra-arc
172 rifting (~~Zhao et al., 2002;~~ Xiao et al., 2004; Ma et al., 2015) or resulted from
173 southward migration of the magmatic front ~~forming that generated~~ the Harlik ~~Arc~~ and
174 Dananhu ~~Arcs;~~ successively (Sun, 2007). The Bogda ~~Belt-Arc~~ is generally
175 interpreted as a Carboniferous magmatic arc and Permian post-collisional magmatic
176 belt (Shu et al., ~~2005,~~ 2011; Chen et al., 2011; Xie et al., 2016a, ~~2016b;~~ Wali et al.,
177 2018), although some authors suggested a Carboniferous ~~(to Permian)~~ rift ~~system~~ (Gu
178 et al., 2000, 2001; Xia et al., 2008, 2012). The Kangguer-Yamansu ~~Belt-Arc~~ is a late
179 Paleozoic arc/fore-arc system (Xiao et al., 2004; Han and Zhao, 2018) ~~which that was~~
180 ~~affected/reworked~~ by Permian ~~post-orogenic~~
181 ~~post-collision/post-orogenic~~ intracontinental dextral ductile ~~dextral-shearing zone~~
182 (Wang et al., 2008, 2014a; Branquet et al., 2012; Zhu et al., 2019).

183 2.2. Geological background of the Harlik Range

184 The Harlik Range (or Harlik Arc) is situated between the Turpan-Hami Basin to

185 the south and the East Junggar Belt to the northeast (Fig. 1b). The oldest stratigraphic
186 unit is the Ordovician Huangcaopo Group, which occurs along the northern foot of the
187 Harlik Range. It mainly consists of weakly metamorphosed marine clastic rocks and
188 tuffs (Ma et al., 1997; Chen et al., 2014). The Silurian strata are barely exposed in the
189 Harlik Range (XBMGR, 1993; Sun, 2007). Ordovician-Silurian (470-420 Ma)
190 intrusions in the Harlik Range mostly belong to calc-alkaline or tholeiitic series and
191 show typical subduction-related geochemical features associated with positive
192 mantle-like whole-rock $\epsilon_{Nd}(t)$ and zircon $\epsilon_{Hf}(t)$ values (Ma et al., 2015; Wang et al.,
193 2016, 2018b; Du et al., 2018a; Han and Zhao, 2018).

194 The Devonian strata, ~~previously defined by~~according to regional facies correlation,
195 are mainly composed of volcanic rocks, carbonates and siliciclastic rocks (XBGMR,
196 1993). The Lower Devonian Dananhu Formation is distributed along the southern
197 Harlik Range and the southern margin of the Turpan-Hami Basin (Fig. 1c). The
198 Middle Devonian Tousuquan Formation is ~~developed~~recognized along the ridge of the
199 Harlik Range, ~~from which, however, s~~Some rhyolites from this formation, however,
200 yielded zircon U-Pb ages of 469 ± 9 Ma (Li et al., 2017) and were intruded by
201 granitoids ~~were~~ dated at 446 ± 3 Ma to 448 ± 7 Ma (Cao et al., 2006; Liu et al., 2017),
202 indicating that some rocks in the Tousuquan Formation should be assigned to the
203 Ordovician. ~~Meanwhile, The~~Upper Devonian sediments is rare in the
204 Harlik Range and thus were poorly ~~studied~~investigated.

205 The Carboniferous strata can be divided into lower and upper units. The lower

206 unit includes the Jiangbasitao and Xiaorequanzi formations, which mainly consist of
207 volcanoclastic and volcanic rocks (XBMGR, 1993). The upper ~~unit~~unit, previously
208 named as Julideneng Formation, is distributed along the southern foot of the Harlik
209 Range and is mainly composed of tuffs, sandstones and tuffaceous sandstones (Sun,
210 2007). ~~Some of these rocks which occur~~ However, to the north of the Qincheng
211 Town, some of these rocks were metamorphosed into greenschist to amphibolite
212 facies (Zhao et al., 1997; Zhou, 2004; Sun, 2007) and their protoliths ages and timing
213 of metamorphism remain unclear. In this study, we separate these metamorphic rocks
214 from the Julideneng Formation and call them as the Julideneng metamorphic complex
215 (JMC). The Carboniferous calc-alkaline diorites and granites from the Harlik Range
216 were formed at 320-300 Ma. These granitoids were likely emplaced during the
217 tectonic transition from convergence to extension (Sun et al., 2005; Song et al., 2018;
218 Zhu et al., 2018).

219 The Lower Permian strata, unconformably overlying the pre-Permian rocks, are
220 mainly composed of ~~unconformable~~ terrestrial conglomerates, sandstones and
221 siltstones intercalated with volcanic rocks, ~~unconformably overlying the older strata~~
222 (Sun, 2007; Shu et al., 2011; Chen et al., 2014). The Permian granitoids are
223 transitional from calc-alkaline to alkaline ~~(Wang et al., 2009)~~ and yielded zircon U-Pb
224 ages of 298-280 Ma ~~(Wang et al., 2009c; Yuan et al., 2010; Chen et al., 2016refs.)~~.
225 They are usually associated with coeval mafic dykes, both were formed in an
226 extensional or transtensional setting (Gu et al., 1999; Wang et al., 2009c, ~~2009d~~; ~~Chen~~

227 ~~and Shu, 2010;~~ Yuan et al., 2010; Chen et al., 2016).

228 **3. Field geology and sample descriptions**

229 ~~F~~Our field investigations were conducted along a section from Qincheng Town
230 to Xiaopu Village, southern Harlik Range (Figs. 2a-~~2~~b). The southern part of the
231 section is dominated by ~~variably~~various schistose tuffs, sandstones and tuffaceous
232 sandstones belonging to the ~~upper~~Upper Carboniferous Julideneng Formation. ~~T~~The
233 northern part of ~~the~~is section consists of ~~M~~middle Devonian sandstones, tuffaceous
234 sandstones and limestones, which were silicified and crosscut by numerous diabase
235 dykes ~~is~~showing NE-SW or nearly E-W ~~striking~~inges (Fig. 2b; XBGMR, 1966; Sun,
236 2007). The central part ~~of the section, in between,~~ is ~~a~~ occupied by NW-SE striking
237 belt of of metamorphic rocks, occurring in along a NW SE striking belt, which
238 extends for >30 km long and ~10 km wide (Figs. 2a-~~2~~b; Zhao et al., 1997, 2002; Sun,
239 2007)-), this belt is made of These metamorphic rocks of the Julideneng metamorphic
240 complex (JMC), includeing garnet sillimanite mica schists, low-grade
241 meta-sandstones, andalusite schists, low-grade meta-sandstones garnet-sillimanite
242 mica schists and migmatites (Zhao et al., 1997; Zhou, 2004; Sun, 2007).
243 Consequently, we to which we propose there to give the name of suggest naming this
244 metamorphic belt as Julideneng Metamorphic Complex (JMC).

245 In the southern part of the ~~JMC metamorphic belt~~, the sedimentary rocks were
246 weakly deformed and slightly metamorphosed. The bedding (S0) can be easily

247 recognized ~~while~~and cleavage (S1) is well developed, both dip to the northeast with
248 S1 steeper than S0 (Figs. 2b, ~~2~~c and 3a), indicating a normal sequence. Further
249 northwards, S0 is gradually transposed into sub-vertical schistosity with increasing
250 metamorphic grade (Sun, 2007). A ~~migmatite zone of ~1 km wide~~ migmatite zone of
251 ~1 km wide occurs in the northern part of the ~~JMC metamorphic belt~~. Migmatites are
252 typically flow-folded (Sawyer, 2008) and contain ~~em~~centimeter-thick ~~leucocratic~~,
253 ~~locally~~ garnet-bearing leucocratic bodies ~~dykes~~, ~~which~~ They display all the
254 intermediates between folded and boudinaged leucosome ribbons, foliated
255 (orthogneissic) sills and ~~crosscutting~~, slightly foliated crosscutting dykes. Leucosomes
256 are surrounded by melanosomes with biotite-rich boundaries and restites of
257 meta-sandstone (Fig. 3b). Foliation in the migmatites is roughly ~~concordant in~~
258 accordance with that in the surrounding meta-sedimentary rocks (Fig. 3c).
259 Flow-folded migmatites and slightly folded small-scale garnet-bearing leucocratic
260 dykes (Fig. 3b and 3d) ~~illustrate~~ indicate a continuum from pre- to late-tectonic in situ
261 partial melting and short-distance transport of ~~anatectic~~ anatexic melts. A progressive
262 lateral change from migmatites into quartzites, schists and crinoidal limestone can be
263 observed farther to the west, and restites of quartzite and limestone (changed into
264 calc-silicate) occur in migmatites more to the north.

265 The southwestern border of the migmatite zone is in fault contact with weakly
266 deformed meta-sandstones (Figs. 2c and 3e). The fault zone, ~5-10 meters ~~wide~~ in
267 width, ~~is~~ was strongly sheared with schistosity/cleavage dipping 70-75° to the south.

268 ~~Owing to~~Considering the difference ~~of~~in metamorphic grade, there was probably a
269 bulk normal-fault motion ~~is likely~~ (Fig. 2c); ~~however~~On the other handIn addition,
270 the complex deformation of the fault zone likely suggests a polyphase motion. The
271 northern side of the migmatite zone ~~was~~is crosscut by a coarse-grained K-feldspar
272 granite dated at 297 ± 2 Ma (zircon U-Pb age; Chen and Shu, 2010). To the north, the
273 granite is in fault contact with low-grade meta-sedimentary rocks of the Middle
274 Devonian Tousuquan Formation (Fig. 2b ~~and 2_c~~). The boundary is an E-~~W~~
275 W-striking mylonite zone dipping steeply to the north, which bears a down-dip
276 stretching lineation. Kinematic indicators in ductilely deformed granites ~~suggest a~~
277 ~~top-down-to-the-north shearing and thus~~ are consistent with a normal-fault motion.
278 Therefore, the high-grade migmatite zone appears in a kind of horst or pop-up
279 structure surrounded by lower-grade meta-sedimentary rocks. Late
280 Carboniferous-~~early~~Early Permian (U-Pb-zircon U-Pb ages: ~~from of~~ 316 ~~to~~ 295 Ma)
281 undeformed granodiorite, biotite granite, leucogranite ~~and~~as well as numerous
282 NE-striking pegmatite and mafic dykes crosscut and thus post-date the metamorphic
283 belt (~~Figs. 2b and 2_e~~); (Wang et al., 2009c; Chen and Shu., 2010; Song et al., 2018;
284 Zhu et al., 2018). In addition, the meta-sedimentary rocks yielded earlyEarly Permian
285 mica-muscovite and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages ranging from 301 to 277 Ma (Sun,
286 2007).

287 In order to ~~further~~constrain the ages and provenances of the meta-sedimentary
288 rocks, and the timing of the migmatization, six representative samples were collected

289 from the ~~metamorphic belt~~JMC ~~and were further analyzed~~. Three mica-schist samples
290 (12TS119A, B, E) were taken from the migmatite zone (Fig. 2c). The sample
291 12TS119A is ~~mainly~~ composed of quartz (45-50 vol. %), biotite (20-25 vol. %),
292 plagioclase (10-15 vol. %), muscovite (5-10 vol. %) and a small amount of sillimanite.
293 The sample 12TS119B is a mylonitized mica-schist and ~~mainly~~ consists of quartz
294 (30-35 vol. %), biotite (20-25 vol. %), muscovite (30-35 vol. %) and plagioclase (5-10
295 vol. %). Another slightly altered sample 12TS119E is ~~primarily made up~~ composed of
296 quartz (30-35 vol. %), chloritized biotite (20-25 vol. %), muscovite (10-15 vol. %),
297 sericite (20-25 vol. %) and minor sillimanite (< 5 vol. %). In these mica-schists, the
298 preferred orientation of biotite and/or muscovite and elongated quartz grains define a
299 well-developed foliations (Figs. 4a-4c).

300 One sample (12TS119F; Fig. 2c) was collected from the meta-sandstones that
301 are in fault contact with the migmatites (Fig. 3e). This meta-sandstone is mainly
302 composed of quartz (60-70 vol. %), chloritized mica (10-15 vol. %) and plagioclase
303 (15-20 vol. %). The chloritized micas are weakly oriented ~~to form and define an~~
304 ~~almost unnoticeable~~ foliations ~~that are sometimes unremarkable~~ due to ~~mostly the~~
305 ~~fine-grained, and angular~~ equidimensional ~~shape of~~ quartz and plagioclase (Fig. 4d).
306 ~~Intensive Un~~undulose extinction and bulging dynamic recrystallization of quartz ~~can be~~
307 ~~commonly observed under~~in thin sections (Figs. 4a-4d), indicating a ductile
308 deformation of these meta-sedimentary rocks under moderate temperature conditions.

309 ~~Additional~~ two ~~more~~ samples were taken from ~~migmatitic gneissic~~

310 ~~granite~~migmatitic gneissic-granite —(12TS119G) and migmatite leucosome
311 (12TS119H) (Fig. 3d). Both of them are mainly composed of quartz (40-45 vol. %),
312 K-feldspar (25-30 vol. %), plagioclase (20-25 vol. %) and minor muscovite and
313 biotite (Figs. 4e-4f). The ~~migmatitic gneissic-granite~~migmatitic gneissic-granite shows
314 a clear foliations defined by the preferred orientation of micas and elongated quartz
315 ribbons (Fig. 3c). The feldspar and quartz exhibit lattice bending, subgrains, undulose
316 extinction and deformation bands, suggesting that these grains accommodated
317 intracrystalline plastic deformation by dislocation creep (Fig. 4e; Gower and Simpson,
318 1992; Hirth and Tullis, 1992; Passchier and Trouw, 2005). In addition, typical
319 chessboard subgrains in quartz and lobate grain boundaries between quartz and
320 feldspar ~~were~~are interpreted to indicate high-temperature ductile deformation ~~under~~
321 ~~high temperature conditions~~ (Gower and Simpson, 1992; Kruhl, 1996; Stipp et al.,
322 2002; Rosenberg and Stünitz, 2003; Zibra et al., 2012). By contrast, the migmatite
323 leucosome (12TS119H) shows nearly equant and diamond-shaped quartz crystals
324 enclosed by optically continuous K-feldspar (Fig. 4f), indicating that ~~the~~ quartz likely
325 crystallized from ~~the anatectic-anatexic~~ melts before K-feldspar crystallized from the
326 remaining melts (Sawyer, 2008). Undulose extinction and recrystallization by grain
327 boundary migration of quartz (Fig. 4f) suggest localized high-temperature ductile
328 deformation ~~under high temperature~~.

329 4. Analytical methods

330 All samples were crushed and milled into powders, from which zircon grains
331 were separated by ~~using~~ heavy liquid and magnetic separation~~ioner~~, and finally
332 handpicked under a binocular microscope fitted with a UV light. Selected zircon
333 grains were mounted in epoxy, polished to about half of their thickness, and then
334 coated with gold. Cathodoluminescence (CL) images of zircons were ~~conducted~~
335 obtained at the State Key Laboratory for Mineral Deposits Research (SKL-MDR),
336 Nanjing University, using a Quanta 400 FEG scanning electron microscope equipped
337 with a Gatan mini-CL detector (Mono CL3+).

338 ~~The analyses of~~ U-Pb dating and trace elements analysis of representative
339 zircons were conducted in two laboratories. The samples 12TS119A and 12TS119B
340 were dated at the SKL-MDR of Nanjing University using Agilent 7500a inductively
341 coupled plasma mass spectrometry (ICP-MS) coupled to a New Wave 193 nm laser
342 ablation system with an in-house sample cell. The detailed analytical procedures are
343 similar to those described in Jackson et al. (2004) and Liu et al. (2014). The U-Pb
344 dating and trace elements analyses of zircons from samples 12TS119E, 12TS119F,
345 12TS119G and 12TS119H were carried out at the State Key Laboratory of Geological
346 Processes and Mineral Resources, China University of Geosciences (Wuhan), where
347 laser sampling was performed using a GeoLas 2005 System and an Agilent 7500a
348 ICP-MS instrument was used to acquire ion-signal intensities. The detailed operating

349 conditions and analytical procedures are described in Liu et al. (2008, 2010a, 2010b).

350 For zircon crystals older than 1000 Ma, $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages were used to
351 plot relative probability diagrams considering large amounts of radiogenic Pb. For
352 zircon grains younger than 1000 Ma, $^{206}\text{Pb}/^{238}\text{U}$ apparent ages are more reliable due to
353 the low content of radiogenic Pb and low uncertainty of common Pb correction.
354 Uncertainties are quoted at 1σ for individual analysis and 2σ (with 95% confidence
355 level) for weighted mean ages, respectively. The results of U-Pb isotopic dating and
356 trace element compositions are listed in Supplementary Table S1 and Table S2,
357 respectively.

358 **5. Results**

359 *5.1. Meta-sandstone*

360 A total of 55 zircon grains were chosen for U-Pb dating from the weakly
361 metamorphosed sandstone sample 12TS119F. The CL images of all dated zircons
362 together with their ages are shown in Supplementary Fig. S1 and those of the
363 representative grains are presented in Fig. 5a. Most zircons have euhedral to
364 sub-euhedral shapes and show clear oscillatory zoning without or with narrow dark
365 rims, indicating original magmatic sources (Connelly, 2000; Corfu et al., 2003;
366 Hoskin and Schaltegger, 2003). A small group of zircons show stubby or sub-rounded
367 shapes and have complex core-rim textures, comprising irregular cores with blurry or

368 patchy zoning and structureless rims. This kind of zircons may have been produced by
369 modification of primary igneous zircons in response to metamorphism (Corfu et al.,
370 2003; Hoskin and Schaltegger, 2003; Rubatto, 2017). The rest few zircons are
371 rounded and ~~unzoned or~~ sector zoned or without zoning, indicative of metamorphic
372 origin (Figs. 5a and S1; Corfu et al., 2003; Hoskin and Schaltegger, 2003).

373 Forty-five out of fifty-five grains yielded concordant ages, a large majority of
374 which have ages < 540 Ma, with two major age peaks at 425 Ma (n = 14; 31.1%) and
375 445 Ma (n = 10; 22.2%), as well as a minor age peak at ca. 490 Ma. The Precambrian
376 zircons show sub-peaks at ~580 Ma, ~780 Ma, and in a range of 850-1000 Ma; only
377 two Mesoproterozoic grains (1280 Ma and 1372 Ma) were ~~found~~identified (Figs.
378 6a-6b; Table S1). The remaining ten analyses yielded discordant ages (Fig. 6a)
379 probably due to Pb loss or disequilibrium of their isotopic systems (Connelly, 2000).

380 Twenty-three zircons with ages around 445-425 Ma were analyzed for rare earth
381 element (REE) compositions. Most grains are characterized by steeply-rising REE
382 patterns with remarkable positive Ce and negative Eu anomalies (Fig. 7a), together
383 with ~~their~~ high Th/U ratios (mostly > 0.4) (Fig. 6b; Table S1), generally consistent
384 with typical magmatic zircons (Hoskin and Schaltegger, 2003; Rubatto, 2017). Only
385 two zircons (Nos. 38 and 51) display relatively higher LREE values and weaker Ce
386 anomalies in comparison to the other zircons, and their REE patterns (Fig. 7a) are
387 similar to those of hydrothermal-~~related~~ zircons (Hoskin, 2005).

388 5.2. Mica-schists

389 From three mica-schist samples, a total of 192 zircon grains were analyzed,
390 which show various sizes, sub-rounded to sub-euhedral shapes and complicated
391 internal textures (Figs. 5 and S1). According to their CL images, four types of zircons
392 can be recognized. (1) Type 1 zircons have core-rim textures in which the cores are
393 bright with oscillatory zoning and the rims are relatively dark and un-zoned,
394 corresponding to originally magmatic zircons surrounded by metamorphic
395 overgrowths (Hoskin and Schaltegger, 2003). (2) Type 2 zircons also show core-rim
396 textures with bright un-zoned cores, which ~~were either~~ could be originally
397 metamorphic ~~and then~~ subjected to secondary metamorphic or hydrothermal
398 overgrowth, ~~or a~~ Alternatively, they could also be originally magmatic but were
399 intensively “reworked” (via solid-state recrystallization or local
400 dissolution-reprecipitation) by the subsequent metamorphism or alteration so that the
401 original magmatic oscillatory zoning ~~were~~ was totally erased. In the latter case, the
402 overgrowth rims may have formed synchronously with the reworking of the cores or
403 even reflect a later metamorphic and/or hydrothermal event (Hoskin and Schaltegger,
404 2003). (3) Type 3 zircons have homogeneous dark to black CL images without visible
405 oscillatory zoning, likely formed by metamorphism or hydrothermal ~~alteration~~
406 activities (Connelly, 2000; Corfu et al., 2003; Hoskin and Schaltegger, 2003). (4) Type
407 4 zircons are characterized by prismatic shapes and moderately bright CL images with

408 clearly concentric magmatic oscillatory zoning, ~~and now~~without visible overgrowths. –

409 In order to obtain sufficiently representative zircon populations, all four types of
410 zircons from each sample were analyzed. Most analyses plot on or close to the
411 Concordia, but a few zircons show remarkable discordance, especially for the sample
412 12TS119E (Figs. 6c, ~~6e~~ and ~~6g~~). One reason for discordant ages can be Pb loss due to
413 metamorphic or hydrothermal alteration. In addition, ~~physical-analytical~~ mixing
414 between two parts of zircons with different origins (e.g., older cores and younger rims)
415 is also highly possible as some of the discordant zircons ~~are quite small~~ with core-rim
416 texture are quite small (Fig. S1). The geological meaning of the discordant ages is
417 ambiguous; ~~thus these~~therefore, discordant zircon ages they are excluded from further
418 discussion and only concordant ages (concordance > 90%) are considered ~~in further~~
419 ~~discussion. In the following, only concordant ages (concordance > 90%) are~~
420 ~~considered.~~

421 For the mica-schist sample 12TS119A, fifty-eight out of sixty dated zircons
422 yielded concordant ages (Fig. 6c) ranging from 313 to 2175 Ma. They show ~~showing~~
423 a dominant age peak at 477 Ma (n = 19; 32.8%), two younger age peaks at 322 Ma (n
424 = 4; 6.9%) and 414 Ma (n = 4; 6.9%), and other populations of 500-550, 600-750,
425 850-1000, 1100-1500, 1600-1800 and 2175 Ma (Fig. 6d). The youngest nine ages
426 (peaked at 322 and 414 Ma) (Fig. 6d; Table S1) are obtained exclusively from type 2
427 zircons with Th/U ratios mostly lower than or near 0.4 (Table S1; Fig. 6d), showing
428 bright or dark cores characterized by surface-controlled alteration (Corfu et al., 2003)

429 and encircled by thin and dark rims (Figs. 5b and S1). Zircons defining the major age
430 peak of 477 Ma mainly belong to the ~~type 1, type 2 and minor type 4~~ type 1 and type
431 2, and show Th/U ratios higher than 0.4 (Table S1; Figs. 5b, 6d and S1). The other
432 older zircons cover ~~all four types~~ types 1 and 2, and have variable Th/U ratios mostly
433 higher than 0.4 (Figs. 6d and S1).

434 Sixty zircons were dated ~~from~~ for the mica-schist sample 12TS119B and all of
435 them yielded concordant ages (Fig. 6e). Their ages ~~ranges~~ and populations are very
436 similar to those of the sample 12TS119A (Fig. 6f). Therein, ~~the~~ three youngest zircons
437 (380-413 Ma) belong to the type 3 displaying homogeneous dark to black CL images
438 (Figs. 5c and S1) and Th/U ratios around 0.4 (Table S1; Fig. 6f). Twenty zircons
439 (33.3%) of type 1 and minor ~~types 3 and 4~~ type 2 and type 4 (Figs. 5c and S1) define
440 an age peak at 477 Ma and show Th/U ratios mostly higher than 0.4 (Fig. 6f; Table
441 S1). Other ages around 500-550, 600-750, 850-1000, 1100-1500, 1600-1800 and
442 2200-2500 Ma (Fig. 6f) were obtained from zircons of all four types, most of which
443 show Th/U ratios higher than 0.4 (Table S1).

444 As for the sample 12TS119E, sixty-one out of seventy-two zircons provided
445 concordant ages ranging from 346 to 1765 Ma (Fig. 6g-6h). A major age peak at 475
446 Ma (n = 11; 18.0%) and a minor age peak at 425 Ma (n = 5; 8.2%) are mainly defined
447 by types 1 and 2 zircons (Figs. 5d and S1), which mostly show Th/U ratios higher
448 than 0.4 (Fig. 6h; Table S1). These zircons show steeply-rising REE patterns,
449 remarkable positive Ce anomalies and negative Eu anomalies (Fig. 7b). Thus, these

450 ages are indicative of magmatic events (Hoskin and Schaltegger, 2003; Hoskin, 2005).
451 One exceptional zircon (No. 57; ~424 Ma) shows a quite high Th/U ratio (2.93; Table
452 S1). ~~and for~~ For some unclear reasons, a ~~UV~~-shaped REE pattern due to its high LREE
453 content ~~is~~ similar to that of some “hydrothermal” zircons (Fig. 7b). Five zircons of
454 types 2 and 3 with dark, homogenous CL images (Figs. 5d and S1) yielded ages
455 ~~offrom~~ 346 to 402 Ma, they display gently-rising REE patterns with weak Ce
456 anomalies and Th/U ratios mostly lower than 0.4 (Figs. 6h and 7b), similar to zircons
457 of hydrothermal origin (Fig. 7b). With only a few exceptions, the other age
458 populations (500-550, 600-800, 850-1000, 1100-1400 and 1600-1800 Ma) correspond
459 to all four zircon types (Figs. 6g-6h) with Th/U ratios mostly ~~>~~higher than 0.4 (Fig. 6h;
460 Table S1).

461 5.3. Migmatites

462 For two migmatite samples, a total of 38 analyses were conducted on 36 zircons.
463 Their CL images and ages are shown in Figs. 8a-8f. Almost all the dated zircons are
464 sub-euhedral to euhedral with prismatic shapes, they have clear oscillatory zoning
465 (Fig. 8) and their Th/U ratios are mostly higher than or close to 0.4 (Table S1),
466 suggesting a magmatic origin.

467 Out of twenty analyses on zircons ~~offrom~~ the migmatitic gneissic-granite
468 ~~migmatitic gneissic-granite~~ 12TS119G, thirteen concordant ages form two age peaks
469 ~~or mean ages~~ at 297.4 ± 2.1 Ma ($n = 8$; 61.5%; MSWD = 0.26) and 322.2 ± 2.3 Ma (n

470 = 5; 38.5%; MSWD = 0.066) (Figs. 8c and 8e). Seven zircons yielded discordant ages
471 (Fig. 8c; Table S1); ~~that are which that are geologically meaningless and they are~~ not
472 considered in the following discussion.

473 Eighteen zircons were dated for the migmatite leucosome sample 12TS119H and
474 fifteen analyses yielded concordant ages (Fig. 8d), ~~which also defined~~ comparable
475 two age ~~groups peaks or mean ages~~ of 297.1 ± 2.7 Ma (n = 4; 26.7%; MSWD = 0.13)
476 and 322.5 ± 2.1 Ma (n = 8; 53.3%; MSWD = 0.13) (Fig. 8f). Three zircons (Nos. 6, 10
477 and 16) yielded older; and probably inherited; ages of 338-365 Ma (Fig. 8d). The
478 remaining three zircons (Nos. 2, 5 and 15) with discordant ages have been rejected.

479 The dated concordant zircons from these two samples were further analyzed for
480 REE compositions. The results show steeply-rising Chondrite-normalized REE
481 patterns characterized by enrichment of HREE relative to LREE, mostly positive Ce
482 anomalies and negative Eu anomalies (Figs. 7c and 7d), in accord with an igneous
483 origin. Only two zircons (Nos. 15 and 16) in sample 12TS119G ~~are~~ have slightly
484 different ~~in~~ REE patterns with relatively higher LREE values and weaker Ce
485 anomalies than typical magmatic zircons (Fig. 7c).

486 6. Discussion

487 6.1. ~~Depositional~~ Protoliths depositional and metamorphic ages of the

488 meta-sedimentary rocks

489 The most remarkable age population of detrital zircons from the meta-sandstone
490 and mica-schists lies in the 540-420 Ma interval. The mica-schists have dominant
491 peaks of 477-475 Ma, while the meta-sandstone shows a peak at 425 Ma ~~which that~~
492 resembles a minor peak of the mica-schist 12TS119E (Fig. 6). Since these detrital
493 zircons are mostly of magmatic origins, their ages ~~allow constraining~~ constrain the
494 maximum depositional ages ~~of their protoliths of meta-sedimentary rocks of the~~
495 ~~meta-sedimentary rocks.~~ ~~The meta-sedimentary rocks are crosscut by granite dated at~~
496 ~~320 ± 3 Ma (Song et al., 2018), thus, the deposition of meta-sedimentary rocks~~
497 ~~occurred between 425 Ma and 320 Ma. The metamorphic ages of the~~
498 ~~meta-sedimentary rocks is are constrained to be at 322 Ma and 297 Ma provide a~~
499 ~~constraint on the minimum sedimentary age (see discussion below).~~ ~~Thus, the~~
500 ~~deposition of detrital protoliths of the meta-sedimentary rocks may have occurred~~
501 ~~between 425 Ma and 322 Ma. The maximum deposition age is is consistent with also~~
502 ~~constrained defined as >320 Ma by the latter crosscutting granite dated at 320 ± 3 Ma~~
503 ~~(Song et al., 2018).~~

504 Zircons ~~at of~~ ~480-420 Ma from sillimanite mica-schists generally exhibit dark
505 rims, whereas detrital zircons of ~425 Ma from the meta-sandstone usually ~~do not~~

506 show ~~no such~~ overgrowths (Figs. 5 and S1). This indicates that zircons from
507 high-grade mica-schists were ~~subjected to important~~ significantly reworked ~~ing in~~
508 ~~various degrees~~ by metamorphism, in contrast to the ~~lower low~~-grade meta-sandstone.
509 Such reworking may also account for the occurrence of discordant detrital zircons in
510 the meta-sedimentary rocks (Fig. 6), most likely due to incomplete metamorphic reset.

511 The youngest zircon group (~420-320 Ma) from the mica-schists, ~~which have~~s
512 no equivalent in the meta-sandstone, displaying diagnostic features of metamorphic/
513 ~~and/or~~ hydrothermal zircons. Therefore, the ~~younger~~ ages suggest partial or total
514 ~~youngest ones were partially or completely~~ reworked ~~ing by during~~ amphibolite facies
515 metamorphism, although it cannot be excluded that some of them were originally
516 (pre-sedimentation) metamorphic. ~~As the youngest age peak of the metamorphic~~
517 ~~zircons is ~322 Ma, it is suggested that the~~ ~~The~~ ~~high temperature~~ metamorphism
518 likely occurred at ~322 Ma, ~~which is the youngest age peak of metamorphic zircons.~~
519 The ~~other~~ older ages (420-322 Ma) possibly resulted from age mixing between
520 primary cores (~~growth zoning~~) and recrystallized areas or overgrowths (Corfu et al.,
521 2003).

522 The two migmatite samples yielded exactly identical age peaks at 322 Ma and
523 297 Ma (Fig. 8). Both ~~zircon groups of zircons~~ show clear concentric oscillatory
524 zonings, high Th/U ratios and steeply-rising REE patterns, ~~indicating~~
525 ~~diagnostic~~ indicative of magmatic origins (Fig. 8; Table S1). Thus, these two ages
526 ~~likely~~ represent two ~~distinct~~ episodes of zircon crystallization. Although ~~both groups~~

527 ~~of~~ zircons from both groups generally show similar morphologies and internal
528 textures, some ~~zircons of~~ 322 Ma grains have ~~vague~~ thin dark rims (Figs. 8a-8b),
529 which may ~~have resulted from slight~~ correspond to overgrowth during the second
530 episode of crystallization at ~297 Ma. This is also confirmed by (1) the occurrence of
531 thin dark rims surrounding the inherited zircons of 338 Ma, 342 Ma and 365 Ma (Fig.
532 8a-8b), ~~which that were probably inherited from the protoliths of the migmatites~~, and
533 (2) ~~clear~~ conspicuous dark rims and zoning-controlled alterations developed in
534 discordant zircons (Figs. 8a-8b).

535 Regional tectonics, metamorphism, and ~~magmatization and deformation are~~
536 ~~known to be in~~ has close spatial and temporal relationships with peraluminous
537 leucogranitoid emplacement genesis (e.g., Barrow, 1893; Vernon, 1982; Barton and
538 Hanson, 1989; Keay et al., 2001; Okay et al., 2014). ~~A comparison between of the new~~
539 ~~zircon U-Pb ages of the meta-sedimentary rocks and migmatites (from this study)~~
540 ~~with and the published zircon U-Pb ages ones of the crosscutting granitic plutons (Figs.~~
541 ~~2b and 9) shows that the Late Paleozoic Carboniferous to eEarly Permian crosscutting~~
542 granite plutons (Figs. 2b and 9) magmatism occurred in two episodes at 330-310 Ma
543 and 305-290 Ma (Sun et al., 2007b; Wang et al., 2009c; Chen and Shu, 2010; Chen et
544 al., 2016; Song et al., 2018reference); ~~(Fig. 9a)~~, which fit the two zircon peak ages
545 peaks of zircons from migmatites (322 Ma and 297 Ma); ~~of zircons in in the~~
546 migmatites (Figs. 8 and 9b). Moreover, the age of the first episode of granitic
547 magmatism is also consistent with the youngest peak age peak (322 Ma) ~~for of~~

548 “metamorphic” zircons of the mica-schists (Fig. 9b). Therefore, ~322 Ma can be
549 reasonably interpreted as the timing of amphibolite facies metamorphism, ~~in~~
550 ~~connection with the~~ migmatization and the first episode of magmatism. As the
551 migmatitic ~~leucosomes~~ also contains ~~zircon grains of zircon~~ at ~297 Ma ~~zircon~~
552 ~~grains~~, it is likely that ~~the migmatites remelted again~~ anatexic melts were not totally
553 crystallized at ~322 Ma probably due to high thermal gradient or continuous addition
554 of melts –at until ~297 Ma, ~~associated in connection~~ with the second episode of
555 granitic magmatism, ~~leading giving birth to the zircon~~ crystallization of the younger
556 zircons, while some ~~inherited~~ zircons ~~at of~~ ~322 Ma were preserved. ~~This hypothesis~~
557 Finally, is supported by the occurrence of ~308 Ma leucogranite ~~ie~~ dykes of ~308 Ma
558 containing a few inherited zircons ~~at with~~ 320-330 Ma ages (Zhu et al., 2018). Such a
559 genetic relationship between migmatites and granites and will needs ~~verification to be~~
560 ~~comforted confirmed~~ with through detailed geochemical investigations.

561 ~~further studies on geochemical balance between migmatites and granites.~~

562 It is also worth noting that mica $^{40}\text{Ar}/^{39}\text{Ar}$ apparent ages of the metamorphic
563 rocks range from 301 to 277 Ma and were considered as the timing of the
564 metamorphism in the Harlik domain (Sun, 2007). However, considering: ~~that~~ (1) the
565 relatively low closure temperature of argon isotopic system of micas (Harrison et al.,
566 1985, 2009), (2) the occurrence of extensive Permian granitic plutons and their close
567 spatial relationships with meta-sedimentary rocks and migmatites, and (3) the good
568 match between ~~the~~ mica $^{40}\text{Ar}/^{39}\text{Ar}$ apparent ages (301-277 Ma) and zircon U-Pb ages

569 of granites (305-290 Ma), we consider the mica $^{40}\text{Ar}/^{39}\text{Ar}$ apparent ages of
570 meta-sedimentary rocks ~~as to be~~ most likely the timing of thermal reset and final
571 cooling ~~event associated with~~ related to the second episode of magmatism.

572 6.2. Provenances of the meta-sedimentary rocks

573 The studied meta-sedimentary rocks contain both Paleozoic and Proterozoic
574 detrital zircons (Fig. 6). Among overall 224 concordant detrital zircons, 126 grains
575 (56%) yielded Paleozoic ages and 98 zircons (44%) yielded Proterozoic ages. For the
576 Paleozoic ages, as aforementioned, the U-Pb system of detrital zircons younger than
577 420 Ma was likely affected by post-depositional metamorphism. Thus, these zircons
578 and their ages should be rejected for provenance investigation. The Ordovician to
579 Silurian detrital zircons (~480-420 Ma with peaks at ~475, ~445 and ~425 Ma) are
580 dominant constituents in the meta-sedimentary rocks (Fig. 9b). This is consistent with
581 the ~~previous study of Sun et al. (2007a) that~~ who found a predominant Ordovician to
582 Silurian zircon population (482-418 Ma) in low-grade sandstones from the study area
583 ~~(Sun et al., 2007a).~~

584 As discussed above, the early Paleozoic zircons are mainly derived from
585 magmatic rocks. Numerous early Paleozoic magmatic rocks ~~at~~ of 440-450 Ma ~~have~~
586 ~~been~~ were previously reported both in the Harlik and Dananhu arcs, while magmatic
587 rocks of 420-430 Ma ~~occur~~ crop out only in the Dananhu area only (Cao et al., 2006;
588 Ma et al., 2015; Wang et al., 2016; Zhang et al., 2016a; Chen et al., 2017; Liu et al.,

589 2017; Du et al., 2018a; Wang et al., 2018b; Zheng et al., 2018; Chai et al., 2019). In
590 addition, very few ~475 Ma magmatic rocks ~~at ~475 Ma~~ have been reported so far in
591 the North Tianshan, and only rhyolites ~~at of~~ 469 ± 9 Ma were documented ~~from in~~ the
592 Harlik area (Li et al., 2017). The angular to sub-angular early Paleozoic detrital
593 zircons indicate short distances of transportation (Sun et al., 2007a), while these
594 samples ~~come are~~ from the Qincheng area ~~which that~~ is situated between the Harlik Arc
595 and Dananhu Arc. ~~As a consequence, thus,~~ it can be suggested that these early
596 Paleozoic detrital zircons (~480-420 Ma) likely came from magmatic rocks of the
597 Harlik and Dananhu arcs.

598 Ordovician to Silurian arc-type magmatic rocks are also ~~occur~~exposed in the
599 Central Tianshan and East Junggar-Altai belts (Fig. 10), which ~~could bear the~~
600 potential sources for the meta-sedimentary rocks. However, the ~~separation of~~ North
601 Tianshan ~~was separation is regarded~~ proposed to be separated from ~~the~~ East
602 Junggar-Altai belts ~~is thought to have occurred~~ before the early Carboniferous (>340
603 Ma) by the ~~opening of~~ Kalamaili oceanic basin (Li et al., 2009; Huang et al., 2012;
604 Zhang et al., 2013; Xu et al., 2015a; Du et al., 2018b; Han and Zhao, 2018; Wang et
605 al., 2019), ~~and while~~ the depositional age of protoliths of the meta-sedimentary rocks
606 ~~the Julideneng Formation~~ is roughly constrained ~~as at between~~ ~420-320-~425- to ~322
607 Ma. Therefore, the available data cannot sufficiently prove or disprove that the East
608 Junggar-Altai magmatic arcs ~~are weremight be the~~ possible sources for the
609 Ordovician-to Silurian detrital zircons of the meta-sedimentary rocks in the Qincheng

610 area.

611 In addition, it is suggested that the North Tianshan (Harlik-Dananhu ~~Arearcs~~) was
612 amalgamated with the Yamansu Arc and Central Tianshan Block at ~320-300 Ma
613 along the Kangguer shear zone after the closure of the Kangguer Ocean (e.g., Li, 2004;
614 Li et al., 2006; Zhang et al., ~~2015b~~, 2016b, 2020; Zhao et al., 2019). However, the
615 rock sequences on both sides of this shear zone are comparable and it ~~may be~~might
616 ~~have been actually~~ located within the North Tianshan belt (Wang et al., 2008, 2014a;
617 Branquet et al., 2012). According to the studies on ophiolites of the North Tianshan
618 Suture zone and Kangguer belt (Xu et al., 2006a, 2006b; Chen et al., 2019), the North
619 Tianshan (or Kangguer) Ocean ~~was opening~~ opened during the mid-late Carboniferous.
620 Considering that the Precambrian zircons most likely came from the Central Tianshan
621 Block (see discussion ~~below~~), it is possible that the Central Tianshan Block ~~also~~
622 have also provided ~~some~~ certain early Paleozoic detritus for the ~~meta~~-sediments in the
623 Qincheng area. ~~Due to the uncertainty about the nature and the timing of the closure of~~
624 the Kangguer Ocean, it is not certain that the Central Tianshan Block is the source
625 area for the early Paleozoic zircons of the meta-sediments in the Qincheng area.

626 The main population of Proterozoic zircons in the meta-sedimentary rocks is the
627 Neoproterozoic group (550-1000 Ma) showing a peak at ~870 Ma and a subordinate
628 peak at ~780 Ma. Minor zircon populations of 1.1-1.5 Ga, 1.6-2.0 Ga, 2.1-2.3 Ga and
629 ~2.5 Ga with peaks at ~1.45 Ga and ~1.7 Ga ~~can be~~ also be foundrecognized (Fig.
630 10a). However, there is no ~~record for~~ a Precambrian basement exposed in the NTB

631 (Xiao et al., 2004; Zhang et al., 2016a). ~~Thus, t~~These Proterozoic zircons were thus
632 most likely transported from nearby ~~Precambrian~~ Precambrian-based continental
633 blocks. Chen et al. (2014) suggested that the Harlik Range ~~belongs to~~ is a part of the
634 Tuva-Mongol-Altai Arc. Nevertheless, the available data indicate that the
635 Tuva-Mongol-Altai Arc and the East Junggar ~~Belt are~~ lack of both magmatic events
636 and detrital records ~~of~~ in ~1.35-1.45 Ga (Fig. 10d-~~10e~~; Jiang et al., 2011), which are
637 common in the North Tianshan (Figs. 10a-~~10b~~; Chen et al., 2014). In contrast, a lot of
638 Mesoproterozoic granitic rocks ~~with ages from ca. of ~1.40 to ~1.45 Ga~~ have been
639 documented in the Central Tianshan Block (Fig. 10c; Ma et al., 2012a; He et al., 2014,
640 2015; Wang et al., 2014b, 2017; Huang et al., 2015b). Moreover, the Central Tianshan
641 Block has a detrital zircon age spectrum similar to that of the Harlik Range and the
642 entire North Tianshan, they all display zircon populations of 750-800 Ma, 850-1000
643 Ma, ~1.45 Ga, 1.6-1.8 Ga and ~2.5 Ga. More importantly, the igneous rocks in the
644 Central Tianshan Block formed during ~800, ~900 Ma and ~1.45 Ga episodes,
645 identical with the detrital zircon age peaks of the meta-sedimentary rocks from the
646 Harlik Range, which are ~~absent, however, lacking~~ in the other neighboring units (Fig.
647 10). Therefore, the Central Tianshan Block is the most probable provenance area for
648 the Precambrian detrital zircons in the studied meta-sedimentary rocks.

649 The Precambrian zircons in the meta-sedimentary rocks are ~~aneu~~hedral in shape
650 and show complex core-rim textures (Figs. 5 and S1), indicating that they ~~are~~ were
651 multiple-cycled. Thus, these Precambrian zircons were probably ~~were~~ transported

652 from the Central Tianshan Block to the North Tianshan Belt (Dananhu Arc) before the
653 opening of the the-North Tianshan (or Kangguer) Ocean, and then werethereafter
654 re-transported into the the-Harlik area. This is consistent in agreement with the fact
655 that zircon populations of Devonian flysch-sediments from the Dananhu Arc are
656 comparable with that of the Central Tianshan Block (Wang et al., 2019). However,
657 due to uncertainty on their deposition age, these zircons could be-alsohave been
658 directly be-transported directly from the Central Tianshan Block as well to the-Harlik
659 because of the rough constraints on their depositional age.

660 Clastic sediments derived from orogens are generally a mixture of multifarious
661 detritus from metamorphic, sedimentary and igneous rocks (e.g., Han et al., 2017).
662 Mixing and preferential elimination of certain zircons during transport can
663 significantly modify zircon populations in sediments, especially in old
664 multiple-cycled populations (Hay and Dempster, 2009; Han et al., 2017). Therefore,
665 comparison of detrital zircon populations must be undertaken with much care. In the
666 present case, provenance from the Central Tianshan Block is most likely, but
667 considering the limited size of the database, other provenances cannot be completely
668 excluded.

669 *6.3. Implications for the late Paleozoic tectonic evolution of the North Tianshan belt*

670 Our new zircon U-Pb data indicate that the meta-sediments from the Julideneng
671 FormationJMC were deposited in the interval between L-late Silurian and early L-late

672 Carboniferous. The predominant early Paleozoic detrital zircons were potentially
673 derived from both the Harlik and Dananhu aArcs. In combination with the low
674 maturity of the meta-sandstone that suggests a near-source deposition (Sun et al.,
675 2007a), an intra-arc basin (Qincheng or Xiaopu basin; Zhao et al., 1997) located
676 between these arcs can be suggested (Fig. 11A). The low maturity of the
677 meta-sandstone suggests near-source deposition (Sun et al., 2007a) and the
678 predominant early Paleozoic detrital zircons were potentially derived from the Harlik
679 and Dananhu Arcs, thus, an intra-arc basin (Qincheng or Xiaopu basin) was
680 suggested (Zhao et al., 1997). In addition, the Precambrian zircons in the Julideneng
681 Formation meta-sedimentary rocks were probably derived from the Central Tianshan
682 Block. As a consequence result, the North Tianshan was likely connected with the
683 northern margin of the Central Tianshan Block before the Late Carboniferous. The
684 North Tianshan was rifted from the Central Tianshan Block in the mid-late
685 Carboniferous (Xu et al., 2006a, 2006b; Chen et al., 2019) due to the opening of the
686 North Tianshan (or Kangguer) Ocean, and was thereafter re-amalgamated to the
687 Central Tianshan Block during the latest Carboniferous (Han et al., 2010; Zhang et al.,
688 2015b, 2016a, 2016b, 2020) (Fig. 11AB-BD).

689 As discussed above, the amphibolite-facies metamorphism and migmatization
690 occurred at ~322 Ma. According to Sun (2007) and our field observations, the
691 garnet-sillimanite-bearing meta-sedimentary rocks are most likely likely the protolith
692 source rocks of the migmatites and associated felsic bodiesdykes. The generally

693 N-dipping foliations ~~that bearing~~ ~NW-SE stretching lineations ~~were likely~~ resulted
694 from sinistral transtension (Sun, 2007). In addition, the HT-LP metamorphism (Zhao
695 et al., 1997) and migmatization are coeval with the ~~co~~-emplacement of ~~undeformed~~
696 high-K calc-alkaline ~~undeformed I- and A-type~~ granites (320-316 Ma) ~~that formed~~
697 ~~probably by with positive whole-rock $\epsilon_{Nd}(t)$ and zircon $\epsilon_{Hf}(t)$ values, both of which are~~
698 ~~diagnostic of decompression melting of juvenile crustal sources~~ in an extensional
699 setting (Song et al., 2018). Similarly, in the nearby Bogda ~~Belt~~area, Carboniferous
700 (350-315 Ma) volcanic rocks are thought to have formed in an intra-arc (Zhang et al.,
701 2017; Wali et al., 2018) or back-arc extensional setting (Chen et al., 2013; Xie et al.,
702 ~~2016a, 2016b, 2016e~~). Taking all these arguments into consideration, we suggest that
703 the meta-sedimentary rocks and migmatites are likely parts of the Harlik arc root, and
704 the migmatization probably occurred due to decompression partial melting in ~~a~~
705 ~~late-orogenic extensional setting~~ a continent-based ~~intra-arc or back-arc~~
706 ~~extensional rift~~ extensional setting (Fig. 11C).

707 The migmatites in the Harlik Range also recorded ed an event at ~297 Ma, which is
708 coeval with the widespread emplacement of undeformed post-~~collisional orogenic~~
709 K-feldspar granites and leucocratic two-mica granites at 298-295 Ma (Wang et al.,
710 2009c; Chen and Shu, 2010). The occurrence of ductilely deformed granites ~~of~~ with
711 ~~the same age~~ along the northern boundary of the metamorphic ~~units~~ belt (Fig. 2b-2c),
712 and ~~down-dip-slip (normal)~~ stretching lineation ~~with normal-fault motion~~ along the
713 north-dipping mylonite zone (see section 3) indicate syn-~~tectonic~~ kinematic

714 emplacement of granites. Therefore, the development of a large volume of latest
715 Carboniferous to earliest Permian post-~~collisional~~-orogenic granitoids (Wang et al.,
716 2009c, 2009d; Chen and Shu, 2010; Yuan et al., 2010; Chen et al., 2016), bimodal
717 dyke swarms (Gu et al., 1999) and nearly synchronous ductile normal faults
718 correspond to the exhumation of the metamorphic units under a regional
719 post-orogenic extensional regime and thus prominent crustal thinning (Fig. 11D).
720 Final cooling at 301-277 Ma revealed by mica $^{40}\text{Ar}/^{39}\text{Ar}$ apparent ages (Sun, 2007)
721 indicates that these events terminated during the EEarly Permian.

722 7. Conclusions

- 723 (1) ~~The Protoliths of the~~ meta-sedimentary rocks ~~of from~~ the Julideneng Metamorphic
724 Complex~~Julideneng Formation~~ in the southern Harlik Range were originally
725 deposited between the latest Silurian and ~~early L~~late Carboniferous (425-322 Ma).
- 726 (2) The Harlik-Dananhu magmatic arcs were likely the major sources for the
727 Ordovician to Silurian detrital zircons in the meta-sedimentary rocks, while the
728 Precambrian detrital zircons were most likely derived from the Central Tianshan
729 Block, although possible provenances from the East Junggar and Chinese Altai
730 cannot be excluded.
- 731 (3) ~~The HT-LP~~High-grade metamorphism and ~~migmatisation~~-migmatization occurred
732 at ~322 Ma in the southern Harlik Range ~~occurred in a~~were probably related to
733 continent-based~~n~~ intra-arc or back-arc crust thinning~~extensional setting~~

734 ~~late-orogenic-extensional-setting~~. The orogenic events in the Harlik Range
735 terminated ~~in~~before the ~~eE~~Early Permian.

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1453

1454 **Figure and Table captions:**

1455 Fig. 1. (a) Tectonic sketch map of Eurasia showing the location of the Central Asian
1456 Orogenic Belt (modified from Sengör et al., 1993). (b) Sketch map of the northern
1457 Xinjiang area, NW China, showing tectonic subdivisions of the Chinese Tianshan
1458 (modified from Wang et al., 2014a ~~and He et al., 2014~~). Abbreviations: NTB = North
1459 Tianshan Belt, CTB = Central Tianshan Belt, STB = South Tianshan Belt. (c)
1460 Geological map of the northeastern Tianshan Belt (modified from 1:1,000,000 scale
1461 geological map of the Chinese Tianshan and surrounding regions, after XGSC, 2007).

1462

1463 Fig. 2. (a) Geological map of the Harlik Range, North Tianshan (modified from
1464 1:200,000 scale geological map No. K-46-XI by XBGMR, 1966). (b) Detailed
1465 geological map of the Qincheng area, North Tianshan showing the metamorphic zone

1466 and sampling sites (modified from Sun, 2007). Dating results are from Sun, 2007;
1467 Chen and Shu, 2010. Abbreviations: Bt = Biotite Ar-Ar age, Mus = Muscovite Ar-Ar
1468 age, Zr = Zircon U-Pb age. (c) Cross-section of the ~~metamorphic belt~~Julideneng
1469 Metamorphic Complex (JMC) in the Qincheng area showing the occurrence of
1470 migmatites and sampling sites. Stereograms of the bedding and foliation are
1471 equal-area Schmidt net, lower hemisphere.

1472

1473 Fig. 3. Representative field photographs of meta-sedimentary rocks and migmatites in
1474 the Qincheng area, North Tianshan. (a) Weakly deformed and metamorphosed
1475 sandstone and siltstone. The cleavage S1 is steeper than the bedding S0 indicating a
1476 normal sequence. (b) Migmatite with leucosome (Leu), melanosome (Mel) and
1477 mesosome (Mes). (c) Parallel and consistent foliations in ~~gneissic~~gneissic-granite and
1478 schist. (d) Migmatite with ~~unregular~~irregular transition between leucosome and
1479 melanosome. (e) ~~The~~Faulted contact ~~zone~~ between meta-sandstones and migmatites.

1480

1481 Fig. 4. Photomicrographs of metamorphic rocks and migmatites from the Qincheng
1482 area, North Tianshan. (a-c) Mica~~s~~schists (12TS119A, B and E) showing preferred
1483 orientations of mica and sillimanite. (d) Meta-sandstone (12TS119F) with weak
1484 orientation of chloritized mica and tabular feldspar grains. (e) Cuspate and lobate
1485 grain boundaries between plagioclase and quartz with chessboard subgrains
1486 (12TS119G). (f) Optically continuous K-feldspar enclosing diamond-shaped quartz

1487 crystals in leucosome (12TS119H). Mineral abbreviations: Kf = K-feldspar; Bt =
1488 biotite; Chl = chlorite; Mus = muscovite; Pl = plagioclase; Qz = quartz; Sil =
1489 sillimanite.

1490

1491 Fig. 5. Cathodoluminescence images for representative ~~detrital~~ zircons from
1492 meta-sandstone (12TS119F) and mica schists (12TS119A, B and E) showing their
1493 apparent $^{206}\text{Pb}/^{238}\text{U}$ ages (<1000 Ma) or $^{207}\text{Pb}/^{206}\text{Pb}$ ages (>1000 Ma). Four types of
1494 zircons can be recognized. See text for more explanations. The CL images of all the
1495 dated zircons can be found in Supplementary Fig. S1.

1496

1497 Fig. 6. Concordia diagrams (a, c, e and g) and U-Pb age probability diagrams (b, d, f
1498 and h), and insets are plots of Th/U ratios vs. U-Pb age for detrital zircons from the
1499 meta-sedimentary rocks, southern Harlik Range.

1500

1501 Fig. 7. Chondrite-normalized REE patterns for detrital zircons from meta-sandstone
1502 12TS119F (a), mica schist 12TS119E (b), and two migmatites 12TS119G and
1503 12TS119H (c-d). Only the Paleozoic detrital zircons with $^{206}\text{Pb}/^{238}\text{U}$ ages between 425
1504 Ma and 475 Ma were analyzed for REE abundances. The grey shaded area is the REE
1505 composition of hydrothermal zircons (after Hoskin, 2005; Yang et al., 2014) and
1506 magmatic zircons of various igneous rocks (Belousova et al., 2002; Hoskin, 2005;
1507 Long et al., 2012a; Yang et al., 2014). Insets are plots of Th/U ratios against U-Pb age.

1508 Chondrite normalization values are from Sun and McDonough (1989).

1509

1510 Fig. 8. (a-b) Cathodoluminescence images showing $^{206}\text{Pb}/^{238}\text{U}$ apparent ages, (c-d)
1511 Concordia diagrams, and (e-f) U-Pb age probability diagrams for the zircons from the
1512 migmatites, Qincheng area, North Tianshan.

1513

1514 Fig. 9. (a) Compilation of zircon U-Pb ages for granites ~~intruding~~ incrosscutting the
1515 meta-sedimentary rocks of the Harlik area (data from Sun et al., 2007b; Wang et al.,
1516 2009c; Chen and Shu, 2010; Chen et al., 2016; Song et al., 2018). (b) U-Pb age
1517 spectra of Paleozoic zircons from the migmatites and meta-sedimentary rocks of the
1518 Qincheng area (this study), North Tianshan.

1519

1520 Fig. 10. Compilation of zircon U-Pb ages from the Qincheng area and neighboring
1521 tectonic units. The right columns show the age distributions of Precambrian zircons
1522 only. DZ: Detrital zircons from sedimentary rocks; IZ: Zircons from igneous rocks
1523 (Inherited zircons were excluded). All the reference data and corresponding literatures
1524 are listed in Supplementary Table S2.

1525

1526 Fig. 11. Tentative cartoon model for the Paleozoic tectonic evolution of the North
1527 Tianshan Belt and adjacent areas.

1528

1529 Table 1. Sample description and analytical data summary.

1530

1531 Supplementary Fig. S1. Cathodoluminescence images for all the dated detrital zircons
1532 from the meta-sedimentary rocks, Qincheng area, North Tianshan.

1533

1534 Supplementary Fig. S2. Discrimination diagrams for magmatic and hydrothermal
1535 zircons of the meta-sedimentary rocks and migmatites (after Hoskin, 2005). (a, c, e
1536 and g) $(\text{Sm}/\text{La})_N$ (chondrite-normalized Sm/La ratio) vs. La (ppm) plots. (b, d, f and h)
1537 Ce/Ce^* (Ce anomaly) vs. $(\text{Sm}/\text{La})_N$ plots. Chondrite normalization values are from
1538 Sun and McDonough (1989).

1539

1540 Supplementary Table S1. LA-ICP-MS zircon U-Pb analytical results of the
1541 meta-sedimentary rocks and migmatites from the Qincheng area, North Tianshan.

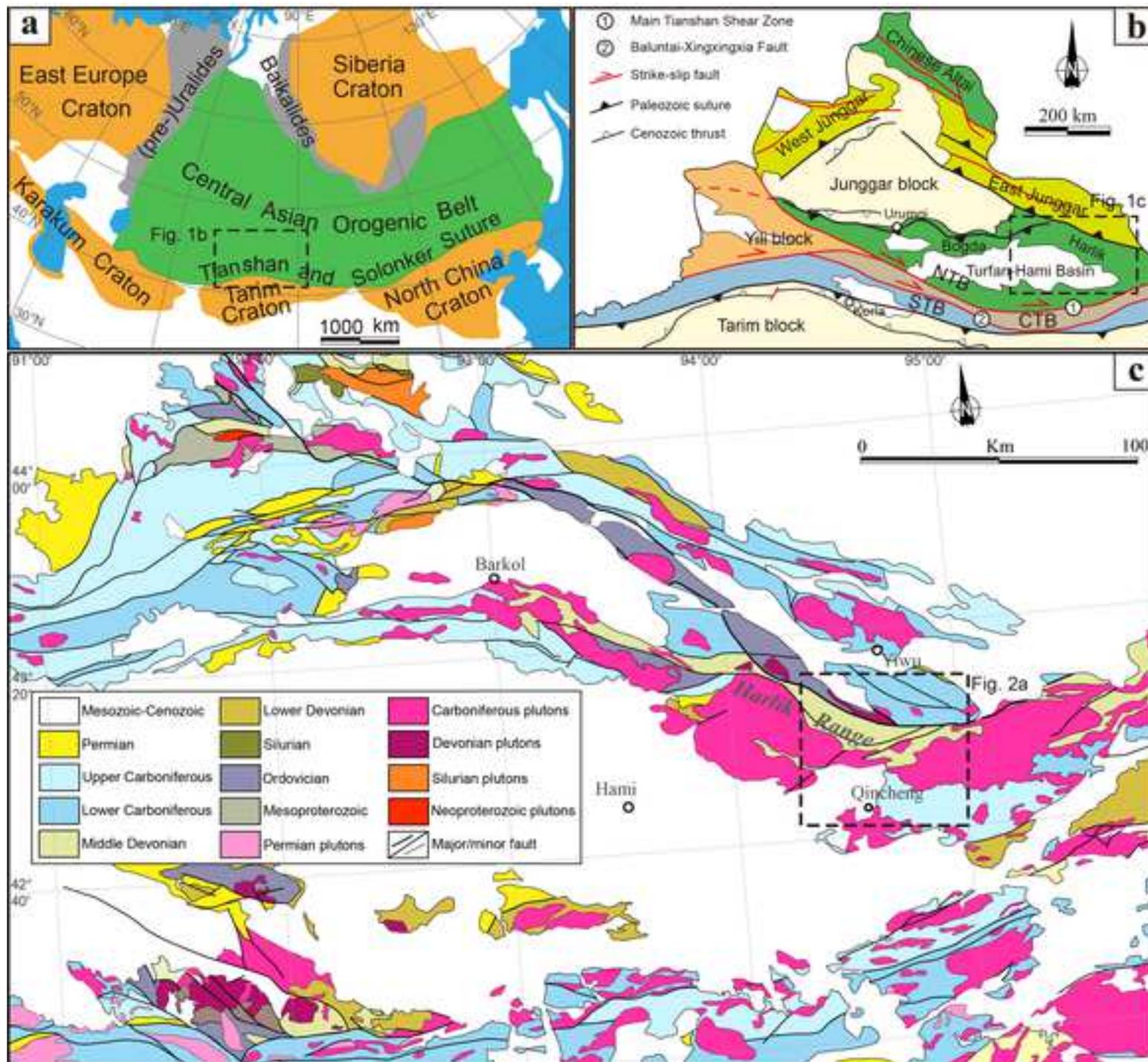
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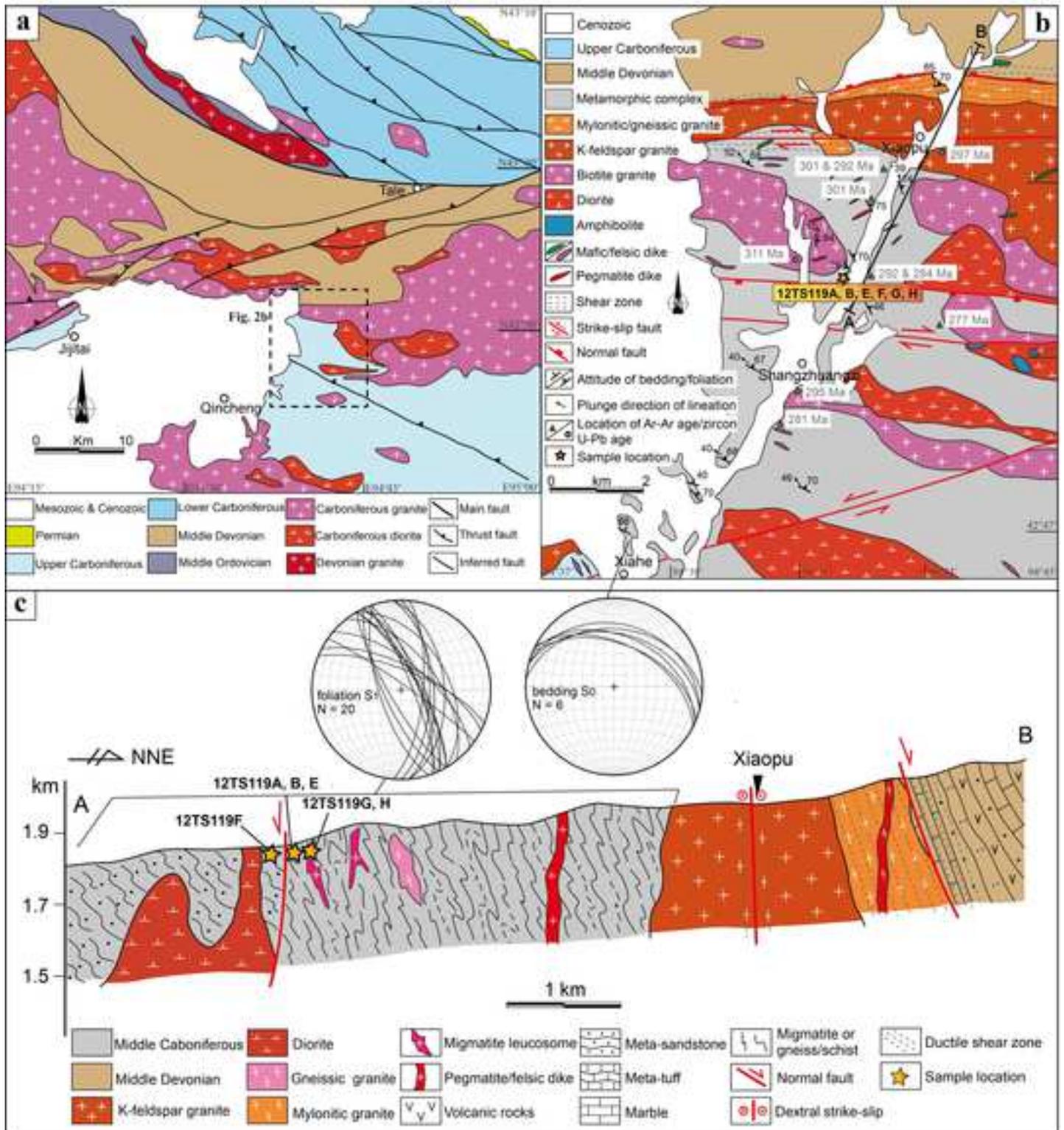
1543 Supplementary Table S2. REE abundances of representative zircons of
1544 meta-sedimentary rocks and migmatites from the Qincheng area, North Tianshan.

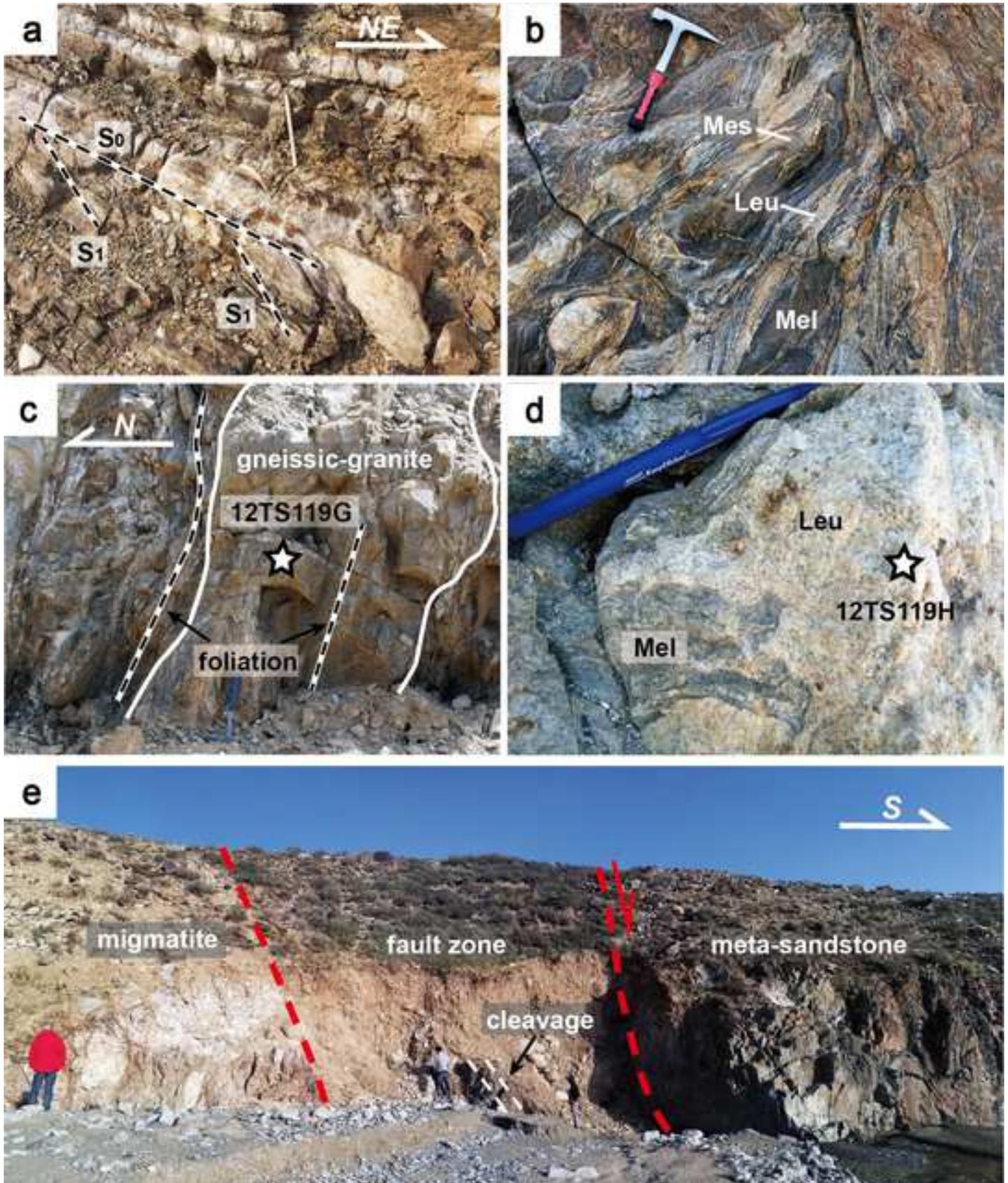
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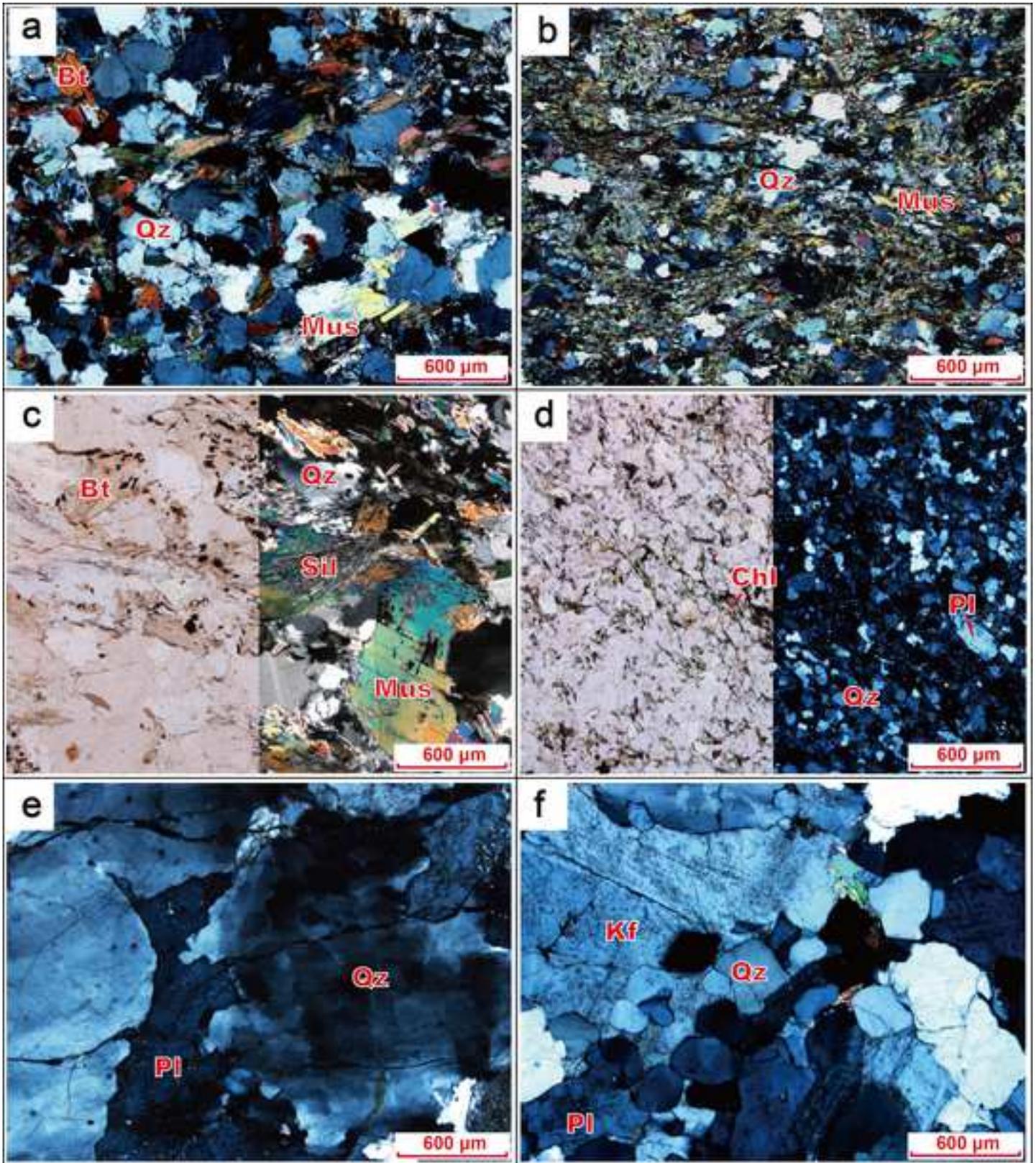
1546 Supplementary Table S3. Compilations of zircon U-Pb ages from the Qincheng area,
1547 North Tianshan and the neighboring Central Tianshan, East Junggar, and Chinese
1548 Altai.

1549









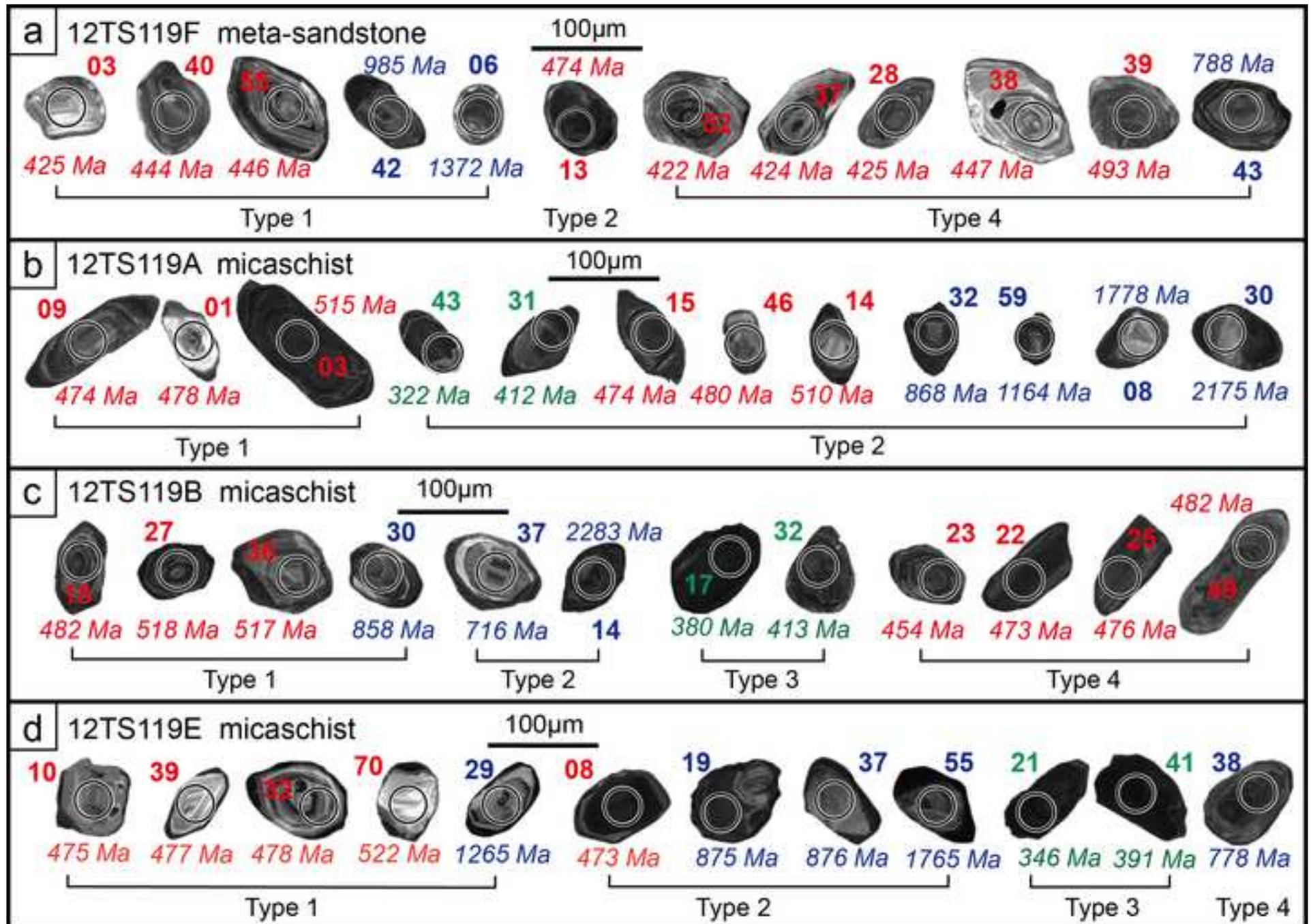
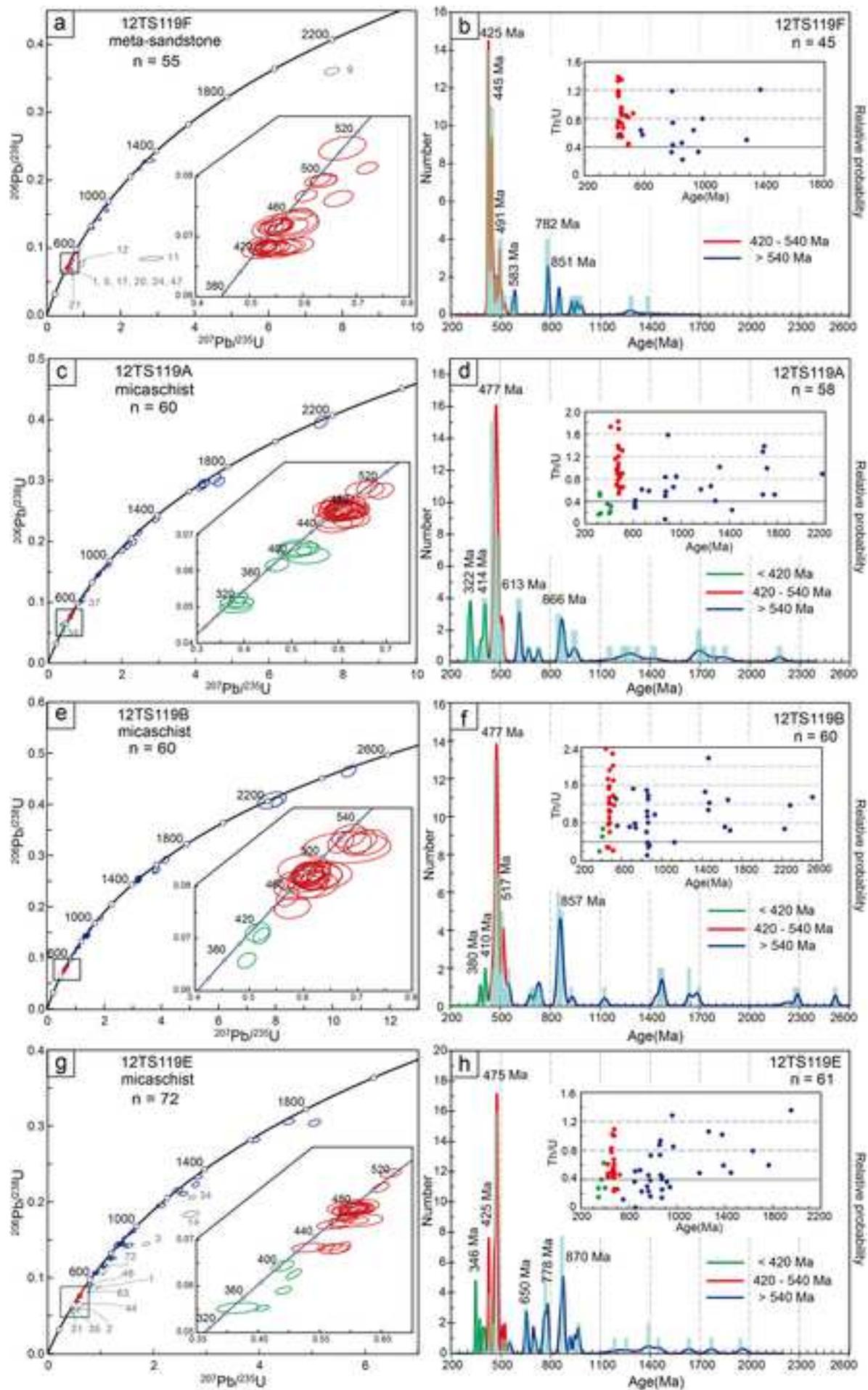
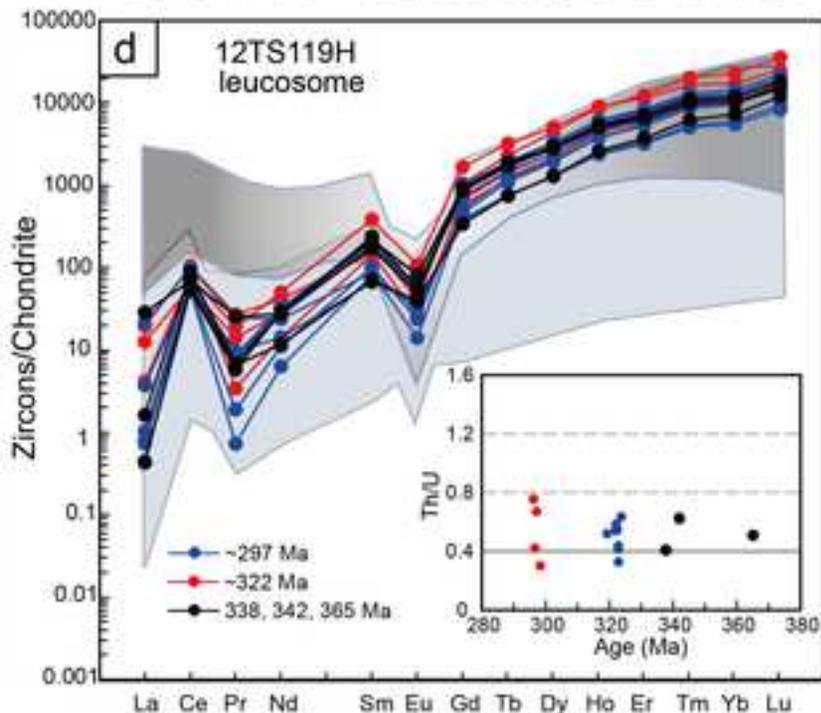
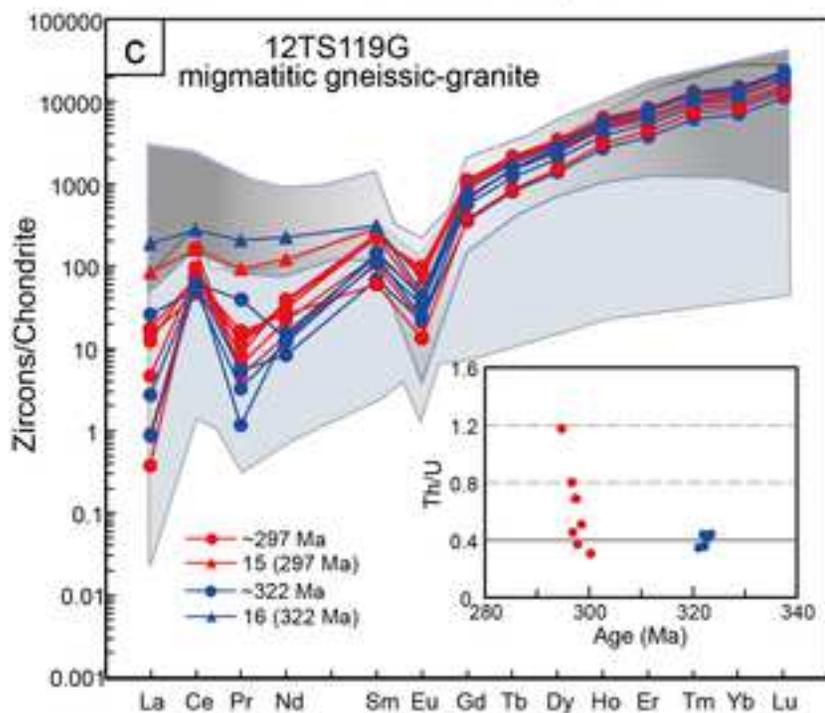
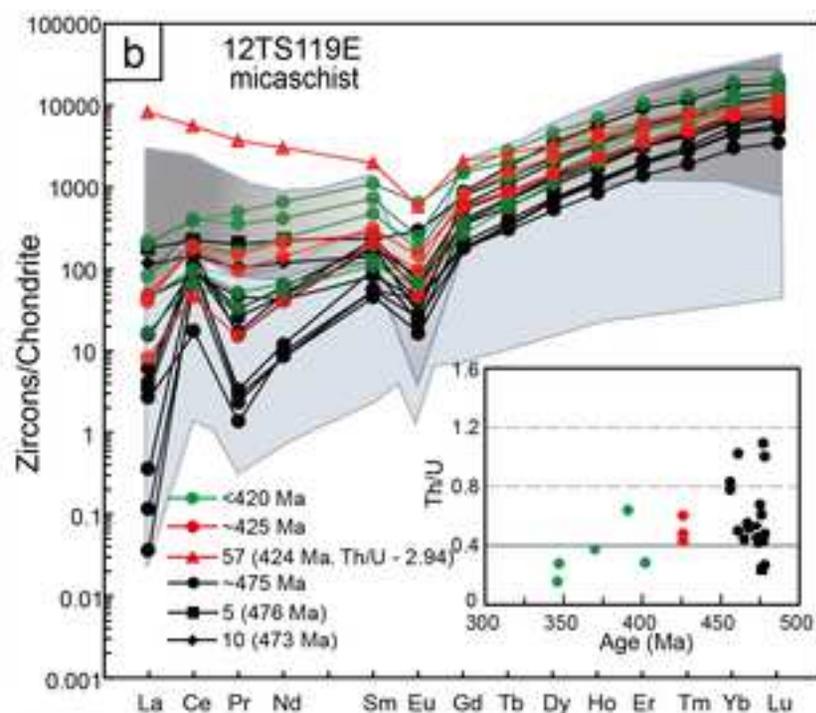
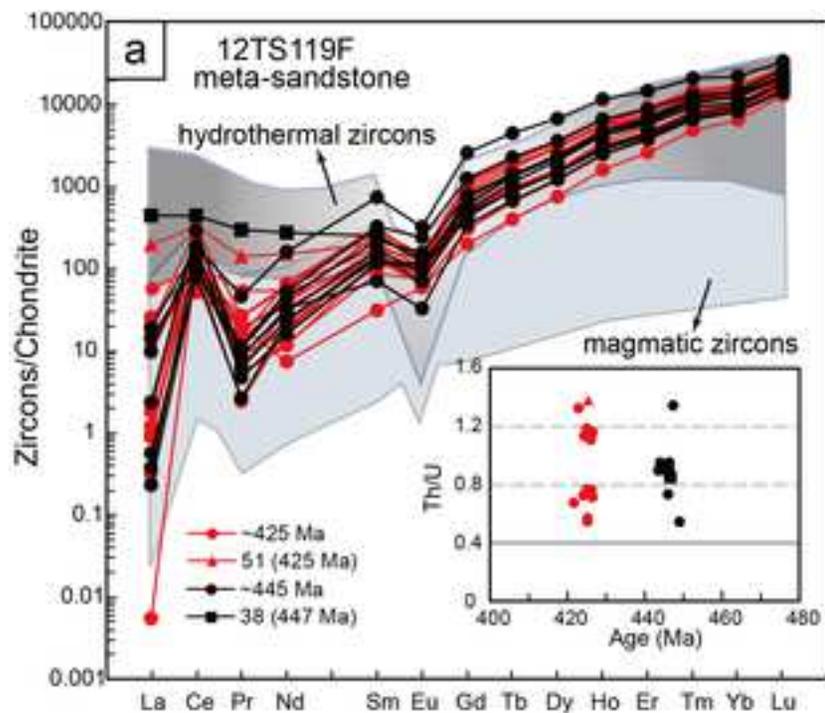
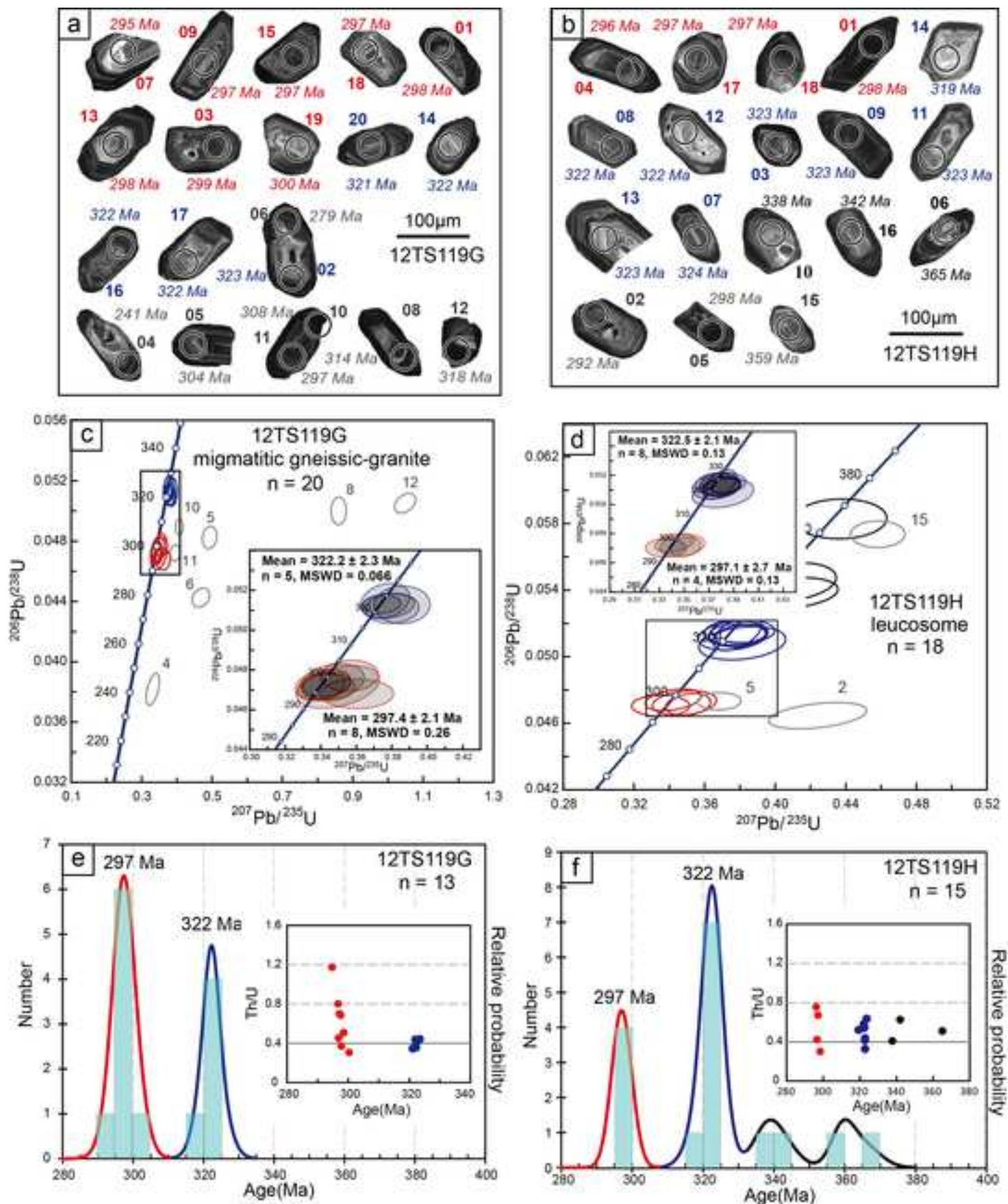


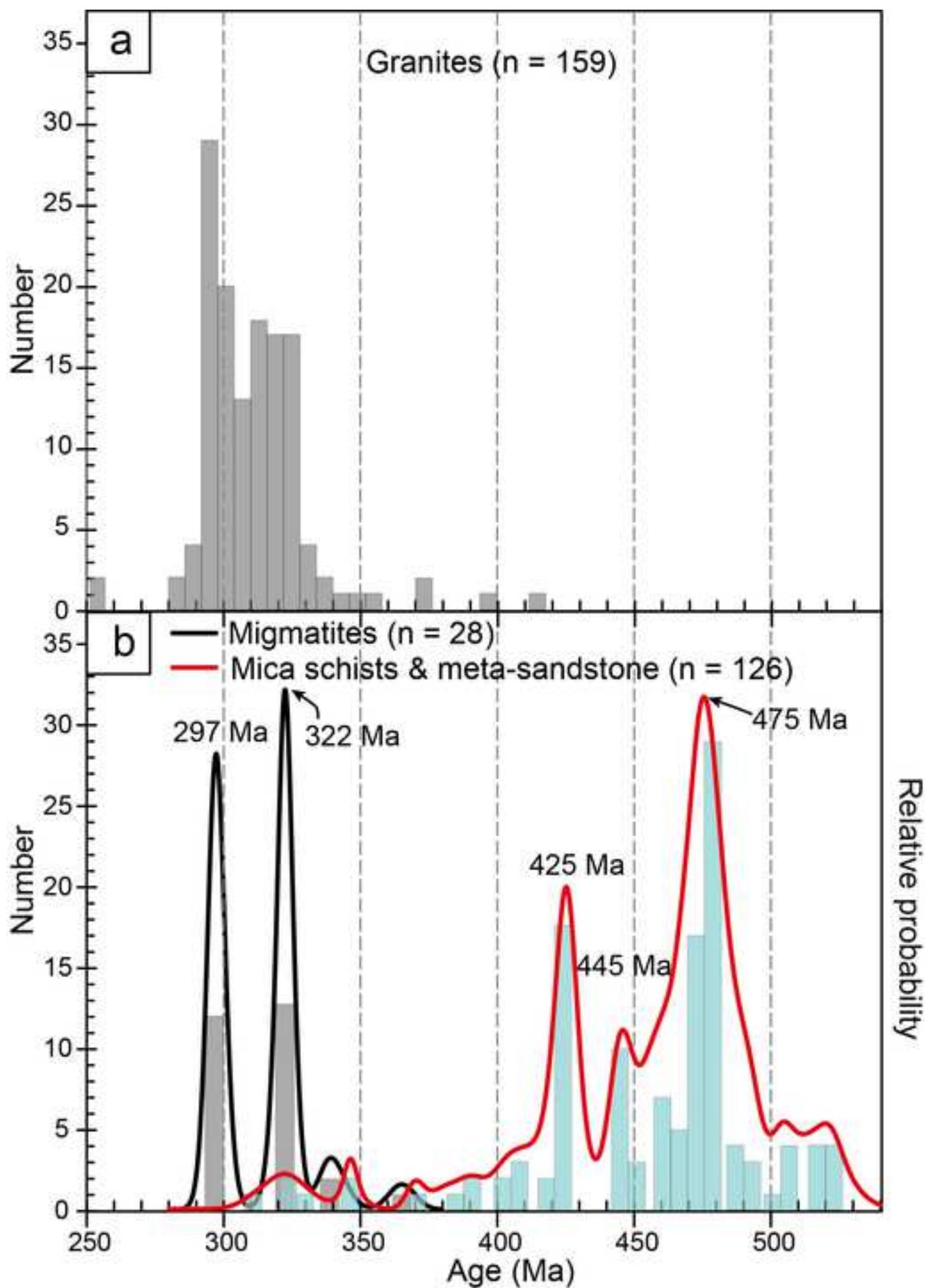
Figure 6

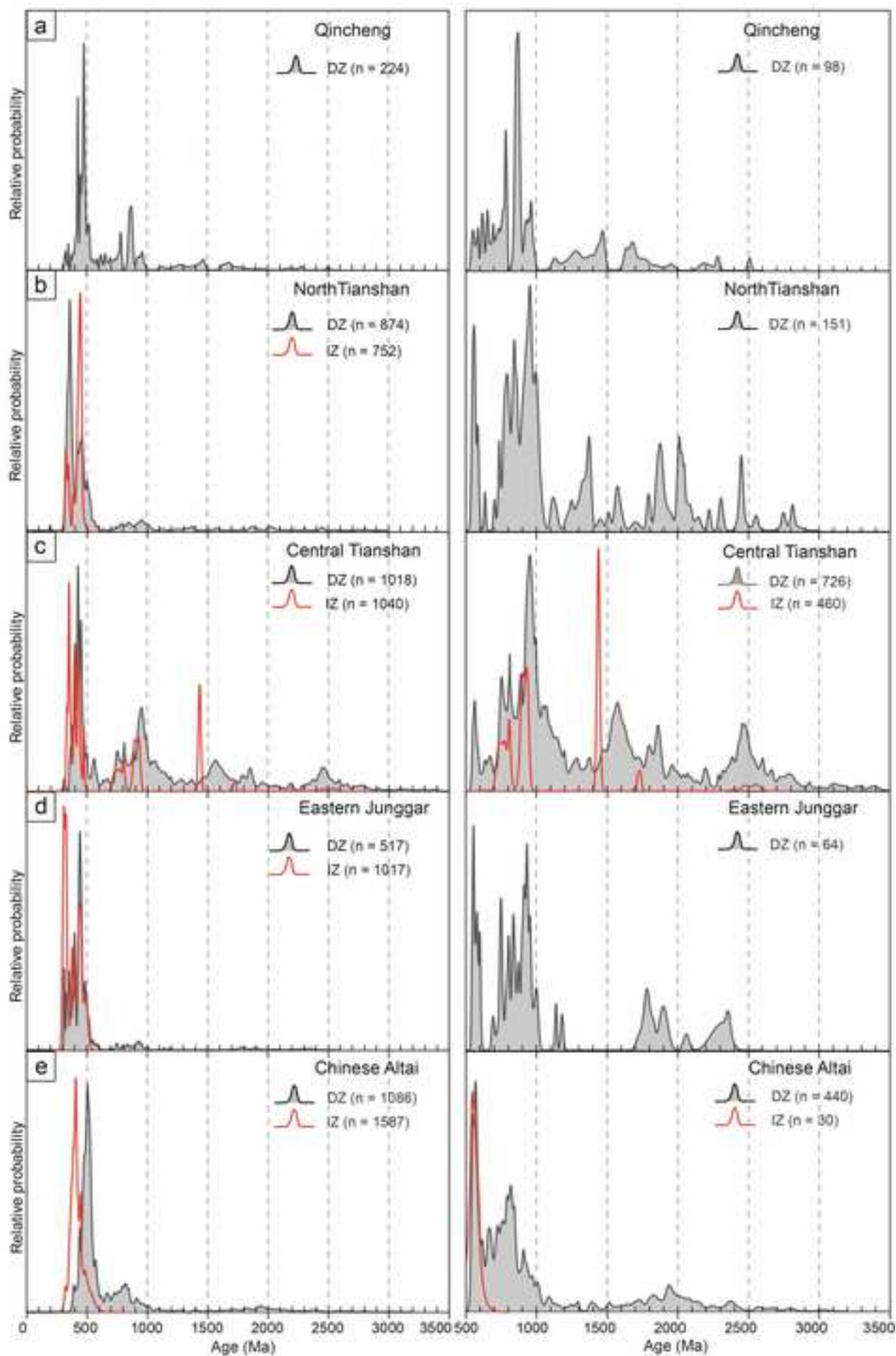
Click here to access/download;Figure;Fig. 6. Concordia diagrams and U-Pb age probability diagrams.jpg



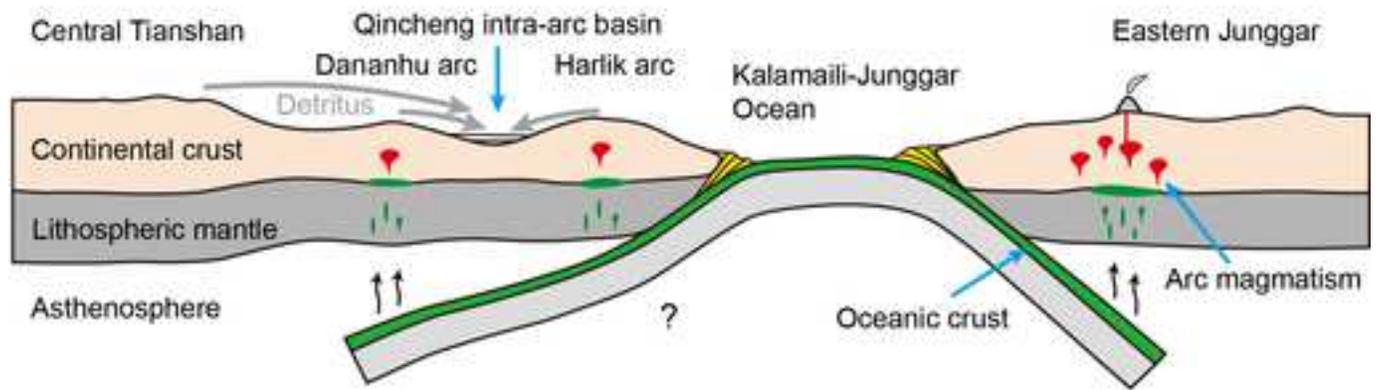




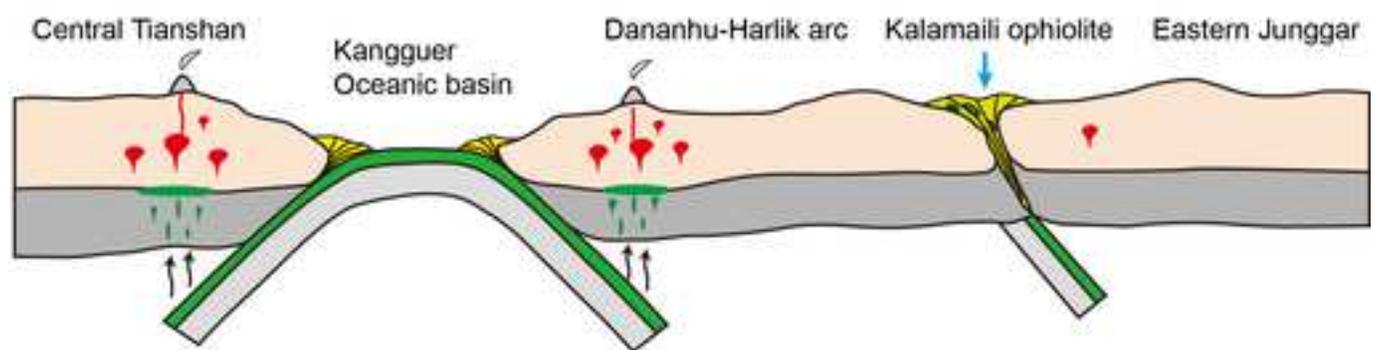




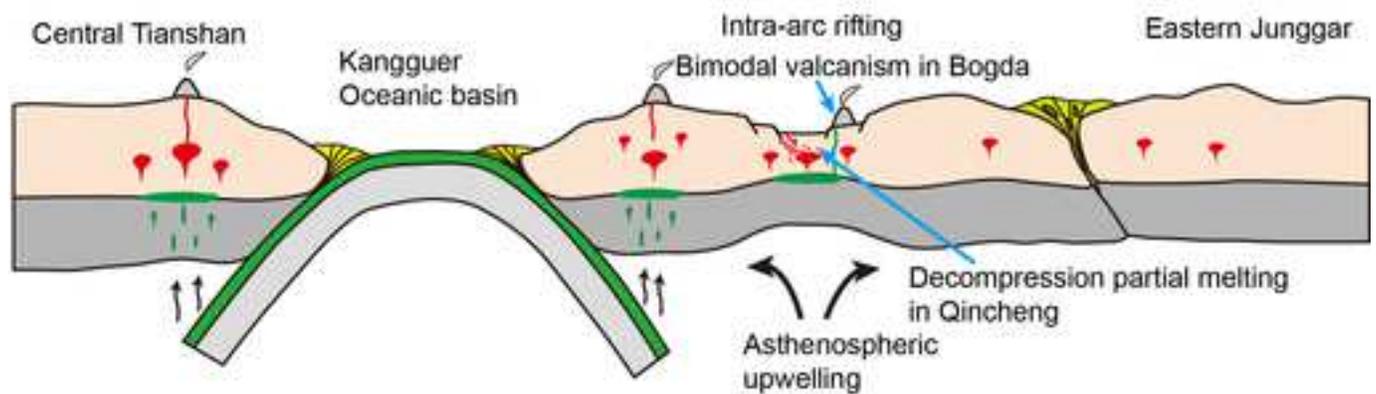
A Pre-Carboniferous?



B Middle Carboniferous (~340 Ma)



C Late Carboniferous (~320 Ma)



D Latest Carboniferous to early Permian (~297 Ma)

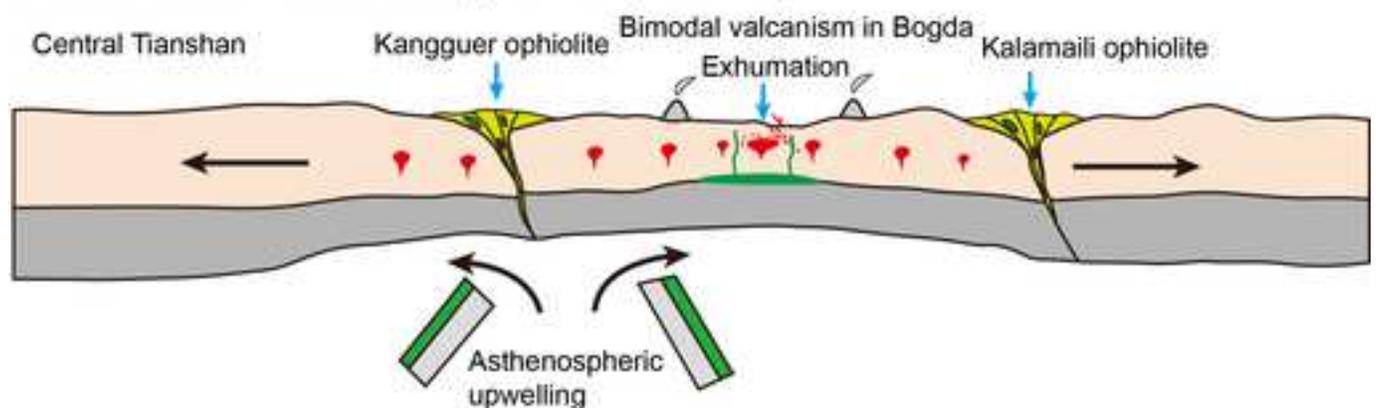
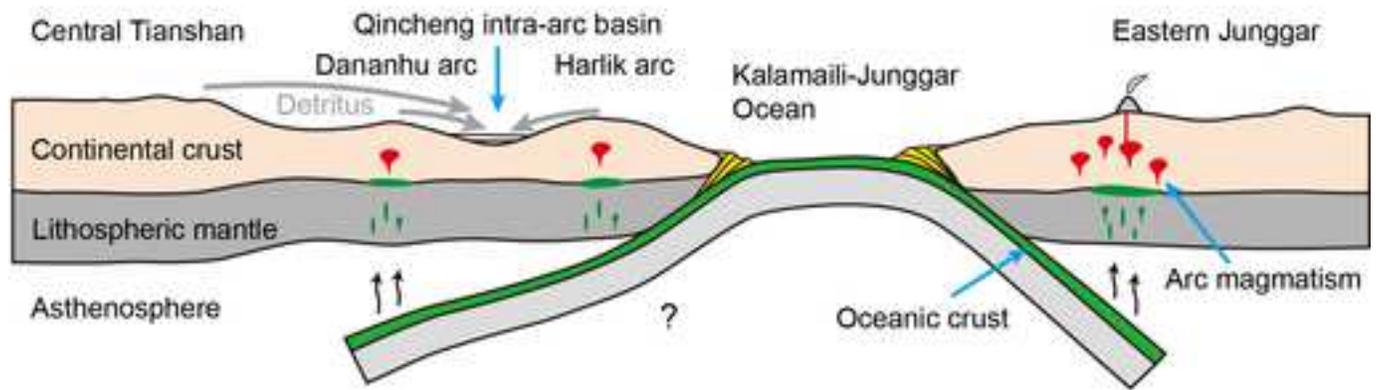


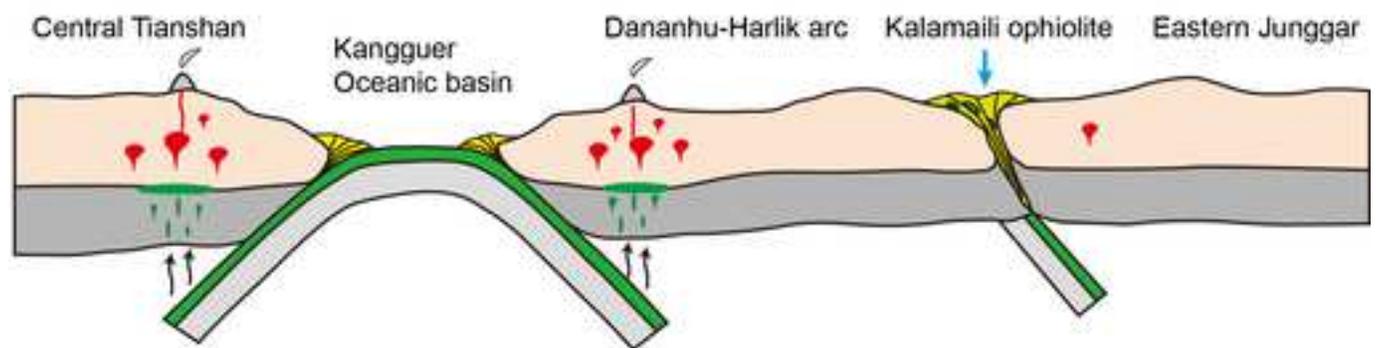
Table 1. Sample description and analytical data summary

Sample No.	Rock type	Petrographic features	Structural features	Age populations
12TS119A	micaschist	Quartz (45-50 vol. %), biotite (20-25 vol. %), plagioclase (10-15 vol. %), muscovite (5-10 vol. %) and a small amount of sillimanite	Oriented biotite and muscovite	Similar age spectra, age populations at: 2500-2175, 1800-1600, 1500-1100, 1000-850, 800-500, ~475, ~425, 420-380, ~346, ~322 Ma
12TS119B	mylonitized micaschist	Quartz (30-35 vol. %), biotite (20-25 vol. %), muscovite (30-35 vol. %) and plagioclase (5-10 vol. %)	Preferred orientation of biotite and muscovite flakes and elongated quartz grains	
12TS119E	micaschist	Quartz (30-35 vol. %), chloritized biotite (20-25 vol. %), muscovite (10-15 vol. %), sericite (20-25 vol. %) and sillimanite (<5 vol. %)	Preferred orientation of biotite and elongated quartz grains	
12TS119F	meta-sandstone	Quartz (60-70 vol. %), chloritized mica (10-15 vol. %), plagioclase (15-20 vol. %)	Weakly oriented tabular feldspar and chloritized mica	Age populations at: 1400-1250, 1000-850, ~780, ~580, ~490, ~445, ~425 Ma
12TS119G	migmatitic gneissic-granite	Quartz (40-45 vol. %), K-feldspar (25-30 vol. %), plagioclase (20-25 vol. %) and a small amount of biotite and muscovite	Lattice bending, undulose extinction, deformation bands and subgrains in quartz and feldspar, lobate grain boundaries	Two age peaks at: 322 and 297 Ma
12TS119H	migmatite leucosome	Quartz (40-45 vol. %), K-feldspar (25-30 vol. %), plagioclase (20-25 vol. %) and a small amount of biotite and muscovite	Optically continuous K-feldspar enclosing equant and diamond-shaped quartz, grain boundary migration recrystallization	Two age peaks at: 322 and 297 Ma. Inherited ages of 338-365 Ma

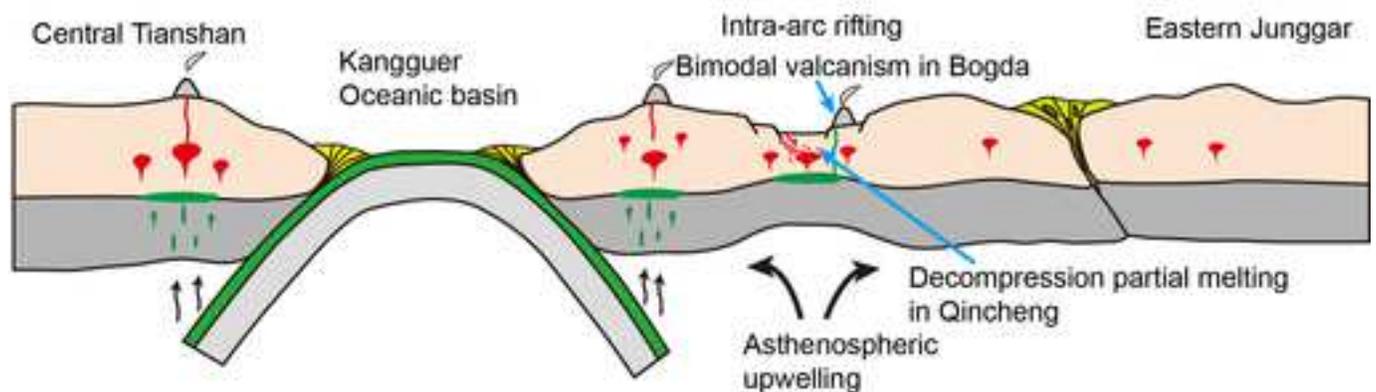
A Pre-Carboniferous?



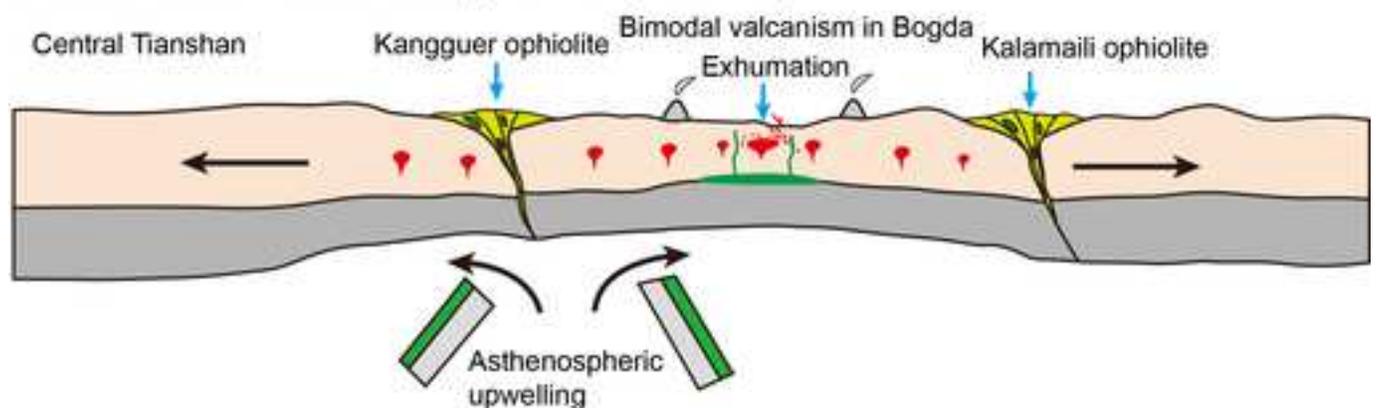
B Middle Carboniferous (~340 Ma)



C Late Carboniferous (~320 Ma)



D Latest Carboniferous to early Permian (~297 Ma)

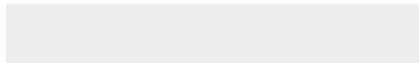








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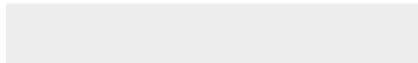


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Declaration of interests

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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Xinghua Ni: Investigation, Conceptualization, Writing-Original Draft, Editing. **Bo Wang:** Supervision, Conceptualization, Funding acquisition, Writing-Reviewing and Editing. **Dominique Cluzel:** Supervision, Investigation, Writing-Reviewing and Editing. **Jiashuo Liu:** Investigation, Writing-Reviewing and Editing. **Zhiyuan He:** Investigation, Writing-Reviewing and Editing.