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

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Abstract:	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.
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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.

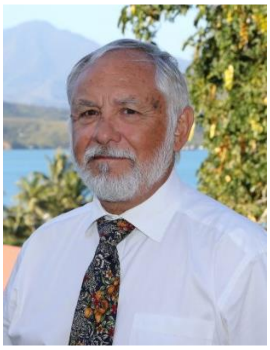
Sincerely,

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.

*Author Agreement

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:

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.

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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-submision.

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.

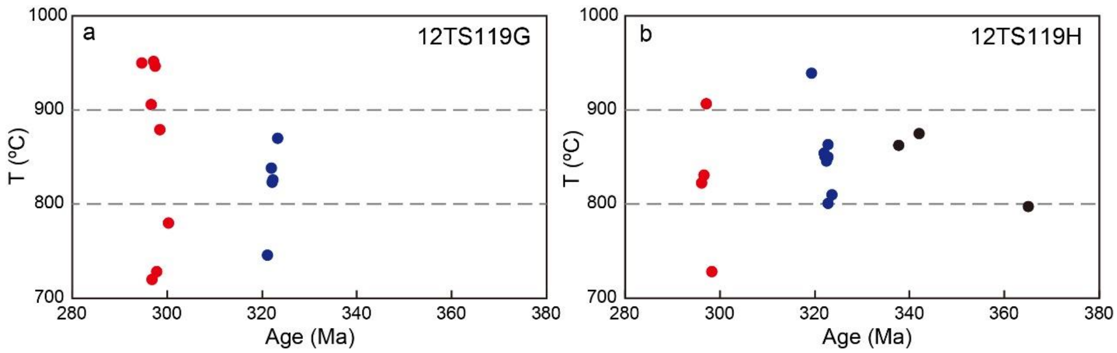

Fig. R1 Calculated crystallization temperature of zircons from two migmatite samples.

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 ℃. 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).

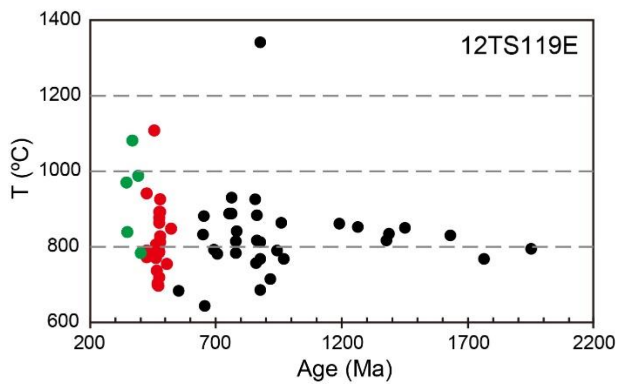

Fig. R2 Calculated crystallization temperature of zircons from the schist sample 12TS119E.

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 carton 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 ^{o} 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 εNd(t) and zircon εHf(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℃, 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 carton 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 carton 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 carton 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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Late Paleozoic tectonic evolution of the North Tianshan Belt: New structural and geochronological constraints from meta-sedimentary rocks and migmatites in the Harlik Range

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Abstract

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 1400-1250, 1000-850, ~780, ~580, ~490, ~445 and ~425 Ma. Three micaschists contain zircon populations of 2500-2175, 1800-1600, 1500-1100, 1000-850, 800-500, ~475, ~425, 420-380, ~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, which are interpreted as two stages of successive partial melting and anatectic melts crystallization. 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 (latest Silurian to late Carboniferous); (2) the Precambrian detrital zircons in the meta-sedimentary rocks were probably derived from the Central Tianshan Block, which was once connected with the NTB; and (3) the migmatization and coeval granitic plutonism occurred at ~322-297 Ma (late Carboniferous), most likely associated with crustal

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

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

1. Introduction

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

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

The Harlik Range is the northeastern part of the Tianshan Orogen where the latter connects with the East Junggar Belt. It is a key area for unraveling the tectonic evolution of the Tianshan Orogen (Xiao et al., 2004; Huang et al., 2018). The tectonic setting and evolution of the Harlik Range remain a matter of debate. Xia et al. (2002, 2012) proposed that it underwent intra-continental rifting in Carboniferous to Permian time; while some other authors suggested a volcanic arc setting during the Ordovician-Carboniferous (Xiao et al., 2004; Han and Zhao, 2018). Additionally, Sun (2007) proposed that it experienced an Ordovician-Silurian arc and a Devonian-Carboniferous back-arc extension.

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

In this study, we present new field structural observations and zircon LA-ICP-MS U-Pb ages of the meta-sedimentary rocks and migmatites from the Harlik Range. These new results combined with previously published data allow us to better constrain the timing of protoliths deposition and metamorphism of these meta-sedimentary rocks, to discuss the provenances of the sediments, and to tentatively replace the high-temperature metamorphism and anatexis in the framework of the late Paleozoic tectonic evolution of the North Tianshan Belt.

2. Geological background

2.1. *Regional tectonic framework*

The Chinese segment of the Tianshan Orogen is geographically divided into eastern and western parts along the Urumqi-Korla line. The eastern Chinese Tianshan is further divided into three tectonic units as the South Tianshan, Central Tianshan and North Tianshan belts (Fig. 1b; Xiao et al., 2004; Li et al., 2006; Charvet et al., 2007). These units are separated from each other by two major faults (namely the Main Tianshan Shear Zone and Baluntai-Xingxingxia Fault), which are dextral strike-slip faults active mainly during the Permian along reactivated older suture zones (Laurent-Charvet et al., 2003; Charvet et al., 2007; Wang et al., 2008, 2014a; de Jong et al., 2009; He et al., 2021).

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

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

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

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

2.2. Geological background of the Harlik Range

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

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

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

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

3. Field geology and sample descriptions

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

In the southern part of the JMC, the sedimentary rocks were weakly deformed and slightly metamorphosed. The bedding (S0) can be easily recognized and cleavage (S1) is well developed, both dip to the northeast with S1 steeper than S0 (Figs. 2b-c and 3a), indicating a normal sequence. Further northwards, S0 is gradually transposed into sub-vertical schistosity with increasing metamorphic grade (Sun, 2007). A migmatite zone of ~1 km wide occurs in the northern part of the JMC. Migmatites are typically flow-folded (Sawyer, 2008) and contain centimeter-thick, garnet-bearing leucocratic dykes. They display all the intermediates between folded and boudinaged leucosome ribbons, foliated (orthogneissic) sills and slightly foliated crosscutting dykes. Leucosomes are surrounded by melanosomes with biotite-rich boundaries and restites of meta-sandstone (Fig. 3b). Foliation in the migmatites is roughly in accordance with that in the surrounding meta-sedimentary rocks (Fig. 3c). Flow-folded migmatites and slightly folded small-scale garnet-bearing leucocratic dykes (Fig. 3b and 3d) indicate a continuum from pre- to late-tectonic in situ partial melting and short-distance transport of anatectic melts. A progressive lateral change from quartzites, schists and crinoidal limestone into migmatites can be observed to the west of the main road, and restites of quartzite and limestone (changed into calc-silicate) locally occur in migmatites.

The southwestern border of the migmatite zone is in fault contact with weakly deformed meta-sandstones (Figs. 2c and 3e). The fault zone, ~5-10 meters in width, was strongly sheared with schistosity/cleavage dipping 70-75° to the south. Considering the difference in metamorphic grade, there was probably a bulk normal-fault motion (Fig. 2c). In addition, the complex deformation of the fault zone likely suggests a polyphase motion. The northern side of the migmatite zone was crosscut by a coarse-grained K-feldspar granite dated at 297 ± 2 Ma (zircon U-Pb age; Chen and Shu, 2010). To the north, the granite is in fault contact with low-grade meta-sedimentary rocks of the Middle Devonian Tousuquan Formation (Fig. 2b-c). The boundary is an E-W-striking mylonite zone dipping steeply to the north, which bears a down-dip stretching lineation. Kinematic indicators in ductilely deformed granites are consistent with a normal-fault motion. Therefore, the high-grade migmatite zone appears in a kind of horst or pop-up structure surrounded by lower-grade meta-sedimentary rocks. Late Carboniferous-early Permian (zircon U-Pb ages of 316-295 Ma) undeformed granodiorite, biotite granite, leucogranite as well as numerous NE-striking pegmatite and mafic dykes crosscut and thus post-date the metamorphic belt (Wang et al., 2009c; Chen and Shu., 2010; Song et al., 2018; Zhu et al., 2018). In addition, the meta-sedimentary rocks yielded Early Permian muscovite and biotite $^{40}Ar/^{39}Ar$ cooling ages ranging from 301 to 277 Ma (Sun, 2007).

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

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

Two samples were taken from migmatitic gneissic-granite (12TS119G) and migmatite leucosome (12TS119H) (Fig. 3d). Both of them are mainly composed of quartz (40-45 vol. %), K-feldspar (25-30 vol. %), plagioclase (20-25 vol. %) and minor muscovite and biotite (Fig. 4e-f). The migmatitic gneissic-granite shows a clear foliation defined by the preferred orientation of micas and elongated quartz ribbons (Fig. 3c). The feldspar and quartz exhibit lattice bending, subgrains, undulose extinction and deformation bands, suggesting that these grains accommodated intracrystalline plastic deformation by dislocation creep (Fig. 4e; Gower and Simpson, 1992; Hirth and Tullis, 1992; Passchier and Trouw, 2005). In addition, typical chessboard subgrains in quartz and lobate grain boundaries between quartz and feldspar indicate high-temperature ductile deformation (Gower and Simpson, 1992; Kruhl, 1996; Stipp et al., 2002). By contrast, the migmatite leucosome (12TS119H) shows nearly equant and diamond-shaped quartz crystals enclosed by optically continuous K-feldspar (Fig. 4f), indicating that quartz crystallized from anatectic melts before K-feldspar crystallized from the remaining melts (Sawyer, 2008). Undulose extinction and recrystallization by grain boundary migration of quartz (Fig. 4f) suggest localized high-temperature ductile deformation.

4. Analytical methods

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

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

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

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

5. Results

5.1. Meta-sandstone

A total of 55 zircon grains were chosen for U-Pb dating from the weakly metamorphosed sandstone sample 12TS119F. The CL images of all dated zircons together with their ages are shown in Supplementary Fig. S1 and those of the representative grains are presented in Fig. 5a. Most zircons have euhedral to sub-euhedral shapes and show clear oscillatory zoning without or with narrow dark rims, indicating original magmatic sources (Connelly, 2000; Corfu et al., 2003; Hoskin and Schaltegger, 2003). A small group of zircons show stubby or sub-rounded shapes and have complex core-rim textures, comprising irregular cores with blurry or patchy zoning and structureless rims. This kind of zircons may have been produced by modification of primary igneous zircons in response to metamorphism (Corfu et al., 2003; Hoskin and Schaltegger, 2003; Rubatto, 2017). The rest few zircons are rounded and sector zoned or without zoning, indicative of metamorphic origin (Figs. 5a and S1; Corfu et al., 2003; Hoskin and Schaltegger, 2003).

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

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

5.2. Micaschists

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

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

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

For the micaschist sample 12TS119A, fifty-eight out of sixty dated zircons yielded concordant ages (Fig. 6c) ranging from 313 to 2175 Ma. They show a dominant age peak at 477 Ma (n = 19; 32.8%), two younger age peaks at 322 Ma (n = 4; 6.9%) and 414 Ma (n = 4; 6.9%), and other populations of 500-550, 600-750, 850-1000,1100-1500, 1600-1800 and 2175 Ma (Fig. 6d). The youngest nine ages (peaked at 322 and 414 Ma) (Fig. 6d; Table S1) 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). Zircons defining the major age peak of 477 Ma mainly belong to the type 1 and type 2, and show Th/U ratios higher than 0.4 (Table S1; Figs. 5b, 6d and S1). The other older zircons cover types 1 and 2, and have variable Th/U ratios mostly higher than 0.4 (Figs. 6d and S1).

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

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

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

5.3. Migmatites

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

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

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

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

6. Discussion

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

The most remarkable age population of detrital zircons from the meta-sandstone and micaschists lies in the 540-420 Ma interval. The micaschists have dominant peaks of 477-475 Ma, while the meta-sandstone shows a peak at 425 Ma that resembles a minor peak of the micaschist 12TS119E (Fig. 6). Since these detrital zircons are mostly of magmatic origins, their ages constrain the maximum depositional ages for the protoliths of meta-sedimentary rocks. 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 as >320 Ma by the crosscutting granite dated at 320 ± 3 Ma (Song et al., 2018).

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

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

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

Regional tectonics, metamorphism, and migmatization have close spatial and temporal relationships with peraluminous leucogranite genesis (e.g., Barrow, 1893; Vernon, 1982; Barton and Hanson, 1989; Okay et al., 2014). Late Paleozoic granite plutons (Figs. 2b and 9) occurred in two episodes at 330-310 Ma and 305-290 Ma (Sun et al., 2007b; Wang et al., 2009c; Chen and Shu, 2010; Chen et al., 2016; Song et al., 2018), which fit the two zircon age peaks of zircons from migmatites (322 Ma and 297 Ma) (Figs. 8 and 9). Moreover, the age of the first episode of granitic magmatism is also consistent with the youngest age peak (322 Ma) of “metamorphic” zircons of the micaschists (Fig. 9b). Therefore, ~322 Ma can be reasonably interpreted as the timing of amphibolite facies metamorphism, migmatization and the first episode of magmatism. As the migmatites also contain zircons of ~297 Ma, it is likely that anatectic melts were not totally crystallized at ~322 Ma probably due to high thermal gradient or continuous addition of melts until ~297 Ma in connection with the second episode of granitic magmatism, giving birth to the crystallization of the younger zircons, while some zircons of ~322 Ma were preserved. Finally, leucogranite dykes of ~308 Ma contain a few inherited zircons with 320-330 Ma ages (Zhu et al., 2018). Such a genetic relationship between migmatites and granites is likely but needs to be confirmed through detailed geochemical investigations.

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

6.2. Provenances of the meta-sedimentary rocks

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

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

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

In addition, it is suggested that the North Tianshan (Harlik-Dananhu arcs) was amalgamated with the Yamansu Arc and Central Tianshan Block at ~320-300 Ma along the Kangguer shear zone after the closure of the Kangguer Ocean (e.g., Li, 2004; Li et al., 2006; Zhang et al., 2020; Zhao et al., 2019). However, the rock sequences on both sides of this shear zone are comparable and it might have been located within the North Tianshan belt (Wang et al., 2008, 2014a; Branquet et al., 2012). 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 also provided certain early Paleozoic detritus for the sediments in the Qincheng area.

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

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.

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

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

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

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

~NW-SE stretching lineation resulted from sinistral transtension (Sun, 2007). In addition, the HT-LP metamorphism (Zhao et al., 1997) and migmatization are coeval with the co-emplacement of undeformed high-K calc-alkaline I- and A-type granites (320-316 Ma) that formed probably in an extensional setting (Song et al., 2018). Similarly, in the nearby Bogda area, 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). Taking all these arguments into consideration, we suggest 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 a continent-based intra-arc or back-arc extensional setting (Fig. 11C).

The migmatites in the Harlik Range also recorded an event at ~297 Ma, which is coeval with the widespread emplacement of undeformed post-orogenic K-feldspar granites and leucocratic two-mica granites at 298-295 Ma (Wang et al., 2009c; Chen and Shu, 2010). The occurrence of ductilely deformed granites along the northern boundary of the metamorphic belt (Fig. 2b-c), and dip-slip (normal) stretching lineation along the north-dipping mylonite zone (see section 3) indicate syn-kinematic emplacement of granites. Therefore, the development of a large volume of latest Carboniferous to earliest Permian post-orogenic granitoids (Wang et al., 2009c, 2009d; Chen and Shu, 2010; Yuan et al., 2010; Chen et al., 2016), bimodal dyke swarms (Gu et al., 1999) and nearly synchronous ductile normal faults correspond to the exhumation of the metamorphic units under a regional post-orogenic extensional regime and thus prominent crustal thinning (Fig. 11D). Final cooling at 301-277 Ma revealed by mica $^{40}Ar/^{39}Ar$ apparent ages (Sun, 2007) indicates that these events terminated during the Early Permian.

7. Conclusions

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

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

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

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Figure and Table captions:

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

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

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

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

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

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

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

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

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

Long et al., 2012a; Yang et al., 2014). Insets are plots of Th/U ratios against U-Pb age. Chondrite normalization values are from Sun and McDonough (1989).

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

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

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

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

Table 1. Sample description and analytical data summary.

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

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

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

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

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

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

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Abstract

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~~ have been done~~, 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 ~~the ~~metamorphic rocks ~~of~~from the~~ Upper Carboniferous Julideneng Formation~~ 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~~west~~. 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 1400-1250, 1000-850, ~780, ~580, ~490, ~445 and ~425 Ma. Three mica~~-~~schists contain zircon populations of 2500-2175, 1800-1600, 1500-1100, 1000-850, 800-500, ~475, ~425, 420-380, ~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, which ~~may be~~are interpreted as ~~the minimum age of youngest protolith~~two stages of successive partial melting and ~~anatectic ~~anatexic ~~magma ~~melts crystallization~~ respectively~~. On the basis of structural features, zircon textures and U-Pb ages, combined~~ing~~ with ~~the ~~already published data, we propose that: (1) the meta-sedimentary rocks of the ~~Julideneng Formation~~JMC were deposited ~~between ~~after 425 Ma and before 322 Ma (latest Silurian to ~~early L~~late Carboniferous); (2) the Precambrian detrital zircons in the meta-sedimentary rocks were probably derived from the Central Tianshan Block, which was once connected with the NTB; and (3) the ~~migmatisation ~~migmatization and coeval granitic plutonism occurred at ~322-297 Ma (l~~L~~ate Carboniferous), most likely associated with crustal thinning resulted ~~in~~from ~~a ~~continent-based~~n~~ intra-arc or back-arc ~~setting to~~or post-orogenic extension~~ setting~~. ~~a late- to post-orogenic setting.~~

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

1. Introduction

The Tianshan Orogen is located in the southernmost part of the Central Asia Orogenic Belt (CAOB), which is one of the largest Phanerozoic orogenic systems on the Earth (Şengör et al., 1993; Windley et al., 2007; Xiao et al., 2013; Safonova, 2017). It recorded the Paleozoic ~~subduction~~consumption of the southern ~~domains of the ~~Paleo-Asian Ocean domains (i.e., the Junggar-~~Balkash ~~North Tianshan Ocean and Paleo-Tianshan Ocean or Turkestan Ocean), successive accretion of ~~various tectonic units including ~~island arcs, accretionary wedges and microcontinents, ~~and~~as well as the final amalgamation/collision ~~of~~between the Kazakhstan and Tarim blocks (e.g., Gao et al., 1998, 2009; Li~~ et al.~~, 2004~~, 2006, 2009~~; Xiao et al., 2004, 2013; Charvet et al., 2007, 2011; Han et al., 2011; –Wang et al., ~~2008,~~ 2011a, 2018~~a; Han et al., 2011~~). Deciphering the subduction-accretion processes~~es~~ of this belt is therefore helpful for a better understanding of the Paleozoic evolution of the southwestern CAOB and Phanerozoic Asia crustal growth (Han and Zhao, 2018; Huang et al., 2020).

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

Carboniferous (Xia et al., 2002, 2012; Ma et al., 2015), late Carboniferous-early Permian (Gao et al., 1998, 2009; Charvet et al., 2007, 2011; Han et al., 2010, 2011; Wang et al., ~~2010, ~~201~~1~~4a~~, 2018a~~;~~ Han et al., 2010, 2011;~~ Han and Zhao, 2018), or end-Permian to mid-Triassic (Xiao et al., 2009; Chen et al., 2020).

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

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

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

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

2. Geological background

2.1. *Regional tectonic framework*

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

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

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

The Central Tianshan Belt (CTB) is composed of a Precambrian basement (Liu et al., 2004; Hu et al., 2010; Ma et al., ~~2012a,~~ 2012b; He et al., 2014~~, 2018b~~; Wang et al., ~~2014b, 2014d,~~ 2017; Han and Zhao, 2018; Huang et al., 2019), Ordovician to early Devonian arc-related volcanic and sedimentary sequences, and ~~early~~ Paleozoic ~~to early Mesozoic~~ intrusive rocks (Xiao et al., 2004, 2013; Shi et al., 2007; ~~Dong et al., 2011;~~ Lei et al., 2011; Ma et al., 2013~~, 2014~~; Zhong et al., 2015; ~~Du et al., 2018a;~~ Han and Zhao, 2018; He et al., 2018b). Both the basement and arc-type rocks are unconformably overlain by unmetamorphosed Carboniferous to Permian ~~sedimentary covers~~sediments (XBGMR, 1993~~; Xiao et al., 2013~~). The CTB is considered either as an independent Precambrian micro-continent involved in the accretion of the Tianshan Orogen (Hu et al., 2000; Huang et al., 2015b, 2017) or as a part of the northern Tarim, which was drifted off and then re-amalgamated with Tarim due to the opening and closure of the South Tianshan back-arc basins (Charvet et al., 2007~~, 2011~~; ~~Wang et al., 2008, 2011a, 2018a;~~ Lei et al., 2011; Ma et al., ~~2012a, 2012b,~~ 2014; Huang et al., 2015a; Gao et al., 2015; Zhong et al., ~~2015,~~ 2017~~, 2019, 2019~~).

The North Tianshan Belt (NTB) refers to the domain between the CTB to the south and the East Junggar Belt to the north (Fig. 1b). This belt is predominantly composed of Ordovician to Carboniferous volcano-sedimentary sequences ~~and~~ crosscut by Paleozoic granitoids~~associated granitesic intrusions~~ (XBGMR, 1993). It is considered as a Paleozoic arc system formed by southward subduction of the Kalamaili Ocean (~~Zhao et al., 2002;~~ Xiao et al., 2004; Yuan et al., 2010; Xie et al., ~~2016a, 2016b,~~ 2016c), and/or by northward subduction of the North Tianshan Ocean (~~Sun, 2007;~~ Ma et al., 2015; Zhang et al., 2017, 2018; Du et al., 2018a; Han and Zhao, 2018; Chen et al., 2019). The NTB is further divided into three sub-units, i.e., the Harlik-Dananhu Arc, Bogda ~~Belt~~ Arc and Kangguer-Yamansu ~~Belt~~ Arc (e.g., Xiao et al., 2004) ~~covering~~ unconformably covered by the Mesozoic-Cenozoic Turpan-Hami Basin ~~whichthat is now filled bywith Mesozoic-Cenozoic sedimentary rocks~~ (Fig. 1b; XBGMR, 1993).

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

2.2. Geological background of the Harlik Range

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

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

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

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

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

3. Field geology and sample descriptions

FOur field investigations were conducted along a section from Qincheng Town to Xiaopu Village, southern Harlik Range (Figs. 2a-2b). The southern part of the section is dominated by variablyvarious schistose tuffs, sandstones and tuffaceous sandstones belonging to the upperUpper Carboniferous Julideneng Formation.; Tthe northern part of theis section consists of Mmiddle Devonian sandstones, tuffaceous sandstones and limestones, which were silicified and crosscut by numerous diabase dykes inshowing NE-SW or nearly E-W strikinges (Fig. 2b; XBGMR, 1966; Sun, 2007). The central part of the section, in between , is a occupied by NW-SE-striking belt of of metamorphic rocks, occurring inalong a NW-SE-striking belt, which extends for >30 km long and ~10 km wide (Figs. 2a-2b; Zhao et al., 1997, 2002; Sun, 2007).), this belt is made of These metamorphic rocks of the Julideneng metamorphic complex (JMC), includeing garnet-sillimanite mica schists, low-grade meta-sandstones, andalusite schists, low-grade meta-sandstones garnet-sillimanite mica schists and migmatites (Zhao et al., 1997; Zhou, 2004; Sun, 2007) . Consequently, we to which we propose there to give the name of suggest naming this metamorphic belt as Julideneng Metamorphic Complex (JMC).

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

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

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

In order to ~~further~~ constrain the ages and provenances of the meta-sedimentary rocks, and the timing of the migmatization, six representative samples were collected from the ~~metamorphic belt~~JMC~~ and were further analyzed~~. Three mica-schist samples (12TS119A, B, E) were taken from the migmatite zone (Fig. 2c). The sample 12TS119A is ~~mainly~~ composed of quartz (45-50 vol. %), biotite (20-25 vol. %), plagioclase (10-15 vol. %), muscovite (5-10 vol. %) and a small amount of sillimanite. The sample 12TS119B is a mylonitized mica-schist and main~~ost~~ly consists of quartz (30-35 vol. %), biotite (20-25 vol. %), muscovite (30-35 vol. %) and plagioclase (5-10 vol. %). Another slightly altered sample 12TS119E is ~~primarily made up~~composed of quartz (30-35 vol. %), chloritized biotite (20-25 vol. %), muscovite (10-15 vol. %), sericite (20-25 vol. %) and minor sillimanite (< 5 vol. %). In these mica-schists, the preferred orientation of biotite and/or muscovite and elongated quartz grains define ~~a~~ well-developed foliations (Fig~~s~~. 4a-4c).

One sample (12TS119F; Fig. 2c) was collected from the meta-sandstones that are in fault contact with the migmatites (Fig. 3e). This meta-sandstone is mainly composed of quartz (60-70 vol. %), chloritized mica (10-15 vol. %) and plagioclase (15-20 vol. %). The chloritized micas are weakly oriented ~~to form~~and define an almost unnoticeable foliation~~s that are sometimes unremarkable~~ due to ~~mostly~~ the fine-grain~~ed,~~ and ~~angular~~ equidimensional shape of quartz and plagioclase (Fig. 4d). ~~Intensive~~ U~~u~~ndulose extinction and bulging dynamic recrystallization of quartz ~~can be commonly observed under~~in ~~thin sections~~ (Fig~~s~~. 4a-4d)~~,~~ indicate~~ing a~~ ductile deformation of these meta-sedimentary rocks under moderate temperature conditions.

~~Additional t~~Two ~~more~~ samples were taken from ~~migmatitic gneissic~~

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

4. **Analytical methods**

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

~~The analyses of~~ U-Pb dating and trace elements analysis of representative zircons were conducted in two laboratories. The samples 12TS119A and 12TS119B were dated at the SKL-MDR of Nanjing University using Agilent 7500a inductively coupled plasma mass spectrometry (ICP-MS) coupled to a New Wave 193 nm laser ablation system with an in-house sample cell. The detailed analytical procedures are similar to those described in Jackson et al. (2004) and Liu et al. (2014). The U-Pb dating and trace elements analyses of zircons from samples 12TS119E, 12TS119F, 12TS119G and 12TS119H were carried out at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (Wuhan), where laser sampling was performed using a GeoLas 2005 System and an Agilent 7500a ICP-MS instrument was used to acquire ion-signal intensities. The detailed operating conditions and analytical procedures are described in Liu et al. (2008, 2010a, 2010b).

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

5. Results

5.1. Meta-sandstone

A total of 55 zircon grains were chosen for U-Pb dating from the weakly metamorphosed sandstone sample 12TS119F. The CL images of all dated zircons together with their ages are shown in Supplementary Fig. S1 and those of the representative grains are presented in Fig. 5a. Most zircons have euhedral to sub-euhedral shapes and show clear oscillatory zoning without or with narrow dark rims, indicating original magmatic sources (Connelly, 2000; Corfu et al., 2003; Hoskin and Schaltegger, 2003). A small group of zircons show stubby or sub-rounded shapes and have complex core-rim textures, comprising irregular cores with blurry or patchy zoning and structureless rims. This kind of zircons may have been produced by modification of primary igneous zircons in response to metamorphism (Corfu et al., 2003; Hoskin and Schaltegger, 2003; Rubatto, 2017). The rest few zircons are rounded and ~~unzoned or~~ sector zoned or without zoning, indicative of metamorphic origin (Figs. 5a and S1; Corfu et al., 2003; Hoskin and Schaltegger, 2003).

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

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

5.2. Mica~~-~~schists

From three mica~~-~~schist samples, a total of 192 zircon grains were analyzed, which show various sizes, sub-rounded to sub-euhedral shapes and complicated internal textures (Figs. 5 and S1). According to their CL images, four types of zircons~~s~~ can be recognized. (1) Type 1 zircons have core-rim textures in which the cores are bright with oscillatory zoning and the rims are relatively dark and un-zoned, corresponding to originally magmatic zircons surrounded by metamorphic overgrowths (Hoskin and Schaltegger, 2003). (2) Type 2 zircons also show core-rim textures with bright un-zoned cores, which ~~were either~~could be originally metamorphic ~~and~~ then subjected to secondary metamorphic or hydrothermal overgrowth.~~,~~ ~~or a~~Alternatively, they could also be originally magmatic but were intensively “reworked” (via solid-state recrystallization or local dissolution-reprecipitation) by the subsequent metamorphism or alteration so that the original magmatic oscillatory zoning ~~were~~ was totally erased. In the latter case, the overgrowth rims may have formed synchronously with the reworking of the cores or even reflect a later metamorphic and/or hydrothermal event (Hoskin and Schaltegger, 2003). (3) Type 3 zircons have homogeneous dark to black CL images without visible oscillatory zoning, likely formed by metamorphism or hydrothermal ~~alteration~~ activities (Connelly, 2000; Corfu et al., 2003; Hoskin and Schaltegger, 2003). (4) Type 4 zircons are characterized by prismatic shapes and moderately bright CL images with clearly concentric magmatic oscillatory zoning, ~~and no~~without visible overgrowths. –

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

For the mica~~-~~schist sample 12TS119A, fifty-eight out of sixty dated zircons yielded concordant ages (Fig. 6c) ranging from 313 to 2175 Ma. They show ~~showing~~ a dominant age peak at 477 Ma (n = 19; 32.8%), two younger age peaks at 322 Ma (n = 4; 6.9%) and 414 Ma (n = 4; 6.9%), and other populations of 500-550, 600-750, 850-1000,1100-1500, 1600-1800 and 2175 Ma (Fig. 6d). The youngest nine ages (peaked at 322 and 414 Ma) (Fig. 6d; Table S1) 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). Zircons defining the major age peak of 477 Ma mainly belong to the~~ type 1, type 2 and minor type 4~~ type 1 and type 2, and show Th/U ratios higher than 0.4 (Table S1; Figs. 5b, 6d and S1). The other older zircons cover~~ all four types~~ types 1 and 2, and have variable Th/U ratios mostly higher than 0.4 (Figs. 6d and S1).

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

As for the sample 12TS119E, sixty-one out of seventy-two zircons provided concordant ages ranging from 346 to 1765 Ma (Fig. 6g-6h). A major age peak at 475 Ma (n = 11; 18.0%) and a minor age peak at 425 Ma (n = 5; 8.2%) are mainly defined by types 1 and 2 zircons (Figs. 5d and S1), which mostly show Th/U ratios higher than 0.4 (Fig. 6h; Table S1). These zircons show steeply-rising REE patterns, remarkable positive Ce anomalies and negative Eu anomalies (Fig. 7b). Thus, these ages are indicative of magmatic events (Hoskin and Schaltegger, 2003; Hoskin, 2005). One exceptional zircon (No. 57; ~424 Ma) shows a quite high Th/U ratio (2.93; Table S1). ~~and f~~For some unclear reasons, a ~~U~~V-shaped REE pattern due to its high LREE content is similar to that of some “hydrothermal” zircons (~~-~~Fig. 7b). Five zircons of types 2 and 3 with dark, homogenous CL images (Figs. 5d and S1) yielded ages ~~of~~from 346 to 402 Ma, they display gently-rising REE patterns with weak Ce anomalies and Th/U ratios mostly lower than 0.4 (Figs. 6h and 7b), similar to zircons of hydrothermal origin (Fig. 7b). With only a few exceptions, the other age populations (500-550, 600-800, 850-1000, 1100-1400 and 1600-1800 Ma) correspond to all four zircon types (Fig~~s~~. 6g-6h) with Th/U ratios mostly ~~>~~higher than 0.4 (Fig. 6h; Table S1).

5.3. Migmatites

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

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

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

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

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

6. Discussion

6.1. ~~Depositional~~ Protoliths depositional and metamorphic ages of the meta-sedimentary rocks

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

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

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

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

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

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

Regional tectonics, metamorphism, and mi~~a~~gmati~~s~~zation ~~and deformation are known to be in~~has close spatial and temporal relationships with peraluminous leucogranite~~oid~~ ~~emplacement~~ genesis (e.g., Barrow, 1893; Vernon, 1982; Barton and Hanson, 1989; Keay et al., 2001; Okay et al., 2014). ~~A comparison betweenof the new zircon U-Pb ages of the meta-sedimentary rocks and migmatites (from this study) withand the published zircon U-Pb agesones of the crosscutting granitic plutons (Figs. 2b and 9) shows that the~~ Late Paleozoic~~Carboniferous to eEarly Permian~~ ~~crosscutting~~ granite plutons (Figs. 2b and 9) ~~magmatism~~ occurred in two episodes at 330-310 Ma and 305-290 Ma (Sun et al., 2007b; Wang et al., 2009c; Chen and Shu, 2010; Chen et al., 2016; Song et al., 2018~~reference~~)~~; (Fig. 9a)~~, which fit the two zircon ~~peak~~ age~~s~~ peaks of zircons from migmatites (322 Ma and 297 Ma)~~; of zircons inin the migmatites~~ (Figs. 8 and 9~~b~~). Moreover, the age of the first episode of granitic magmatism is also consistent with the youngest ~~peak~~ age peak (322 Ma) ~~for~~ of “metamorphic” zircons of the mica–schists (Fig. 9b). Therefore, ~322 Ma can be reasonably interpreted as the timing of amphibolite facies metamorphism, ~~in connection with the~~ migmatization and the first episode of magmatism. As the migmatit~~ic leucosom~~es also contain~~s~~ zircon~~-grain~~s of ~~zircons at~~ ~297 Ma~~ zircon grains~~, it is likely that ~~the migmatites remelted again~~anatexic melts were not totally crystallized at ~322 Ma probably due to high thermal gradient or continuous addition of melts ~~at~~until ~297 Ma~~,~~ ~~associated~~ in conne~~x~~ction with the second episode of granitic magmatism, ~~leading~~ giving birth to the ~~zircon~~ crystallization of the younger zircons, while some ~~inherited~~ zircons ~~at~~of ~322 Ma were preserved. ~~This hypothesis~~ Finally, ~~is supported by the occurrence of ~308 Ma~~ leucogranite~~ic~~ dykes of ~308 Ma contain~~ing~~ a few inherited zircons ~~at~~with 320-330 Ma ages (Zhu et al., 2018).~~,~~ Such a genetic relationship between migmatites and granites ~~and~~ will need~~s~~ ~~verification~~ to be ~~comforted~~confirmed ~~with~~ through detailed geochemical investigations.

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

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

6.2. Provenances of the meta-sedimentary rocks

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

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

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

In addition, it is suggested that the North Tianshan (Harlik-Dananhu ~~Arc~~arcs) was amalgamated with the Yamansu Arc and Central Tianshan Block at ~320-300 Ma along the Kangguer shear zone after the closure of the Kangguer Ocean (e.g., Li, 2004; Li et al., 2006; Zhang et al., ~~2015b,~~ 2016b, 2020; Zhao et al., 2019). However, the rock sequences on both sides of this shear zone are comparable and it ~~may be~~might have been ~~actually~~ located within the North Tianshan belt (Wang et al., 2008, 2014a; Branquet et al., 2012). 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 ~~was opening~~opened during the mid-late Carboniferous. Considering that the Precambrian zircons most likely came from the Central Tianshan Block (see discussion ~~blew~~below), it is possible that the Central Tianshan Block ~~also~~ have also provided ~~some~~certain early Paleozoic detritus for the ~~meta-~~sediments in the Qincheng area.~~Due to the uncertainty about the nature and the timing of the closure of the Kangguer Ocean, 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.~~

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

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

The Precambrian zircons in the meta-sedimentary rocks are ~~an~~euhedral in shape and show complex core-rim textures (Figs. 5 and S1), indicating that they ~~are~~were multiple-cycled. Thus, these Precambrian zircons were probably ~~were~~ transported from the Central Tianshan Block to the North Tianshan Belt (Dananhu Arc) before the opening of the ~~the~~ North Tianshan (or Kangguer) Ocean, and ~~then were~~thereafter re-transported into the ~~the~~ Harlik area. This is ~~consistent~~in agreement with the fact that zircon populations of Devonian flysch ~~sediments~~s ~~from~~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 ~~be also~~have been ~~directly be~~ transported directly from the Central Tianshan Block as well.~~to the Harlik because of the rough constraints on their depositional age.~~

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

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

Our new zircon U-Pb data indicate that the meta-sediments from the ~~Julideneng Formation~~JMC were deposited in the interval between l~~L~~ate Silurian and ~~early L~~late

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

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

N-dipping foliations that bear~~ing~~ ~NW-SE stretching lineation~~s~~ ~~were likely~~ resulted from sinistral transtension (Sun, 2007). In addition, the HT-LP metamorphism (Zhao et al., 1997) and migmatization are coeval with the co-emplacement of undeformed high-K calc-alkaline ~~undeformed~~ I- and A-type granites (320-316 Ma) that formed probably ~~by with positive whole-rock $\varepsilon_{Nd}(t)$ and zircon $\varepsilon_{Hf}(t)$ values, both of which are diagnostic of decompression melting of juvenile crustal sources~~ in an extensional setting (Song et al., 2018). Similarly, in the nearby Bogda ~~Belt~~area, 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., ~~2016a,~~ 2016b~~, 2016c~~). Taking all these arguments into consideration, we suggest 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 ~~a late-orogenic extensional setting~~ a continent-based~~n~~ intra-arc or back-arc ~~extensional~~~~rift~~extensional setting (Fig. 11C).

The migmatites in the Harlik Range also recorded an event at ~297 Ma, which is coeval with the widespread emplacement of undeformed post-~~collisional~~ orogenic K-feldspar granites and leucocratic two-mica granites at 298-295 Ma (Wang et al., 2009c; Chen and Shu, 2010). The occurrence of ductilely deformed granites ~~of~~with ~~the same age~~ along the northern boundary of the metamorphic ~~units~~ belt (Fig. 2b-~~2~~c), and ~~down~~ dip-slip (normal) stretching lineation ~~with normal-fault motion~~ along the north-dipping mylonite zone (see section 3) indicate syn-~~tectonic~~ kinematic emplacement of granites. Therefore, the development of a large volume of latest Carboniferous to earliest Permian post-~~collisional~~ orogenic granitoids (Wang et al., 2009c, 2009d; Chen and Shu, 2010; Yuan et al., 2010; Chen et al., 2016), bimodal dyke swarms (Gu et al., 1999) and nearly synchronous ductile normal faults correspond to the exhumation of the metamorphic units under a regional post-orogenic extensional regime and thus prominent crustal thinning (Fig. 11D). Final cooling at 301-277 Ma revealed by mica $^{40}Ar/^{39}Ar$ apparent ages (Sun, 2007) indicates that these events terminated during the Ee~~E~~arly Permian.

7. **Conclusions**

(1) ~~The~~ Protoliths of the meta-sedimentary rocks ~~of~~ from the Julideneng Metamorphic Complex~~Julideneng Formation~~ in the southern Harlik Range were originally deposited between the latest Silurian and ~~early L~~late Carboniferous (425-322 Ma).

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

(3) ~~The HT-LP~~High-grade metamorphism and ~~migmatisation~~ migmatization occurred at ~322 Ma in the southern Harlik Range ~~occurred in~~ a~~were~~ probably related to continent-based~~n~~ intra-arc or back-arc crust thinning~~extensional setting~~a

~~late-orogenic extensional setting~~. The orogenic events in the Harlik Range terminated ~~in~~ before the eE~~E~~arly Permian.

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Figure and Table captions:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Table 1. Sample description and analytical data summary.

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

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

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

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

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

Figure 1 Click here to access/download;Figure;Fig. 1. Map of North Tianshan.jpg

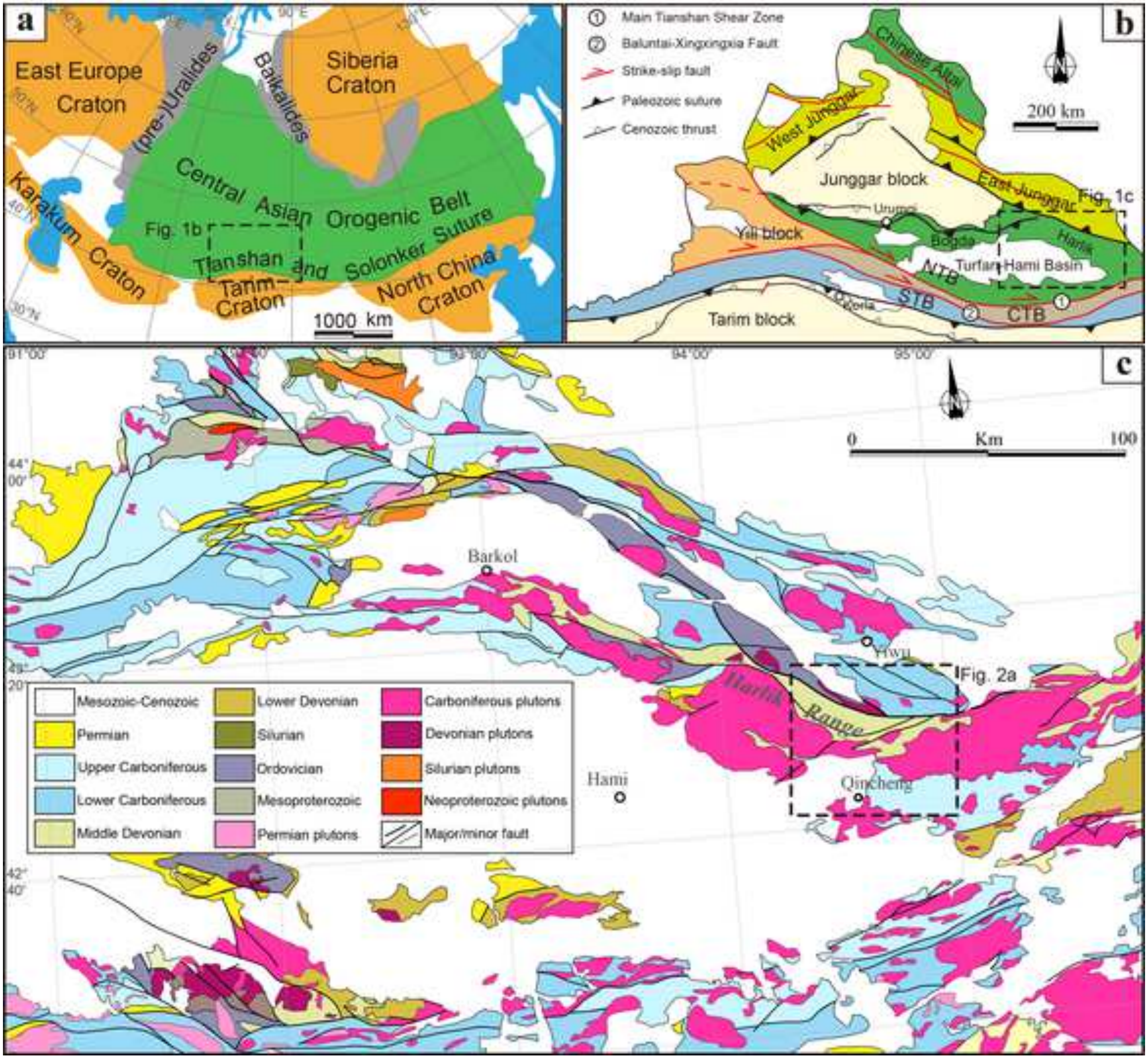


Figure 2

Click here to access/download;Figure;Fig. 2. Geological map of the Qincheng area.jpg

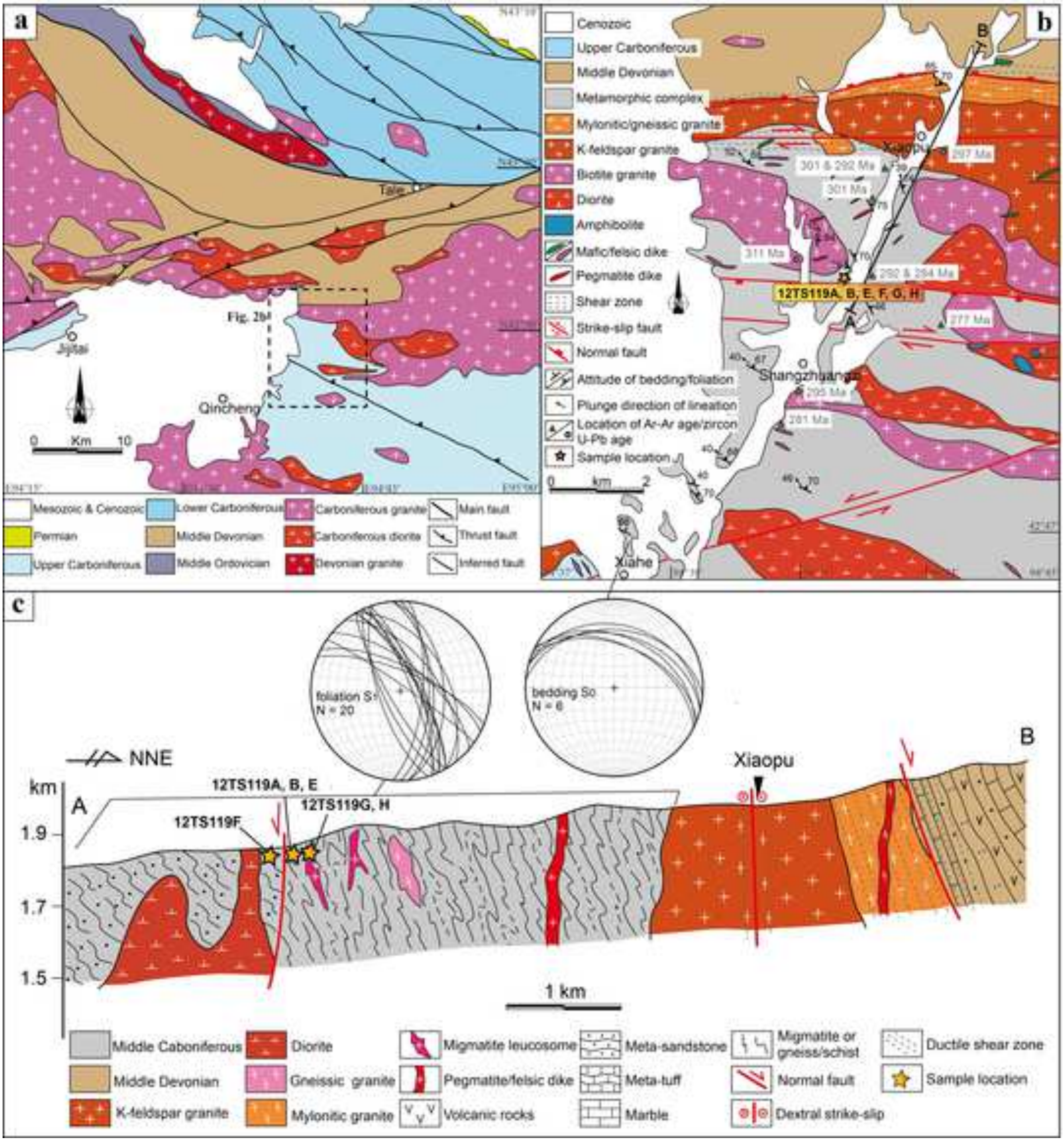


Figure 3

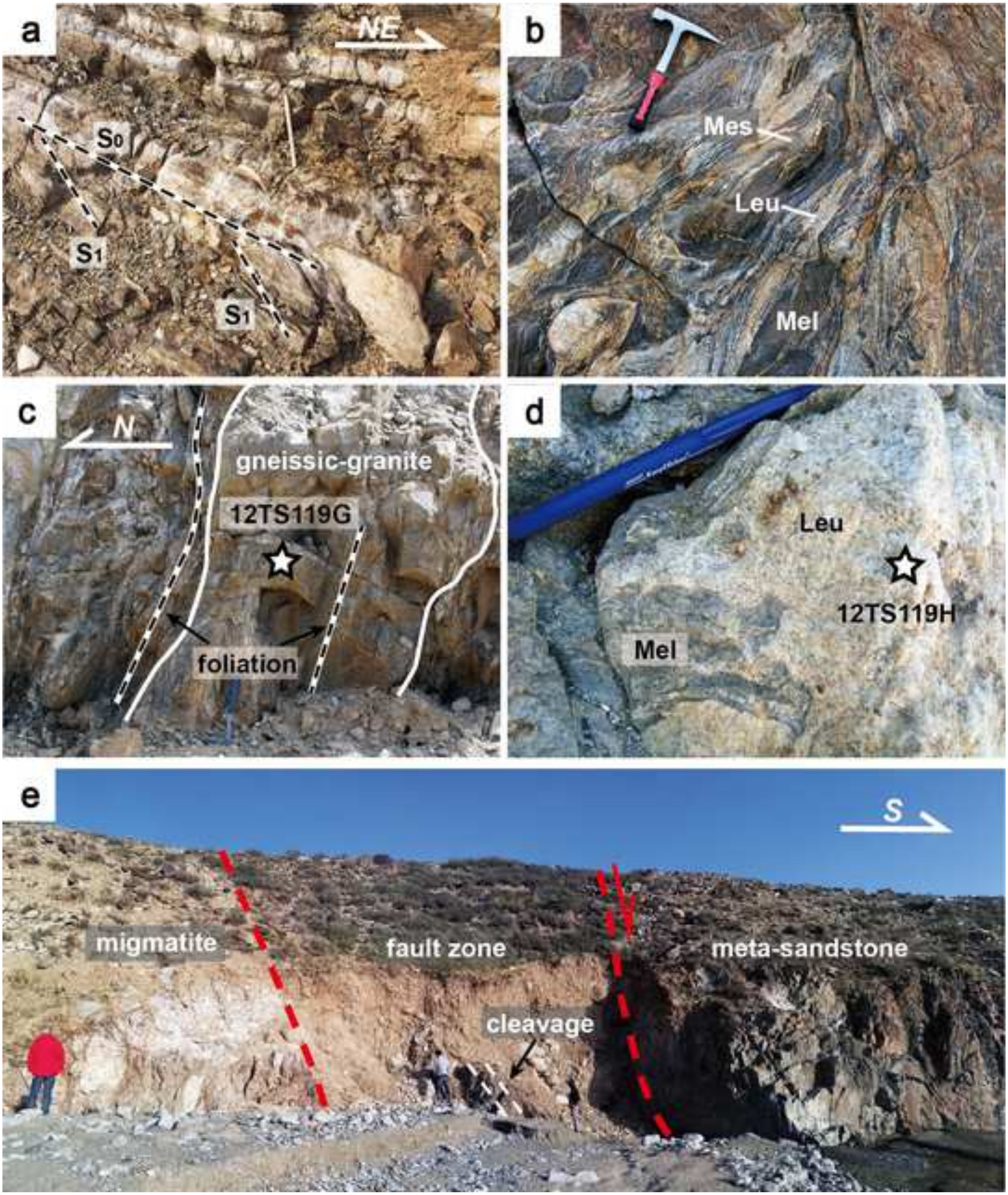

a
NE
S0
S1
S1
b
Mes
Leu
Mel
c
N
gneissic-granite
12TS119G
foliation
d
Leu
12TS119H
Mel
e
S
migmatite
fault zone
meta-sandstone
cleavage

Figure 4

Click here to access/download;Figure;Fig. 4. Photomicrographs of metamorphic rocks and migmatites.jpg

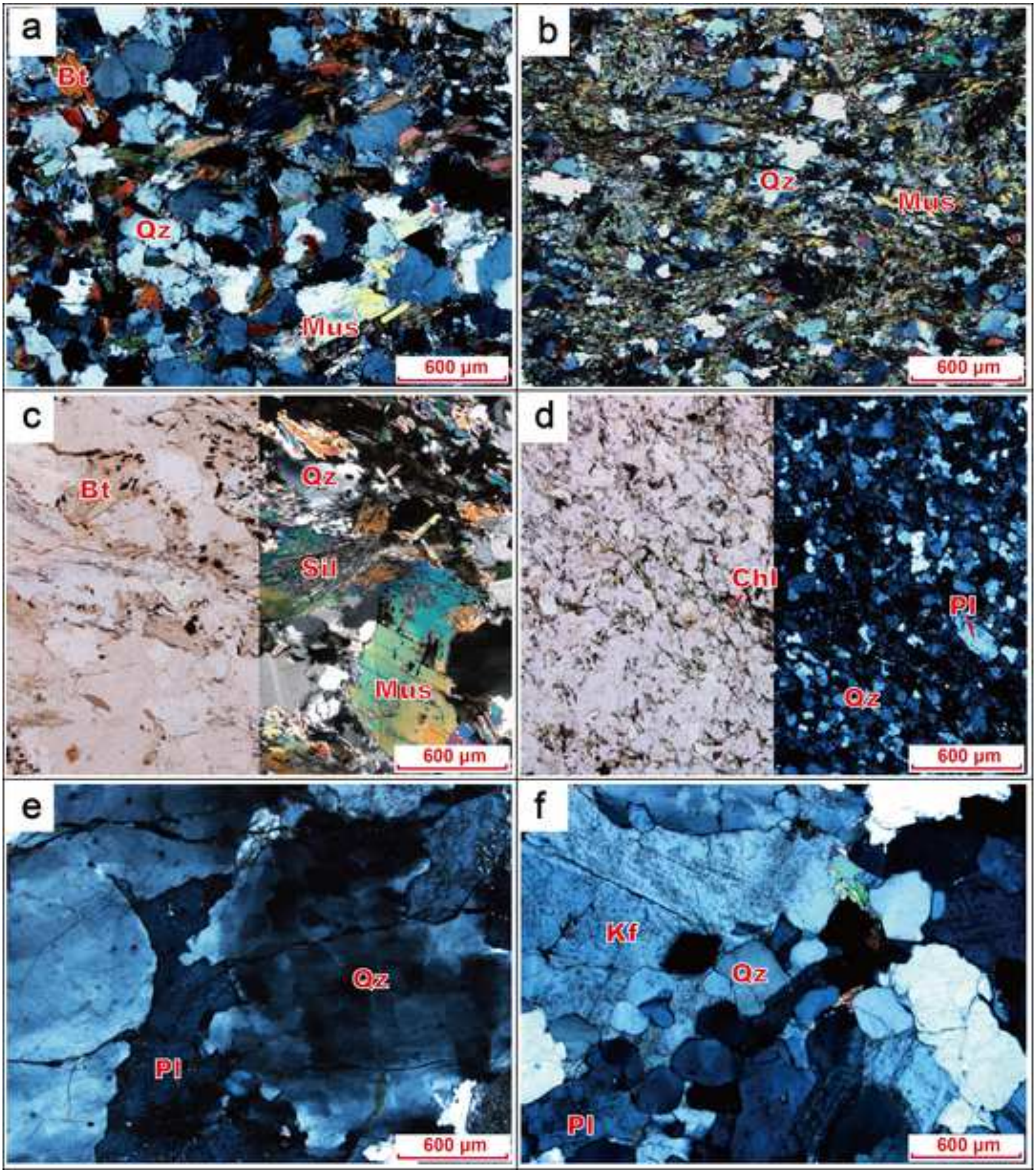


Figure 5

Click here to access/download;Figure;Fig. 5. CL images for representative detrital zircons.jpg

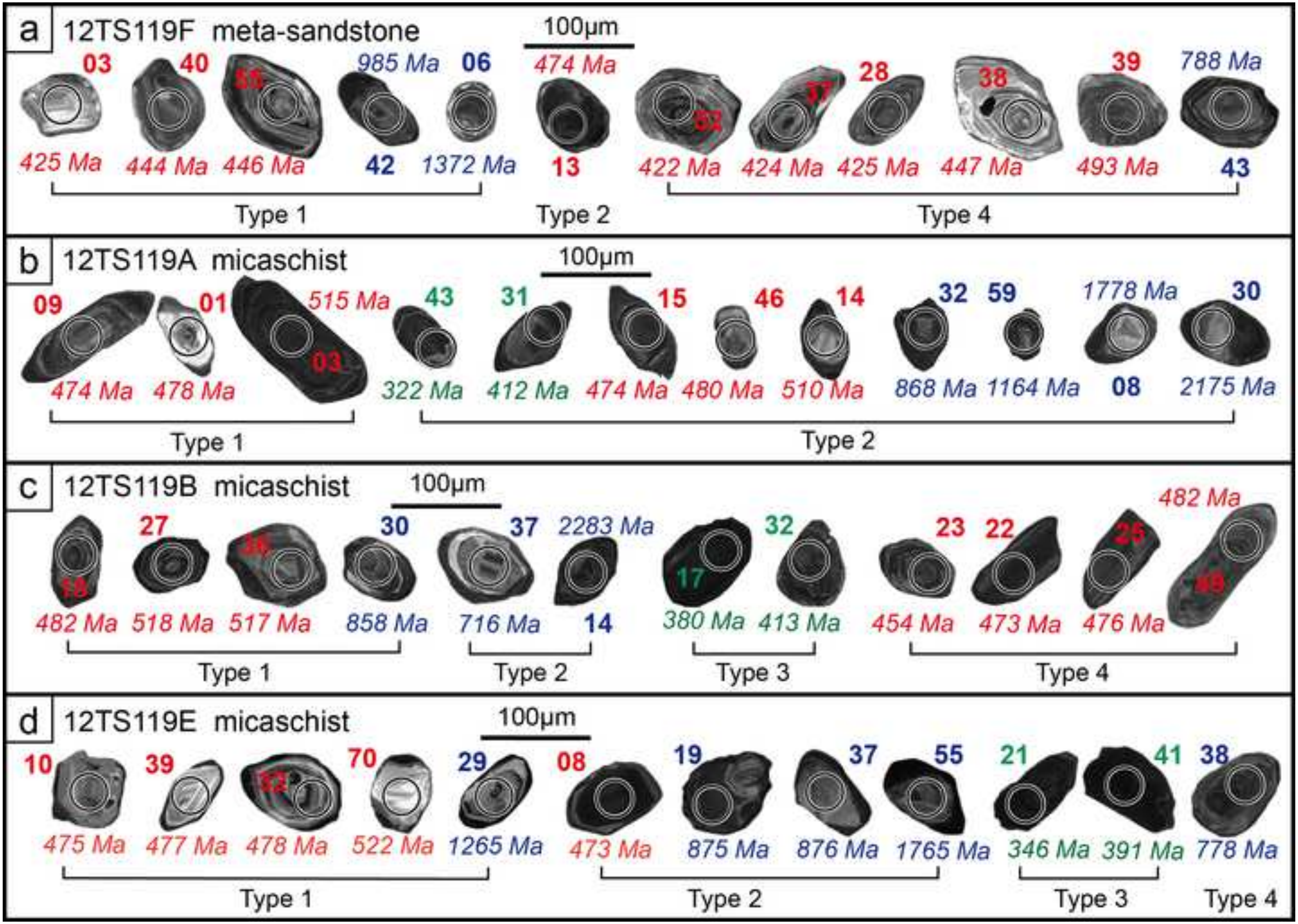
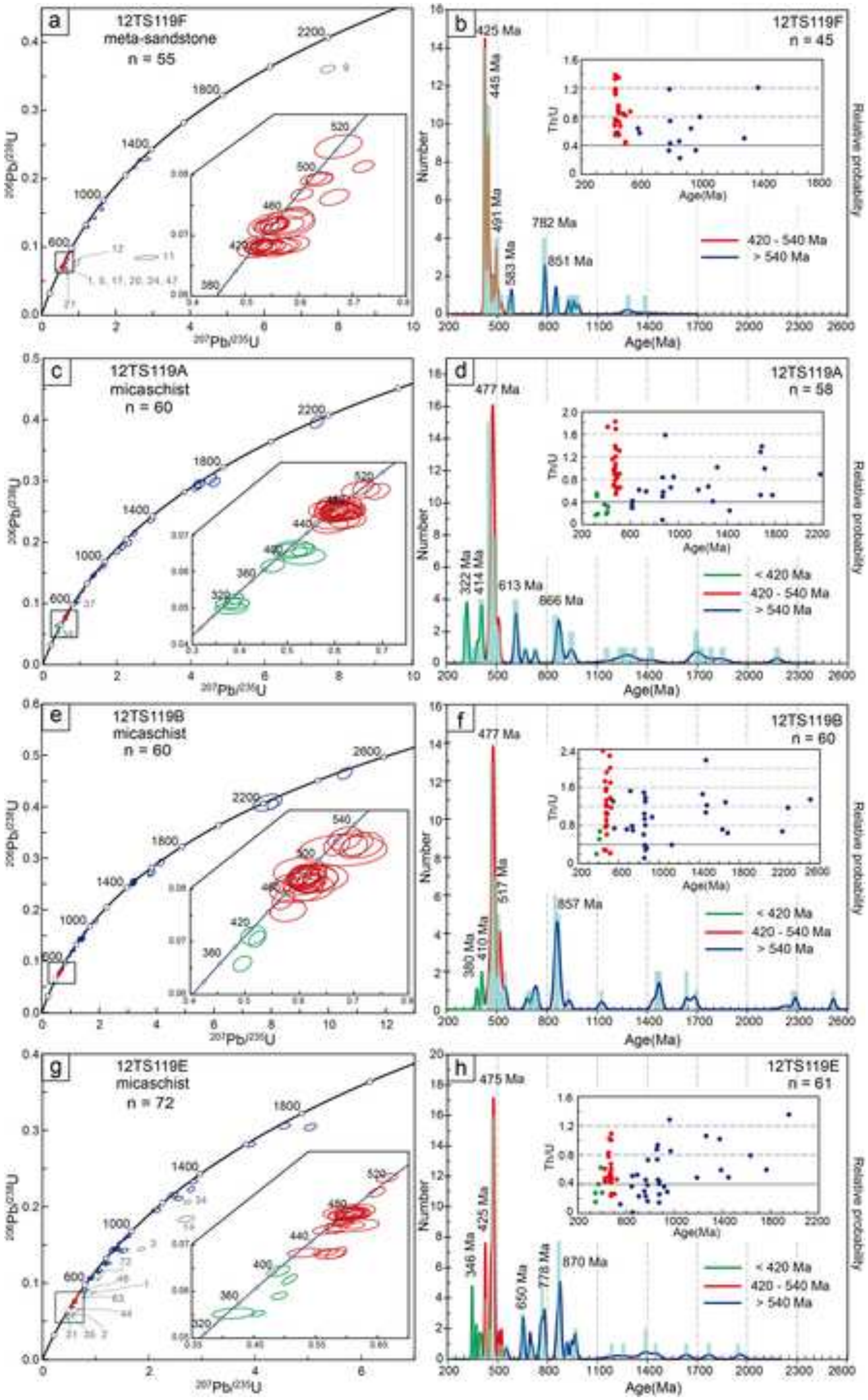


Figure 6


a
12TS119F
meta-sandstone
n = 55
b
12TS119F
n = 45
425 Ma
445 Ma
491 Ma
583 Ma
782 Ma
851 Ma
420 - 540 Ma
> 540 Ma
c
12TS119A
micaschist
n = 60
d
12TS119A
n = 58
477 Ma
322 Ma
414 Ma
613 Ma
866 Ma
< 420 Ma
420 - 540 Ma
> 540 Ma
e
12TS119B
micaschist
n = 60
f
12TS119B
n = 60
477 Ma
517 Ma
380 Ma
410 Ma
857 Ma
< 420 Ma
420 - 540 Ma
> 540 Ma
g
12TS119E
micaschist
n = 72
h
12TS119E
n = 61
475 Ma
346 Ma
425 Ma
650 Ma
778 Ma
870 Ma
< 420 Ma
420 - 540 Ma
> 540 Ma
Number
Age(Ma)
Th/U
Relative probability

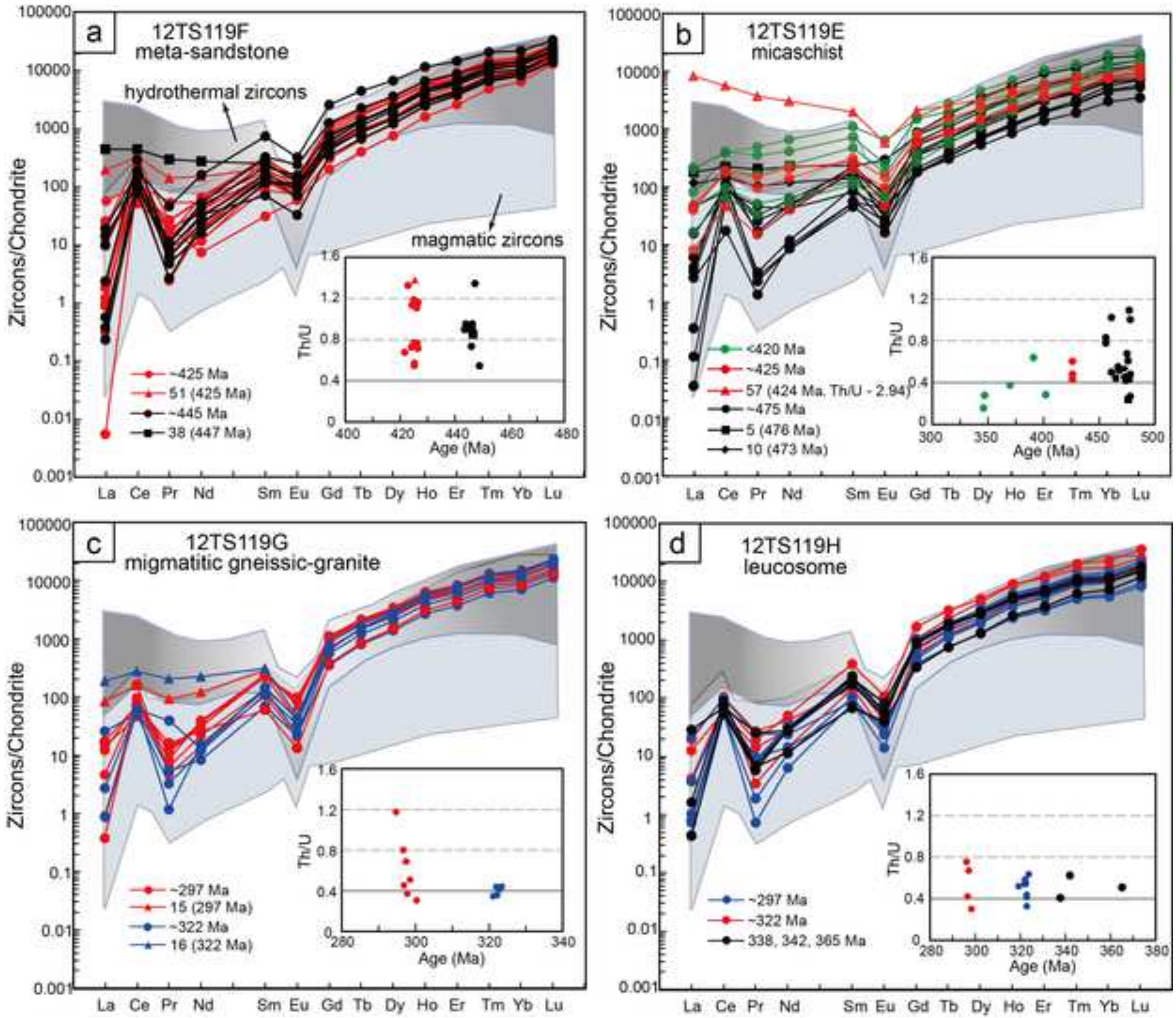

a
12TS119F
meta-sandstone
hydrothermal zircons
magmatic zircons
Zircons/Chondrite
~425 Ma
51 (425 Ma)
~445 Ma
38 (447 Ma)
Th/U
Age (Ma)
b
12TS119E
micaschist
<420 Ma
~425 Ma
57 (424 Ma, Th/U - 2.94)
~475 Ma
5 (476 Ma)
10 (473 Ma)
c
12TS119G
migmatitic gneissic-granite
~297 Ma
15 (297 Ma)
~322 Ma
16 (322 Ma)
d
12TS119H
leucosome
~297 Ma
~322 Ma
338, 342, 365 Ma
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu

Figure 8

Click here to access/download;Figure;Fig. 8. CL images, concordia and U-Pb age.jpg

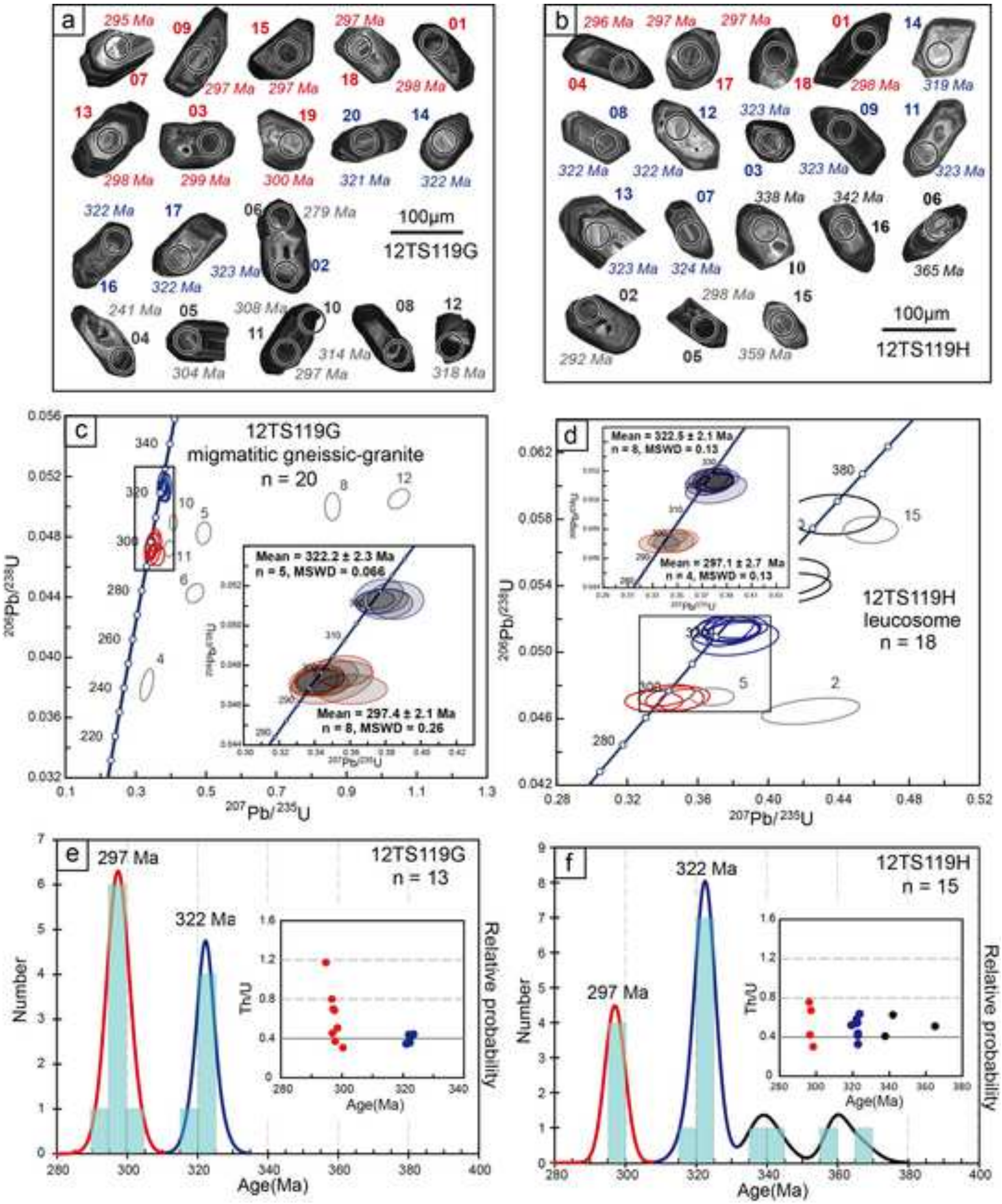


Figure 9

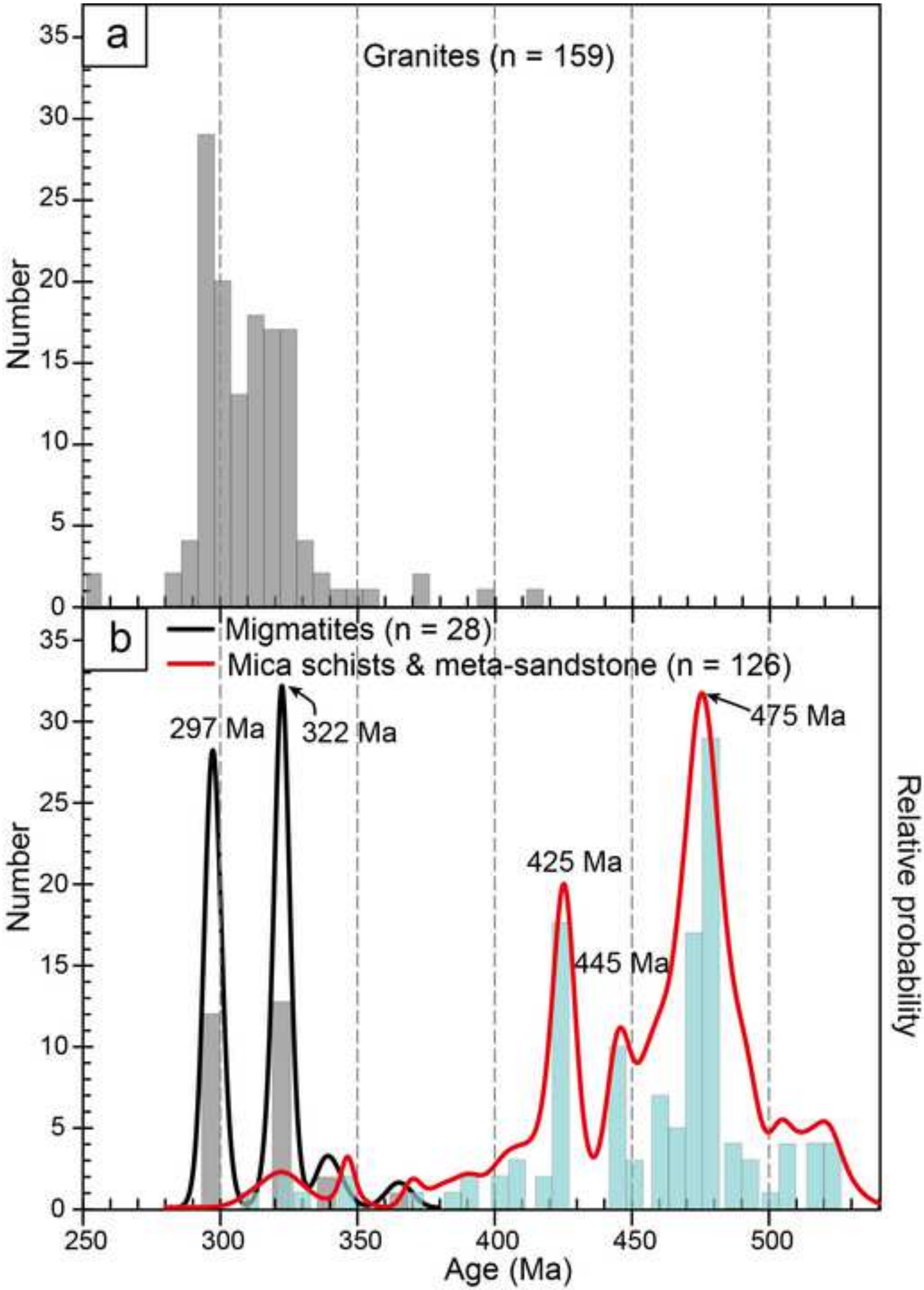

a
Granites (n = 159)
Number
35
30
25
20
15
10
5
0
b
Migmatites (n = 28)
Mica schists & meta-sandstone (n = 126)
297 Ma
322 Ma
425 Ma
445 Ma
475 Ma
Relative probability
250
300
350
400
450
500
Age (Ma)

Figure 10

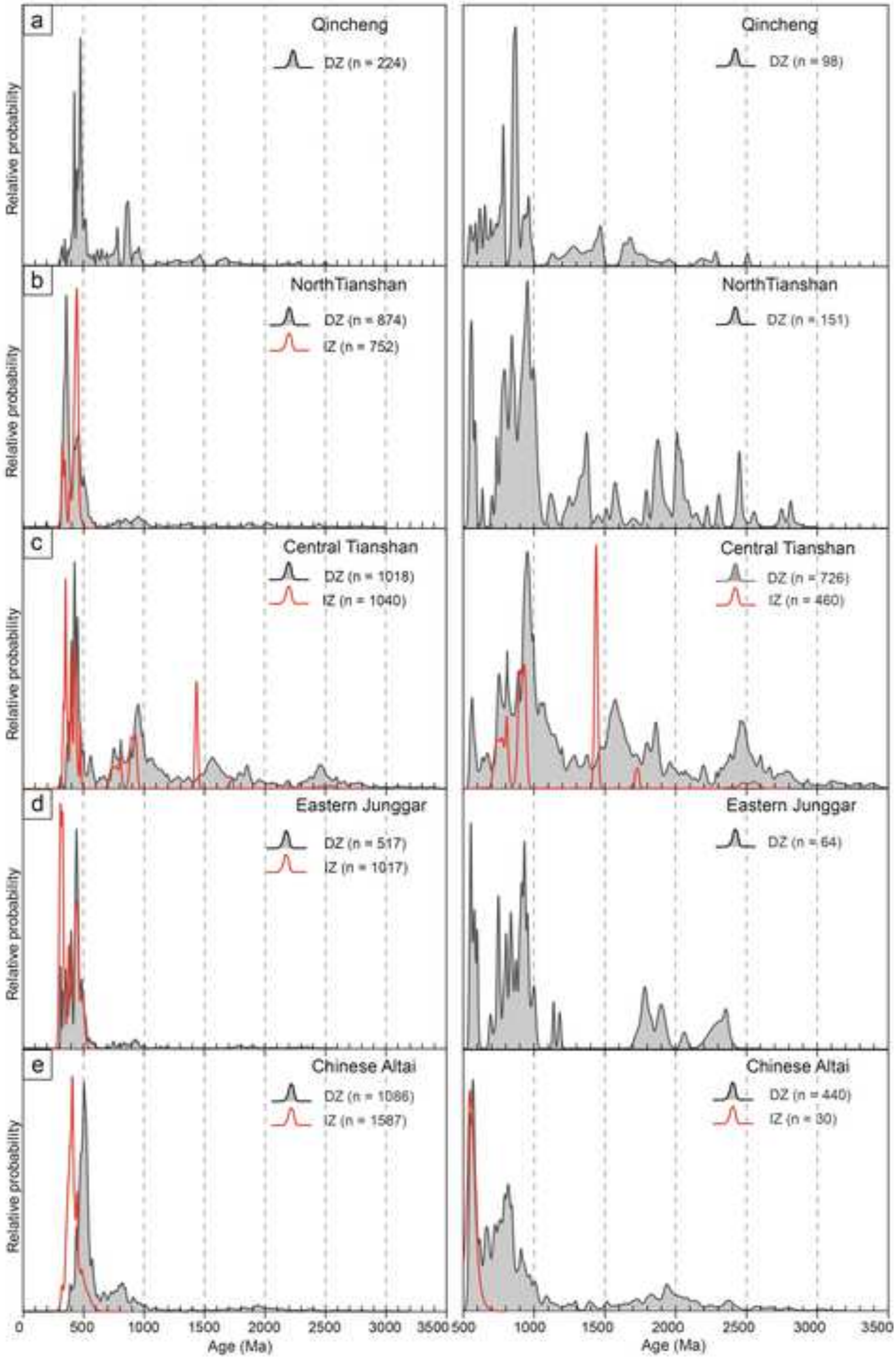

a
Qincheng
DZ (n = 224)
Qincheng
DZ (n = 98)
b
NorthTianshan
DZ (n = 874)
IZ (n = 752)
NorthTianshan
DZ (n = 151)
c
Central Tianshan
DZ (n = 1018)
IZ (n = 1040)
Central Tianshan
DZ (n = 726)
IZ (n = 460)
d
Eastern Junggar
DZ (n = 517)
IZ (n = 1017)
Eastern Junggar
DZ (n = 64)
e
Chinese Altai
DZ (n = 1086)
IZ (n = 1587)
Chinese Altai
DZ (n = 440)
IZ (n = 30)
Relative probability
Age (Ma)
0
500
1000
1500
2000
2500
3000
3500

Figure 11

Click here to access/download;Figure;Fig. 11. Tentative cartoon model.jpg

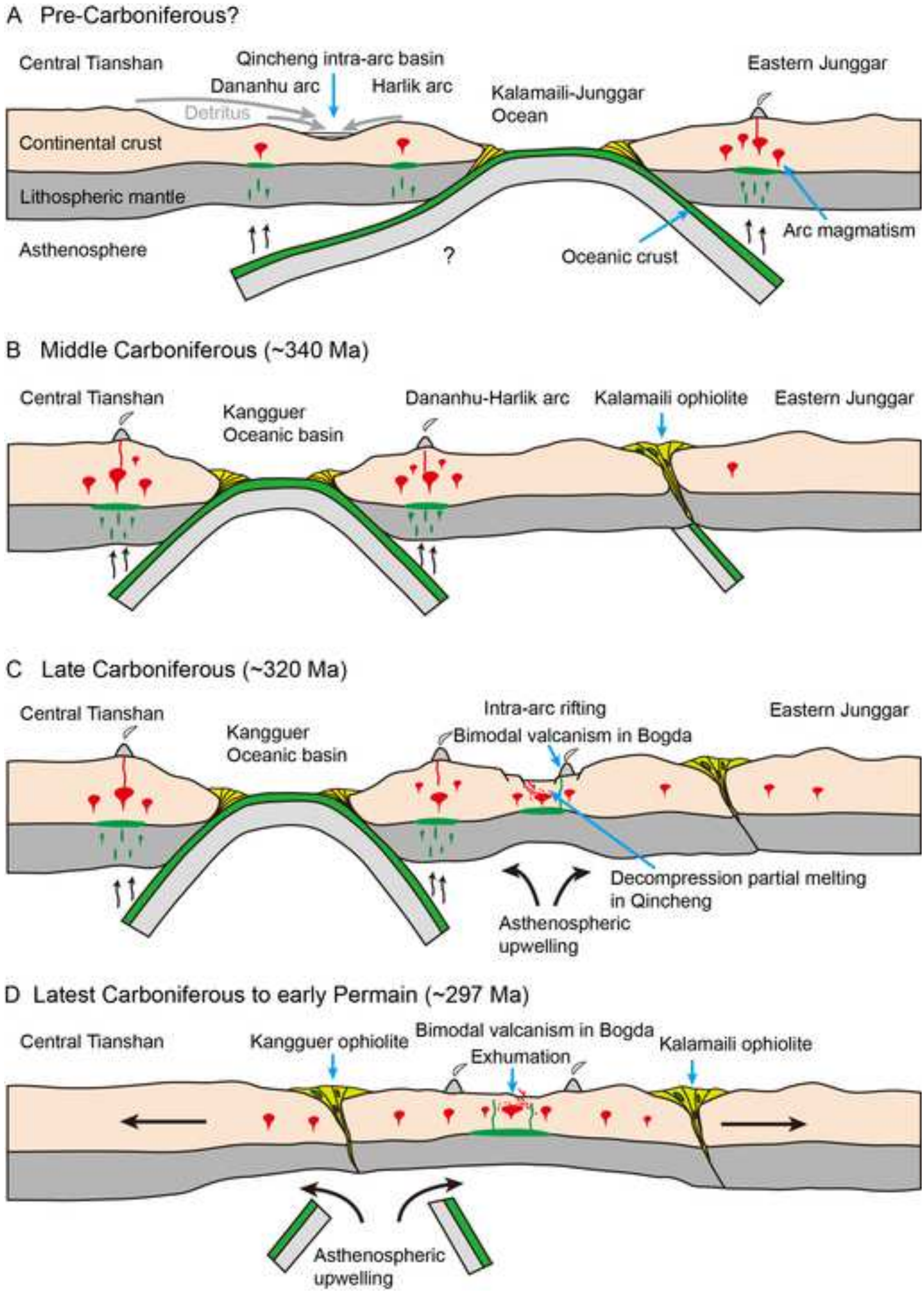
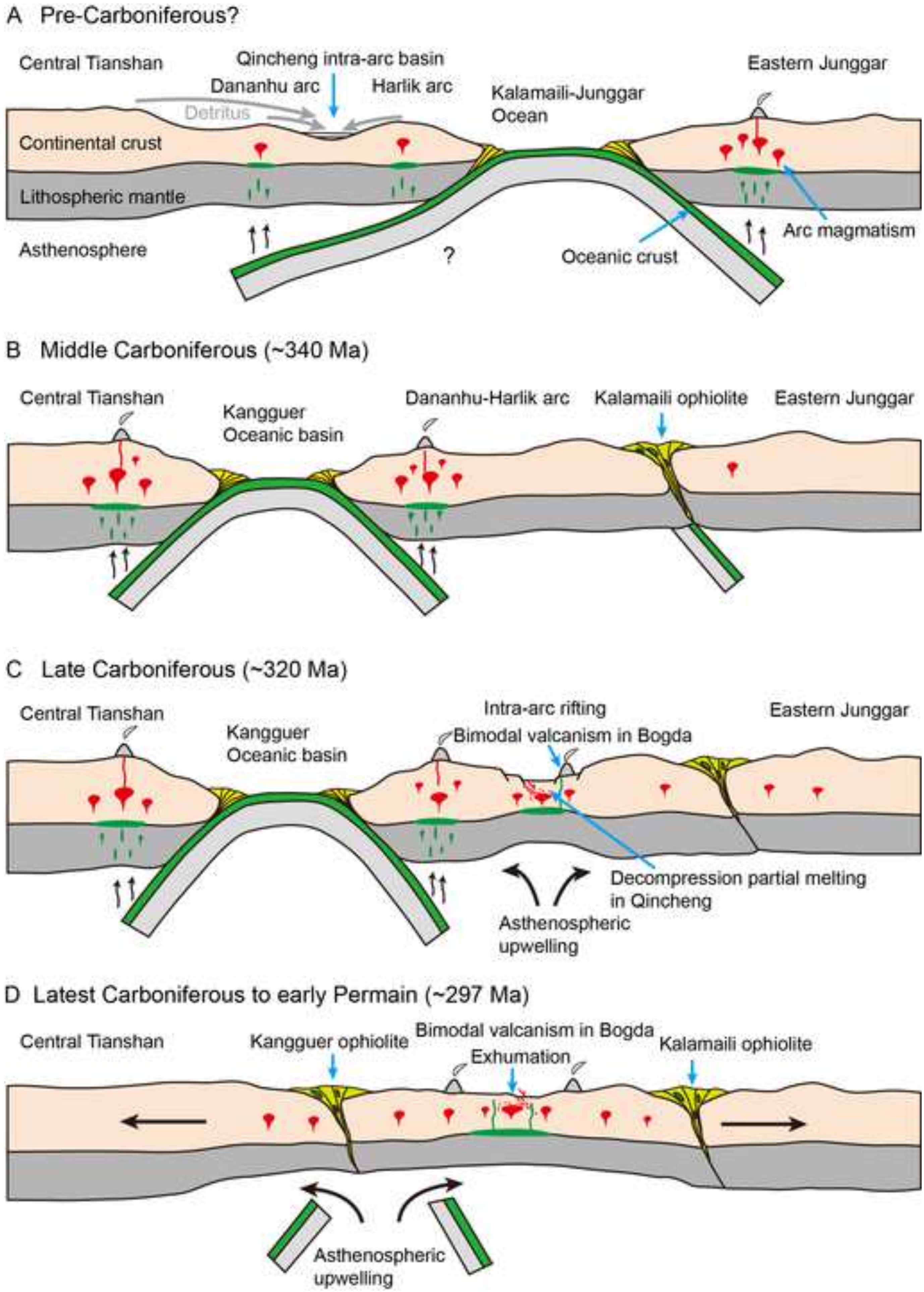


Table 1

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 silimanite	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?
Central Tianshan
Qincheng intra-arc basin
Dananhu arc
Harlik arc
Detritus
Kalamaili-Junggar Ocean
Eastern Junggar
Continental crust
Lithospheric mantle
Asthenosphere
?
Oceanic crust
Arc magmatism
B Middle Carboniferous (~340 Ma)
Central Tianshan
Kangguer Oceanic basin
Dananhu-Harlik arc
Kalamaili ophiolite
Eastern Junggar
C Late Carboniferous (~320 Ma)
Central Tianshan
Kangguer Oceanic basin
Intra-arc rifting
Bimodal valcanism in Bogda
Eastern Junggar
Decompression partial melting in Qincheng
Asthenospheric upwelling
D Latest Carboniferous to early Permain (~297 Ma)
Central Tianshan
Kangguer ophiolite
Bimodal valcanism in Bogda
Exhumation
Kalamaili ophiolite
Asthenospheric upwelling

Supplementary Figure S1

Supplementary Figure S2

Supplementary Table S1

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Supplementary Material
Supplementary Table S1.xls

Supplementary Table S2

Supplementary Table S3

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Supplementary Material
Supplementary Table S3.xls

*Declaration of Interest Statement

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.